

UNIVERSIDADE DE SÃO PAULO
ESCOLA POLITÉCNICA

PAULO VALLE

**Assessing the Vapor Intrusion Pathway:
Applicability of International Regulatory Guidelines for Contaminated Sites in Brazil**

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**Assessing the Vapor Intrusion Pathway:
Applicability of International Regulatory Guidelines for Contaminated Sites in Brazil**

Final

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Orientador: Prof. Dr. Paulo Lojkasek Lima

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Paulo Valle

RESUMO

Valle, Paulo de Tarso Ammon. Assessing the Vapor Intrusion Pathway: Applicability of International Regulatory Guidelines for Contaminated Sites in Brazil. 2022. 64 f. Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de Brownfields) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2022.

O órgão ambiental americano EPA define Intrusão de Vapores (IV) como a migração de vapores de uma fonte de contaminação subterrânea, como solo e águas subterrâneas contaminadas, até o interior de casas ou edifícios sobrepostos. O resultado de uma investigação de IV é um fator decisivo na definição da estratégia de gestão de risco de uma área contaminada. No entanto, apesar da crescente conscientização sobre os processos que regem a IV, ainda há países sem normas reguladoras para estruturar a avaliação da IV e seu processo de decisão (o Brasil, por exemplo). O presente estudo fornece uma visão geral dos principais elementos envolvidos nas avaliações de IV e discute a aplicabilidade de normas reguladoras publicadas nos EUA e na Europa para sites contaminados no Brasil. A caracterização de IV normalmente envolve o uso de modelagem e ferramentas de avaliação de risco conservadoras para estimar se a IV está ocorrendo, e campanhas de amostragem confirmatória nos receptores identificados. Caracterizar a IV é um processo complexo que requer uma compreensão ampla da distribuição de contaminantes em subsuperfície e dos processos que governam o transporte dos vapores presentes no solo até os potenciais receptores. Os padrões climáticos regionais e as condições locais observadas nos edifícios e casas afetadas influenciam consideravelmente o processo de atenuação que ocorre da fonte ao receptor, portanto, o uso de conjuntos de dados empíricos que refletem as condições locais geralmente resultam em tomadas de decisão mais precisas e um melhor gerenciamento do risco. Este documento descreve a importância da elaboração de Modelos Conceituais de Intrusão de Vapores específicos que representem com precisão os processos que ocorrem no subsolo e nos receptores potencialmente afetados, e propõem elementos a serem incluídos em uma norma reguladora para gerenciamento de IV em áreas contaminadas no Brasil.

Palavras-chave: Áreas Contaminadas. Intrusão de Vapores. Normas Técnicas.

ABSTRACT

Valle, Paulo de Tarso Ammon. Assessing the Vapor Intrusion Pathway: Applicability of International Regulatory Guidelines for Contaminated Sites in Brazil. 2022. 64 f. Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de Brownfields) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2022.

The USEPA defines Vapor Intrusion (VI) as the migration of vapors from a subsurface source, such as contaminated soil and groundwater, into overlying buildings or enclosed spaces. The outcome of a VI assessment is a decisive factor in defining the risk management strategy for a contaminated area. However, despite of the growing awareness of the processes governing VI, there are still countries without guidelines to structure the VI assessment and its decision-making process (Brazil as an example). The current study provides an overview of key elements involved in VI assessments, and discuss the applicability of US and European regulatory guidelines for contaminated sites in Brazil. The general VI assessment approach involves using conservative modeling and risk assessment tools to assess if VI is occurring, and sampling campaigns to confirm if the VI pathway is complete. Characterizing the VI pathway is a complex process that requires a thorough understanding of the contaminant distribution in subsurface and of the processes governing soil gas transport towards potential receptors. Regional climate patterns and local building conditions will influence considerably the attenuation process occurring from source to the receptor, therefore the use of empirical data sets that reflect local country conditions generally results in more accurate risk based decision-making. This document describes the importance of elaborating receptor specific Vapor Intrusion Conceptual Site Models that represent accurately the processes occurring in the subsurface and in the receptors, and propose elements to be included in a VI guideline document for sites located in Brazil.

Keywords: Contaminated Areas. Vapor Intrusion. Regulatory Guidelines.

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ACRONYMS AND ABBREVIATIONS

AF	Attenuation Factor
CAS-RN	Chemical Abstracts Service – Registry Number
CETESB	<i>Companhia Ambiental do Estado de São Paulo</i> – Environmental Protection Agency of the State of São Paulo
CGP	Code of Good Practice
COC	Contaminants of Concern
CONAMA	<i>Conselho Nacional do Meio Ambiente</i> – National Environmental Council
CSIA	Compound Specific Isotope Analysis
CSM	Conceptual Site Model
DoD	Department of Defense
DRF	Dutch Reference Framework
EPA	Environmental Protection Agency
GAC	<i>Gerenciamento de Áreas Contaminadas</i> – Management of Contaminated Areas
HPT	Hydraulic Profiling Tool
HVAC	Heating, Venting and Air Conditioning
IAER	Indoor Air Exchange Rate (Q_{Bldg} – USEPA, 2015)
ICC	International Code Council
IECC	International Energy Conservation Code
ITRC	Interstate Technology & Regulatory Council
LIZ	Lateral Inclusion Zone
LNAPL	Light Non-Aqueous Phase Liquid
m-bgl	Meters Below Ground Level
MIP	Membrane Interface Probe
MLE	Multiple Lines of Evidence
NAPL	Non-Aqueous Phase Liquid
NJDEP	New Jersey Department of Environmental Protection
OSWER	Office of Solid Waste and Emergency Response
OVAM	<i>Openbare Vlaamse Afvalstoffenmaatschappij</i> – Public Waste Agency of the Region of Flanders, Belgium
PHC	Petroleum Hydrocarbons
PVI	Petroleum Vapor Intrusion
RCRA	Resource Conservation and Recovery Act
RIVM	<i>Rijksinstituut voor Volksgezondheid en Milieu</i> – National Institute for Health and Environment of the Netherlands
SSAF	Sub-Slab-to-Indoor-Air Attenuation Factor
SSD	Sub-Slab Depressurization
TCE	Trichloroethylene
USEPA	United States Environmental Protection Agency
VER	Vapor Exchange Rate (Q_{Soil} – USEPA, 2015)
VI	Vapor Intrusion
VICSM	Vapor Intrusion Conceptual Site Model
VIG	Vapor Intrusion Guidance
VIR	Vapor Intrusion Risk
VISL	Vapor Intrusion Screening Levels
VSD	Vertical Separation Distance
1,2-DCA	1,2-Dichloroethane

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1. INTRODUCTION

Vapor Intrusion (VI) is defined as the process by which volatile contaminants present in soil and/or groundwater migrate into buildings and degrade the quality of the indoor air. VI is one of the human health risk pathways associated with the exposure to soil and groundwater pollution, and its outcome is a decisive factor in dictating the need for remediating a given Site or mitigating the impacts at a given receptor.

The concern around soil and groundwater pollution dates back to the 1970s when a few contamination cases started to become known and to receive public attention. In Europe, one of the first cases to get public attention was the “Contamination Scandal of Lekkerkerk”¹, a Dutch community located close to Rotterdam in the Netherlands. In this area, a residential neighborhood with over 300 homes was constructed on a landfill built using heavily polluted grounds (a practice that was not uncommon during this period). The residents started noticing odors, and the problem came to light after an underground water line was damaged by the action of aggressive chemicals present in the subsoil (see Photo 1).



*Photo 1. Chemical waste excavated in Lekkerkerk
(Date: 23 April 1980)*

Source: Dijk, Hans van / Anefo - Fotocollectie Anefo. Nationaal Archief, Den Haag, nummertoeegang 2.24.01.05, bestanddeelnummer 930-7893.

The Lekkerkerk scandal received a lot of public attention in the Netherlands, and together with a few other scandals like the Volgermeerpolder in Amsterdam², it led the country to become one of the first European nations to develop a specific regulatory framework to deal with cases of soil and groundwater contamination. As a result, the Dutch Soil Protection Act came into effect on 1 January 1987, rapidly becoming a reference for many other countries across the globe that were facing similar challenges.

Brazil was one of these countries, and much of the environmental legislation and regulatory guidelines applied in Brazil during its early days was based on the Dutch Reference Framework (DRF). To this day, the DRF is still one of the most well know and used European references

¹ For more info: https://nl.wikipedia.org/wiki/Gifschandaal_Lekkerkerk

² For more info: <https://nl.wikipedia.org/wiki/Volgermeerpolder>

for dealing with soil and groundwater contamination, and many countries that still did not develop their own legislative framework rely on the DRF as a guiding principle.

Despite of the growing awareness of the potential environmental and human-health impacts associated with soil and groundwater pollution, the regulatory guidelines developed during this initial period (considered here as before year 2000) gave limited attention to VI. Most of the soil and groundwater guidelines did recognize the potential risks associated with the vapor exposure route and required its assessment; however, they did not set a framework on how to perform the assessments, leading in many cases to Conceptual Site Models (CSM) where the VI pathway was not properly characterized or understood.

This situation started to change after year 2000, when regulatory agencies started developing specific guidelines to support the assessment of potential VI impacts. The United States Environmental Protection Agency (USEPA) has been from the start one of the driving forces behind this process, and by 2002 the USEPA had already published the following federal guidance documents for supporting the evaluation of the VI pathway:

- December 2001 – RCRA³ Draft Supplemental Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway (Vapor Intrusion Guidance); and
- November 2002 – OSWER⁴ Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance) (EPA530-D-02-004).

Although draft in nature, these documents established an initial framework on how to perform VI assessments and ignited a global interest around the theme, with many states in US and countries around the globe starting to develop and publish their own protocols.

In June 2015 the USEPA issued an update of the VI draft guidance documents listed above (OSWER Publication 9200.2-154 – Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air). The goal of this document was to update where needed the technical recommendations of the USEPA related to VI, and to promote a more consistent approach when assessing and mitigating VI impacts.

³ RCRA – Resource Conservation and Recovery Act – is the public law in US that regulates the proper management of hazardous and non-hazardous solid waste.

⁴ OSWER – Office of Solid Waste and Emergency Response – is the former name of the current Office of Land and Emergency Management (OLEM) of the USEPA.

Following the issuing of this revised document in 2015, many states in US also issued new or revised versions of their own protocols. According to Eklund et al. (2018), as of January 2018 around 80% of states in US already had published some level of Vapor Intrusion Guidance (VIG) document, with more than half of these states issuing new or updated reports in the past 5 years.

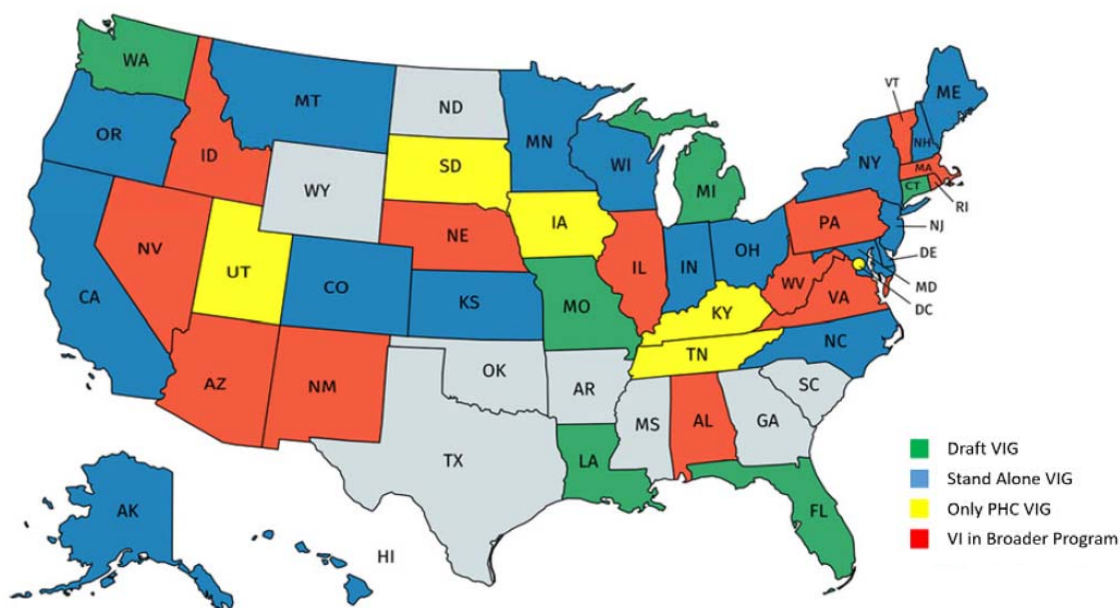


Figure 1. States with draft or final Vapor Intrusion Guidelines (VIG) (as of January 2018)
(Eklund et al., 2018)

A similar situation has been developing in Europe, with more countries issuing specific guidance documents to address the VI exposure pathway since 2000. In the Netherlands, the National Institute for Health and Environment RIVM (*Rijksinstituut voor Volksgezondheid en Milieu*) published in 2007 a guideline for performing air measurements in the context of VI investigations (RIVM Report 711701048/2007 – July 2007 – *Richtlijn voor luchtmetingen voor de risicobeoordeling van bodemverontreiniging*). In this document, the RIVM describes a stepped approach to assess potential human health risks to the residents/users of a building located above or near soil and/or groundwater pollution, and highlights the importance of an effective investigation strategy for the correct characterization of the VI pathway.

One of the most recent documents published in Europe was issued in Belgium in 2019. The Flemish regulatory agency OVAM (*Openbare Vlaamse Afvalstoffenmaatschappij*) published a Code of Good Practice (CGP) summarizing technical recommendations for assessing the

potential intrusion of vapors into indoor air from subsurface sources (OVAM CGP – March 2019 – *Code van Goede Praktijk: Evaluatie van uitdampingsrisico's in het kader van bodem- en grondwater-verontreinigingen*). The OVAM document focused on the elaboration of project specific CSMs to understand the different vapor intrusion exposure scenarios, and based on that, to select the appropriate soil gas and indoor air sampling strategies needed to assess the potential human health risks.

This profusion of regulatory VIG documents across the globe is a positive recognition by regulatory agencies of the importance of this risk exposure route in the management of contaminated sites. However, despite of the growing number of documents being issued, there are still a considerable number of countries without specific guidelines to address the VI pathway (Brazil as an example).

It is a common practice for countries without VIG to rely on documents issued by other regulatory bodies. In Brazil, the USEPA guidelines are currently considered by the Environmental Protection Agency of the State of São Paulo CETESB, as well as other state regulatory agencies, as good references for assessing potential human-health risks and the exposure pathway from subsurface vapor sources to indoor air.

However, given that some of the recommendations and proposed strategies included in these regulatory documents are based on local conditions and empirical data sets, their direct applicability for sites located in Brazil is often questioned. That is the case for example of the empirical Attenuation Factors (AF) published by the USEPA, where (among other factors) the composition of the shallow soils, the country climate zonation's, and the characteristics of the buildings being affected by the subsurface impacts can have a profound impact in the outcome of the VI assessment and the decisions that follows.

This essay will explore the approaches recommended by selected regulatory agencies when assessing the potential for VI associated with soil and groundwater impacts, and discuss the applicability of some of the recommendations listed in these guidelines for sites located in Brazil.

2. OBJECTIVES AND JUSTIFICATION

Soil and groundwater contamination in Brazil is regulated at federal level by the CONAMA 420/2009 resolution. The CONAMA 420/2009 provides a national framework for the management of contaminated sites in Brazil and establish regulatory values for a number of chemical substances generally associated with soil and groundwater pollution.

In addition to the federal legislation, states in Brazil may also have their own protocols, enforcing additional guidelines and regulatory values. One of the most complete and thorough state guidelines available in Brazil is the “*Manual de Gerenciamento de Áreas Contaminadas (GAC)*” (CETESB, 2021). The CETESB GAC manual is not only used as a reference for the management of contaminated areas in São Paulo, but as a guideline in many other Brazilian states as well.

The CETESB GAC manual provides a detailed framework and stepped approach for 1) assessing areas suspected of contamination, 2) for investigating the areas where contamination has been confirmed, and 3) for remediating the areas where the impacts pose a risk to human health or the environment.

Many of the substances regulated in the Brazilian federal and state guidelines for soil and groundwater are volatile compounds that can pose a risk to human health via the vapor intrusion pathway. From the 83 regulated substances⁵ currently included in the list of reference values for soil and groundwater for the state of São Paulo (DD125/2021/E, dated 9/12/2021), the vast majority are classified as volatile. Although the CETESB GAC manual provides a clear framework for the assessment of these substances in soil and groundwater, the manual does not include specific guidance on how to perform VI assessments for these compounds.

In 2016 the NICOLE Brasil team published a white paper summarizing key technical aspects



Figure 2. Cover of the White Paper: Intrusão de Vapores em Ambientes Fechados – Conceitos Básicos, Avaliação e Gerenciamento de Áreas Contaminadas no Brasil
NICOLE Brasil – José Carlos Rocha Gouvêa Júnior [et al]. São Paulo, 2016.

⁵ Excluding PCB Indicators, TBT and its associated compounds, and Dioxins & Furans

involved in the VI exposure route (Figure 2 – NICOLE Brasil – May 2016 – *Intrusão de Vapores em Ambientes Fechados – Conceitos Básicos, Avaliação e Gerenciamento de Áreas Contaminadas no Brasil*). The NICOLE white paper was one of the first documents promoting the discussion on how to deal with VI within a Brazilian context.

Gouvea Junior et.al (2018) provided further perspective on how VI is being managed in Brazil. Given the absence of local procedures, Brazilian regulatory agencies often apply (with variable consistency) guidelines published in other countries. In Brazil (as in many other countries), predictive modeling and human health risk assessment are the basis of the assessment framework, and there is still limited use of the Multiple Lines of Evidence (MLE) approach to support the VI decision-making process. The MLE concept and the use of site-specific data appear to be growing in Brazil; however, the lack of a regulatory guideline for characterizing the VI pathway in sites in Brazil makes it very difficult for local regulatory agencies, consulting companies, and site owners to implement a consistent approach when assessing potential VI risks.

The goal of this essay is to provide an overview of the key regulatory elements involved in a VI assessment, and to discuss the applicability of the approaches listed in selected VI guidelines published in US and Europe for contaminated sites in Brazil.

3. METHODOLOGY

The current study was developed based on the review of VIG issued by regulatory agencies, and technical documents published by the scientific community where VI was the key theme discussed.

In order to obtain regulatory perspectives from both the United States and Europe, selected documents published by the USEPA, the ITRC (Interstate Technology & Regulatory Council), the RIVM, and OVAM were consulted.

The USEPA and the Dutch RIVM are regulatory references generally used in the absence of local guidelines, and the ITRC is an internationally renowned US state-led coalition that includes technical representatives from both the public (US state EPAs) and the private sectors. The CGP published by OVAM was consulted during the review process because it is one of the most recent VI guidelines published in Europe, and according to the author, representative of a growing tendency in many countries in Europe.

During the regulatory review process, the following documents were selected for a more extensive review (organized by country):

- United States of America:
 - Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance) – EPA Report 530-D-02-004 – November 2002;
 - Vapor Intrusion Pathway: A Practical Guideline – ITRC Technical & Regulatory Guidance Publication – January 2007;
 - Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios – ITRC Technical & Regulatory Guidance Publication – January 2007;
 - Petroleum Vapor Intrusion Guideline: Fundamentals of Screening, Investigation, and Management – ITRC Technical & Regulatory Guidance Publication – October 2014; and
 - Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air – OSWER Publication 9200.2-154 – June 2015.

- The Netherlands:
 - Guideline for Air Measurements for the Risk Assessment of Soil Contamination (“*Richtlijn voor luchtmetingen voor de risicobeoordeling van bodemverontreiniging*”) – RIVM Report 711701048/2007 – July 2007;
 - Note on the Advice for Air Measurements for Vinyl Chloride (“*Notitie advies luchtmetingen van vinylchloride*”) – M. Ramlal, M. H. Broekman, E. Schols – October 2012; and
 - Information Sheet: Understanding Volatile Compounds (“*Informatieblad Grip op vluchtige verbindingen*”) – RIVM– 2015.
- Belgium:
 - Code of Good Practice: Evaluation of Vapor Intrusion Risks in the Context of Soil and Groundwater Contamination (“*Code van Goede Praktijk: Evaluatie van uitdampingsrisico’s in het kader van bodem- en grondwaterverontreinigingen*”) – OVAM Report – March 2019.

For the search of scientific articles, the web based databases Scopus, Google Scholar, ResearchGate.net, and NGWA were consulted. The search process used the following key words, separately or combined, in both English and Portuguese language: Vapor Intrusion (*Intrusão de Vapores*); Regulatory Review (*Revisão de Normas Regulatoras*); Risk Management (*Gerenciamento do Risco*); Vapor Sources (*Fontes de Vapores*); and Soil and Groundwater Impacts (*Impactos no Solo e na Água Subterrânea*).

The search results were ranked based on the publication year, and screened based on their title and the content of their abstract. Technical papers that included information relevant to the scope of the present study were further reviewed.

Case studies and data from actual projects were also incorporated in the essay in order to endorse specific technical information provided, or to illustrate certain views from the author. For confidentiality reasons, any project identifiable information may have been removed or altered in such a way that the sites/projects presented in the case studies can no longer be identified directly or indirectly.

Finally, this study also included the review of other sources of information available in books or internet websites.

4. VAPOR INTRUSION : FUNDAMENTAL CONCEPTS

Vapor Intrusion (VI) is defined as the migration of vapors from a subsurface source, such as contaminated soil and groundwater, into overlying buildings or enclosed spaces (USEPA, 2015). In the context of soil and groundwater investigations, for VI to occur and create a potential human health risk, the following conditions should be present:

- The substances present in soil and/or groundwater are volatile and can emit vapors that create potential safety hazards (explosive conditions), health effects (toxic levels), or aesthetic problems (bad odors);
- The impacted soil and/or groundwater is located underneath or close to an existing building (or in an area where future buildings will be installed);
- The vapors formed in subsurface have a pathway to migrate towards the building, and the building is susceptible to the entry of vapors;
- The substances observed in soil gas are also present in the indoor environment (or expected to be present in the case of future buildings); and
- The resulting concentrations in the indoor air environment (which are associated with the subsurface impacts and not with other emission sources) exceed regulatory guidelines defined for the applicable land-use scenario (residential or commercial/industrial).

According to the USEPA, when the conditions listed above are met, the VI pathway is referred to as “complete” and the implementation of mitigation/remediation measures are generally required (USEPA, 2015).

The need to investigate the VI pathway is defined during the elaboration of the Conceptual Site Model (CSM) of the project. A CSM is a simplified representation of the physical, chemical and biological processes occurring in a contaminated area, and generally includes a description of the subsurface conditions, any relevant surface features, and the potential exposure pathways associated with the contamination (NJDEP⁶, 2019).

Figure 3 (USEPA, 2015) illustrates the key elements that a CSM elaborated as part of a VI assessment could include. The CSM is an essential tool to identify data gaps in the VI

⁶ NJDEP – New Jersey Department of Environmental Protection

characterization process and to understand the potential risks posed by the soil gas plume to human receptors.

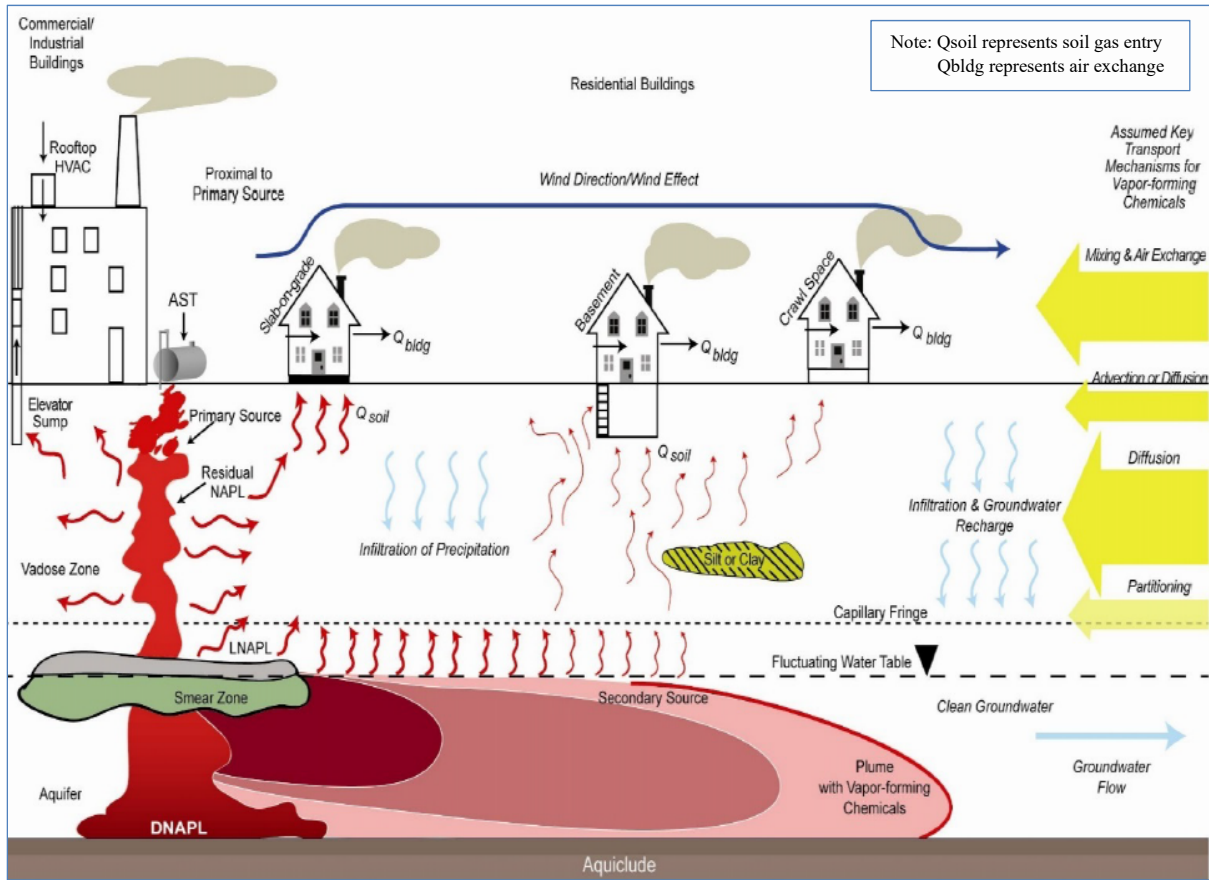


Figure 3. Key elements of the conceptual model of soil vapor intrusion (USEPA, 2015)

In the context of VI assessments, the following questions should be explored during the elaboration of the CSM:

- Are the contaminants present in subsurface *Volatile Compounds*? Can they pose a potential human-health risk through the VI pathway?
- What are the main *Transport and Attenuation Processes* occurring in subsurface? What is the extent of the soil gas plume?
- Are there any *Potential Receptors* located above or near the contaminated area that can be impacted by the soil gas plume? Any preferential pathways or conditions that can facilitate or hinder the VI pathway?

These questions are key to define the potential receptors to be investigated, and the VI investigation strategy to be adopted, which may vary depending on specific characteristics observed in each receptor.

4.1 Volatile Compounds

Within the subsurface, the vadose zone is the top soil layer and extends from the ground surface until the top of the groundwater table. It is also called the zone of aeration, or unsaturated zone, and contains a three-phase system composed of solid materials (solid phase – mineral grains, organic matter), and open spaces filled by water (liquid phase) and soil gases (gaseous phase) (Fetter, 1994).

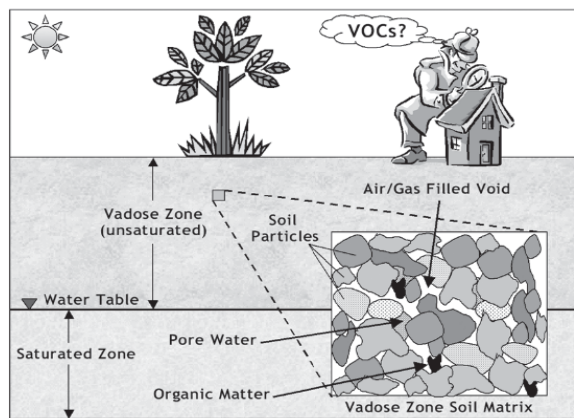


Figure 4. Cross-section depicting the vadose zone and the saturated zone
(Geoprobe Systems, 2006)

The distribution of the contaminant in subsurface and its equilibrium between the different phases in the vadose zone (soil, water and soil gas) is dictated by the physical and chemical properties of the contaminants present, and the characteristics of the impacted media. In the vadose zone, part of the contaminant mass may be sorbed to the solid particles, part may be present as a separate free phase (NAPL⁷), part may be dissolved in any water present in the pores, and part may be present in the soil gas (Geoprobe Systems, 2006).

The soil gas present in the vadose zone is mainly composed of Nitrogen and Oxygen, just like the atmospheric air. However, when volatile chemicals are released in the subsurface, they will begin to volatilize and become part of the soil gas. By migrating in the vadose zone or travelling via underground structures/utilities, the impacted soil gas can enter buildings and degrade the indoor air quality, creating the potential human health risk associated with VI.

VI regulatory guidelines generally consider volatile compounds as substances that have a Vapor Pressure (P^0) greater than 1 mm Hg at room temperature (25°C), and an Henry's Law constant (K_H) greater than 10^{-5} atm m³ mol⁻¹ (NJDEP, 2005b).

⁷ NAPL – Non-Aqueous Phase Liquid

Vapor Pressure (P^0) is defined as the pressure of the vapor of a compound when in equilibrium with its pure condensed phase (liquid or solid) (Schwarzenbach et al., 1993). In source zones, where immiscible fluid (NAPL) may still be present in the vadose zone, the Vapor Pressure (P^0) of the contaminant will indicate its tendency to transfer to a gaseous phase. The higher the vapor pressure of the compound, the more likely the substance is to volatilize and to create a vapor intrusion risk.

Figure 5 (Schwarzenbach et al., 1993) illustrates the ranges in Vapor Pressure (P^0) values at 25°C for different classes of organic compounds.

The Henry's Law constant (K_H) is the coefficient that represents the equilibrium partitioning between the liquid and the gas phase. When a contaminant is present as a dissolved phase in groundwater, or in the pore-water in the vadose zone, the Henry's law constant will indicate its ability to transfer from the water to the vapor phase. The Henry's Law constant (K_H) (Equation 1) can be expressed as the ratio between the concentration of the substance in the vapor phase (C_{Air}) and its concentration in the liquid phase (C_{Water}) and is often used to estimate potential concentrations in soil gas based on concentrations measured in groundwater.

$$\text{Equation 1: } K_H = \frac{C_{Air}}{C_{Water}}$$

As for the Vapor Pressure (P^0), the higher the Henry's Law constant (K_H) of a substance, the more likely the substance present in water is to volatilize and become part of the soil gas.

A complicating factor in the management of contaminated areas is that the Contaminants of Concern (COC) very rarely occur isolated, and more often are present in soil and groundwater as part of a complex mixture. The chemical and physical properties of a mixture of two or more substances depend on its exact chemical composition (Pankow and Cherry, 1996), therefore understanding the composition of the mixture is key to understand the partitioning and distribution of the contaminants in subsurface.

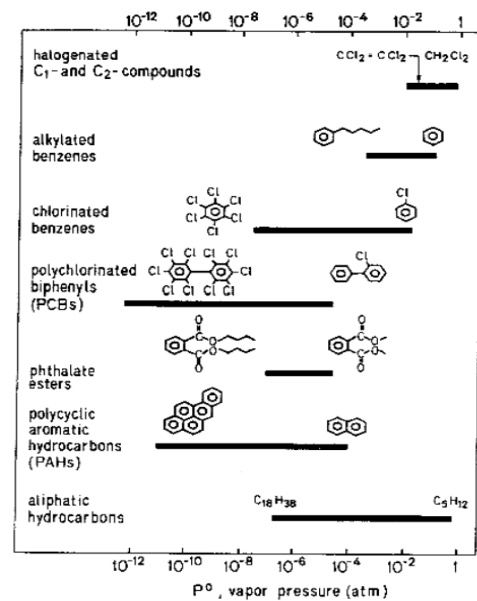


Figure 5. Vapor pressure (P^0) ranges at 25°C for different classes of organic compounds (Schwarzenbach et al., 1993)

When the NAPL present in the vadose is composed of a mixture, the mass transfer between the NAPL and the vapor phase will be governed by the Raoult's Law. According to the Raoult's Law, the Total Vapor Pressure of a NAPL mixture will be equal to the sum of the Partial Vapor Pressures (P_i) of the different substances present in the mixture (Equation 2). The Partial Vapor Pressure (P_i) of each substance can be obtained by multiplying the Vapor Pressure (P^0) of the substance in its pure phase by its molar fraction (X) in the mixture.

$$\text{Equation 2: } P_{NAPL} = P^0_{C1} * X_{C1} + P^0_{C2} * X_{C2} + \dots + P^0_{Cn} * X_{Cn}$$

Where

P^0_C = Vapor Pressure of compound in its pure phase

X_C = Molar Fraction of compound in the mixture

In NAPL mixtures, the Partial Vapor Pressure (P_i) of the different substances present in the mixture should be used to estimate their concentrations in the vapor phase.

Table 4.1 below presents the Vapor Pressure (P^0) and Henry's Law constant (K_H) values of some of the most common volatile compounds encountered during soil and groundwater investigation projects (based on the 2020 CETESB report on rehabilitated areas in the State of Sao Paulo – CETESB, 2020 – as well as the professional experience from the author).

Table 4.1 Summary of volatile compounds most commonly encountered during soil and groundwater investigation projects

Volatile Compound	CAS-RN	(P^0) Vapor Pressure (mm Hg)*	(K_H) Henry's Law Constant (atm-m ³ /mol)*
AROMATIC HYDROCARBONS			
Benzene	71-43-2	9.67E+01	5.55E-03
Toluene	108-88-3	2.88E+01	6.64E-03
Ethylbenzene	100-41-4	9.53E+00	7.88E-03
Xylenes	1330-20-7	5.03E+00	5.18E-03
Styrene	100-42-5	6.22E+00	2.75E-03
CHLOROETHENES			
Tetrachloroethene	127-18-4	1.67E+01	1.77E-02
Trichloroethene	79-01-6	7.29E+01	9.85E-03
Cis-1,2-Dichloroethene	156-59-2	1.12E+02	4.08E-03
Trans-1,2-Dichloroethene	156-60-5	2.57E+02	4.08E-03
1,1-Dicloroeteno	75-35-4	4.95E+02	2.61E-02
Vinyl Chloride	75-01-4	2.97E+03	2.78E-2

Volatile Compound	CAS-RN	(P ⁰) Vapor Pressure (mm Hg)*	(K _H) Henry's Law Constant (atm·m ³ /mol)*
CHLOROETHANES			
1,1,1-Trichloroethane	71-55-6	1.26E+02	1.72E-02
1,2-Dichloroethane	107-06-2	4.62E+01	1.18E-03
1,1-Dichloroethane	75-34-3	2.18E+02	5.62E-03
CHLOROMETHANES			
Dichloromethane	75-09-2	3.78E+02	3.25E-03
Chloroform	67-66-3	1.86E+02	3.67E-03
Carbon Tetrachloride	56-23-5	1.08E+02	2.76E-02

* Source: CETESB Risk Assessment sheets, FisQui tab, EPI

4.2 Transport and Attenuation Processes

Understanding the contaminant distribution in subsurface and the processes governing soil gas transport towards potential receptors is key to assess vapor intrusions risks. According to the USEPA (2012), the four main processes controlling vapor transport in the subsurface are Diffusion, Advection, Phase Partitioning and Biodegradation.

Diffusion is the process in which differences in composition in the soil gas will generate movement of molecules from an area of elevated concentrations to an area of low concentrations. The intensity of the diffusive flux will depend on a variety of factors, including (but not limited to) temperature, concentration gradient, type of compound (molecule size and structure), and soil characteristics (porosity, water content).

Advection is the transport mechanism where the soil gas moves as a bulk in response to pressure gradients or variable vapor densities (i.e. when the COC vapors are denser or lighter than the soil gas). The pressure gradients are generally associated with temperature differences linked to changing weather conditions, building structures and underground utility lines, and/or systems operating inside the receptors (e.g. air conditioners, heating units) (NICOLE BRASIL, 2016).

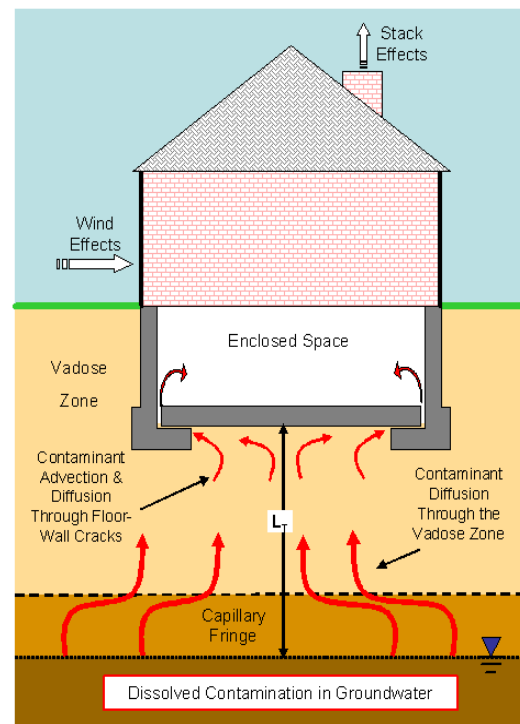


Figure 6. Diffusive and advective transport of vapors near a building (USEPA On-line Tools for Site Assessment)

Phase Partitioning refers to the distribution of the COCs in the subsurface and its equilibrium between the different compartments/phases in the vadose zone (soil particles, pore water and soil gas). There are multiple high-resolution tools commercially available in Brazil (e.g MIP , HPT , passive soil gas samplers) that can provide screening-level information on the partitioning of the contaminant mass in the subsurface. These tools can be implemented in a dynamic and cost-effective manner, and combining their application with the collection of discrete samples of the different environmental compartments (soil gas, soil and groundwater) generally results in a more accurate CSM (ITRC, 2019; Sitolini 2020). Phase partitioning can hinder vapor transport in subsurface when the conditions are still changing; however, once the mass transfer between the phases approaches equilibrium its impact in the transport of the soil gas is rather limited (USEPA, 2012).

Biodegradation is the process where the microorganisms present in subsurface breakdown the COCs present in the soil gas into other chemicals, limiting their transport in the vadose zone. Given the abundance of oxygen in the vadose zone, biodegradation can play a fundamental role in limiting potential vapor intrusion impacts of compounds that can biodegrade aerobically (such as Petroleum Hydrocarbons (PHC)). However, certain factors such as elevated concentrations of the COCs in subsurface, the presence of other carbon sources (such as ethanol), and large building foundations can reduce the availability of oxygen in the shallow soil layers and hinder the biodegradation processes occurring in the area (ITRC, 2014).

In addition to these four processes, the VI Whitepaper prepared by NICOLE BRASIL in 2016 also mentioned two other factors that can also influence vapor transport in subsurface – mechanical dispersion and the presence of ethanol in the mixture.

Mechanical Dispersion is the process associated with the spreading of the soil gas plume in directions beyond its primary flow paths (where advective flow is dominant). It is caused by the interaction of the vapors with the solid phase in the vadose zone, and results in vapors migrating via different tortuous flow paths and at different flow velocities.

Ethanol is an additive of the gasoline commercialized in Brazil. According to Ferreira et al. (2003), Ethanol is added to the gasoline in fractions between 20 and 24%. The relevance of Ethanol in the vapor transport processes occurring in the vadose zone is connected to its ability to increase the vapor pressure of the mixture, and as a result, increase the volatilization rates of the organic compounds present in the mixture (NICOLE BRASIL, 2016).

Characterizing the transport mechanisms mentioned above and incorporating them in the CSM is an important step in the delineation of the contaminated area and the design of an adequate sampling strategy to assess potential VI risks. Regulatory guidelines often recommend collecting multiple lines of evidence to assess if the VI pathway is complete, and some regulatory documents provide guidance on the type and number of samples to be collected and the sampling methodologies to be used.

As the primary goal of a VI assessment is to evaluate if the indoor air quality has been degraded by the impacts in subsurface, indoor air samples are often the most important line of evidence considered in VI decision-making (C Lutes et al. ,2021). However, indoor air contaminant concentrations tend to vary over time, which can lead to questions on the representativeness of the indoor air samples collected (Holton, 2015). Moreover, factors such as elevated background levels (fairly common in urban and industrial areas), and the presence of indoor vapor sources in the building (e.g. cleaners, paints, glues) can contribute to increased indoor air concentrations, making it difficult to establish a clear link between the impacts observed in subsurface and the indoor air present in the building.

Figure 7 (Holton, 2015) illustrates variations of indoor air Trichloroethylene (TCE) concentrations measured in a study house during a 30-month period. Considering the results obtained in this study house, low-frequency short-term sampling (such as daily samples collected on a seasonal basis) may not provide a representative estimate of the VI impacts, while long-term sampling could dilute peak concentrations of COCs, something important when investigating compounds with low short-term exposure threshold values such as TCE.

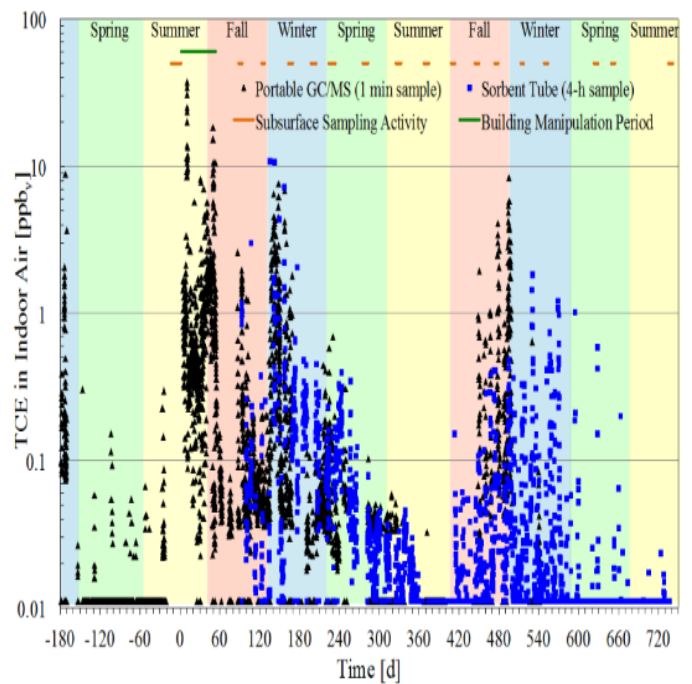


Figure 7. Indoor air TCE concentrations measured in a study house during a 30-month period (Holton, 2015)

USEPA (2001; 2002; 2012; 2015) recommends investigating potential VI risks following a tiered approach, and applying conservative risk-based screening levels (for soil, groundwater, and soil gas) to identify rapidly the receptors that will not require further VI investigations (i.e. low-risk sites). An important parameter considered in the elaboration of the screening levels is the Attenuation Factor (AT) between the impacts in soil gas underneath the building and the indoor air (often referred as the Sub-Slab-to-Indoor-Air Attenuation Factor – SSAF).

Soil vapors can enter buildings via porous surfaces, cracks in floors or walls, conduits or sewer pipes, and very often via a combination of these processes. The level of mixing of the soil gas vapors with indoor air will vary throughout the year following seasonal patterns, but will also change during the course of a day due to factors such as day/night temperature differences, sudden changes in weather conditions, opening and closing of doors or windows, or intermittent operation of automated HVAC⁸ systems.

Figure 8 (Holton, 2015) illustrates variations of air exchange rates in a study house during a 20-month monitoring period.

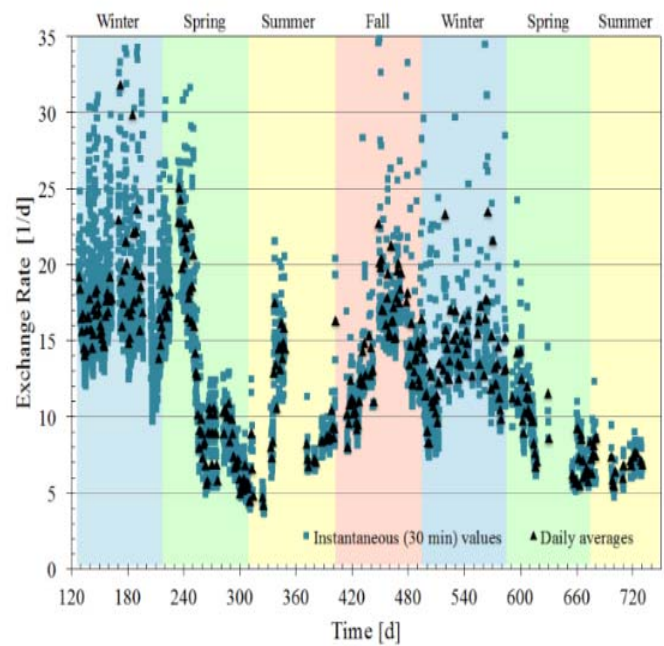


Figure 8. Instantaneous and daily-average indoor air exchange rate of the lower level of a study house during a 20-month period (Holton, 2015.)

According to Holton (2015), the biggest variation in exchange rate in the study house occurred between seasons; however, daily variations were also observed, with the greatest short-term variability occurring in the colder months (between fall and spring).

Variations in air-exchange rates happen in every receptor and it will directly influence the mixing and dilution of intruding soil gas, resulting in different indoor air contaminant concentrations and consequently different SSAFs (Brewer et. al, 2014).

⁸ HVAC – Heating, Venting and Air Conditioning

According to Brewer et. al (2014), the 2 most common ways of estimating the SSAF are:

- By dividing the Concentration in Indoor Air (CIA) by the Concentration in Sub-Slab Soil Gas (CSSSG) (Equation 3),

$$\text{Equation 3: } SSAF = \frac{\text{Concentration in Indoor Air } (C_{IA})}{\text{Concentration in Sub - Slab Soil Gas } (C_{SSSG})}$$

- Or by dividing the Vapor Entry Rate (Q_{Soil} – USEPA, 2015) by the Building Indoor Air Exchange Rate (Q_{Bldg} – USEPA, 2015) (Equation 4).

$$\text{Equation 4: } SSAF = \frac{\text{Vapor Entry Rate } (Q_{Soil})}{\text{Building Indoor Air Exchange Rate } (Q_{Bldg})}$$


The first approach (Equation 3) uses sub-slab and indoor air data pairs to derive a SSAF, and it was via this method that the USEPA calculated generic SSAFs for the Sub-Slab-to-Indoor-Air pathway (USEPA, 2012). Based on VI results from over 1000 residential properties included in the USEPA database, a generic SSAF of 0.03 was calculated. The value of 0.03 represented the 95th percentile⁹ of the data set used, and resulted in a soil gas screening level 33 times higher than the indoor air value (Eklund B et. al, 2018).

Many states in US, as well as other countries across the globe (Brazil included), adopted this empirical attenuation factor into their soil gas screening values; however, the USEPA approach was received with less enthusiasm by some segments of the Vapor Intrusion scientific community. Although USEPA took measures to screen out data that was potentially influenced by indoor air sources and/or elevated background levels, questions remained regarding the accuracy and reliability of some of the data incorporated in the calculation due to uncertainties associated with the sampling approach or with the pairing of the samples.

More importantly, despite of the fact that the USEPA database included only data from vapor intrusion assessments performed in residential receptors, USEPA recommended the use of the generic Sub-Slab-to-Indoor-Air attenuation factors for both residential and non-residential buildings (USEPA, 2015).

⁹ A SSAF value corresponding to the 95th percentile means that 95% of the data pairs used in the calculation (i.e. pairs of sub-slab soil gas and indoor air samples) generated a SSAF lower or equal to 0.03 .

USEPA justified that decision on the fact that some commercial buildings are in fact converted residential buildings, and therefore exhibit vapor intrusion conditions (e.g. building size, slab thickness, indoor air exchange rates) similar to those observed in residences. However, USEPA also recognized that the proposed AFs may be overly conservative for larger non-residential buildings where higher rates of interior mixing and dilution are expected to occur (see extract of the USEPA 2015 guideline below).



“There are theoretical considerations to support expectations that larger nonresidential buildings that are constructed on thick slabs will have lower attenuation factors than residential buildings. These considerations include:

- *Given that the size (e.g., interior height and footprint area) and air exchange rate tend to be larger for many nonresidential buildings (...), it is expected that building ventilation rates for many nonresidential buildings would be higher than those for residential buildings. A higher ventilation rate is expected to result in greater overall vapor dilution as vapors migrate from a subsurface vapor source into a building. On this basis, many nonresidential buildings would be expected to have lower attenuation factors than those for residential buildings, all else being equal.*
- *Comparing buildings with slab-on-grade construction, nonresidential buildings tend to have thicker slabs than residential buildings. With thicker slabs, a given amount of differential settling would be expected to lead to less cracking in the slab and would be less likely to create cracks that extend across the entire slab thickness. Buildings with thicker slabs would, therefore, be expected to exhibit lower soil gas entry rates, all else being equal.*

Where appropriate, EPA may consider appropriate building-specific data, information, and analysis when evaluating vapor intrusion into large nonresidential buildings.”

(USEPA, 2015)

In 2021 Hallberg et.al (2021) published a study where a similar empirical approach was used, but considering a different data source – VI sampling results collected at commercial, industrial, and other non-residential buildings present at sites of the Department of Defense (DoD) of the US. According to Halberg et. al (2021), the DoD database is comparable in size to the EPA’s VI database, but includes only chlorinated VOC data from non-residential

buildings, where more attenuation is expected to occur due to lower Vapor Entry Rates (VER) and higher Indoor Air Exchange Rates (IAER). Based on the DoD data set, Hallberg et.al (2021) suggests that a SSAF of 0.001 would be more adequate for developing soil gas sub-slab screening levels for non-residential buildings (i.e. commercial/industrial receptors).

Brewer et. al (2014) calculated SSAF values using the second approach (Equation 4), which considers the ratio between Vapor Entry Rates (Q_{Soil}) and Building Indoor Air Exchange Rates (Q_{Bldg}). Based on the climate zones defined in the International Energy Conservation Code (IECC) maps (ICC, 2012), the authors defined four Vapor Intrusion Risk (VIR) Regions in US (i.e. Cold, Warm, Mediterranean and Tropical), and assigned different climate-weighted VER and IAER for each VIR region. The climate-weighted rates considered the number of cooling/heating days per year in each region, as well as other factors such as regulatory default values proposed in states included in the VIR regions and minimum ventilation requirements in US.

Figure 9 illustrates the VIR regions proposed by the authors based on the different US climate zones, and Table 4.2 presents the VER and IAER assigned by the authors for each VIR region, and the calculated Sub-Slab-to-Indoor-Air Attenuation Factor (SSAF).

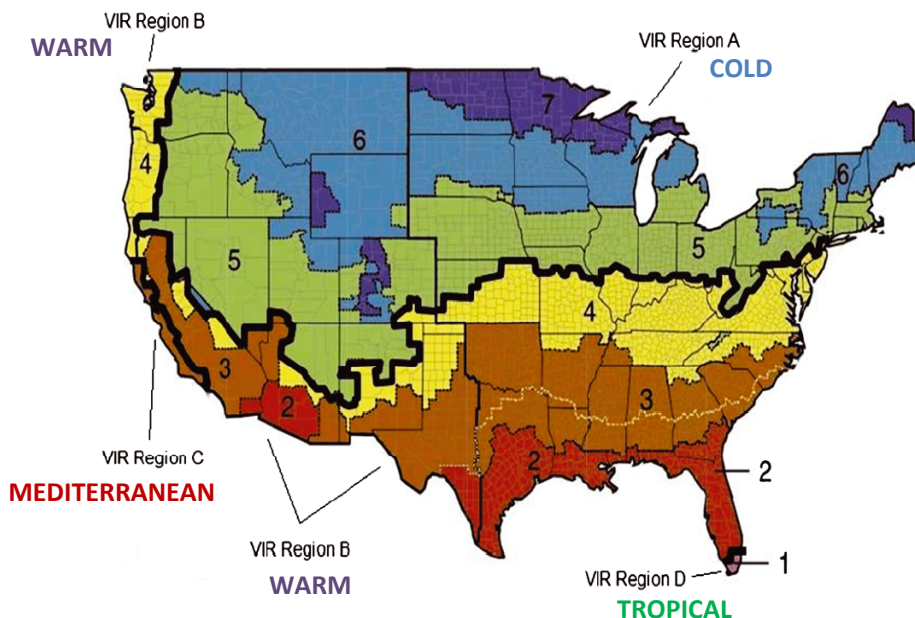


Figure 9. Illustration of Vapor Intrusion Risk (VIR) Regions proposed by Brewer et. al (2014). (Brewer et. al, 2014)

Table 4.2 SSAF Estimated for VIR Regions (Brewer et. al, 2014)

Climate Zone ¹	Default Vapor Entry Rate ² (L/min)	Default Indoor Air Exchange Rate ³ (L/min)	Subslab Attenuation Factor ⁴	
Region A (Cold) ⁵	4.5	0.35/h	1423	0.0032
Region B (Warm) ⁶	4.0	0.5/h	2033	0.0020
Region C (Mediterranean) ⁷	3.4	1.0/h	4067	0.0008
Region D (Tropical) ⁸	2.0	1.0/h	4067	0.0005

¹Vapor intrusion risk regions

²Annual-average vapor entry rate

³Reflects assumed interior house volume of 244 m³ and default building slab (or crawl space) area of 100 m².

⁴Ratio of vapor entry rate to indoor air exchange rate.

⁵Cold climate region represented by northern and Rocky Mountain states with mean daily temperature >65 °F from at least July through August.

⁶Warm climate region represented by southern and southwestern states with mean daily temperature >65 °F from at least June through September.

⁷Mediterranean climate region represented by coastal central California with cool summers and mean daily temperature >55 °F from mid-April through October.

⁸Tropical climate region represented by Hawai'i, southernmost Florida, Puerto Rico, the United States Virgin Islands, and Guam, with year-round mean daily temperature >65 °F.

(Source: Brewer et. al, 2014)

As illustrated above, the method applied by Brewer et. al (2014) resulted in SSAFs varying between 0.0032 (for the cold climate regions) and 0.0005 (for the tropical climate regions), which are 1 and 2 orders of magnitude different than the values published by the USEPA (2012; 2015). Although the authors did not present empirical data to support their theoretical calculations, the results obtained by Brewer et.al (2014) confirmed the expectations that areas with warmer temperatures and higher ventilation rates will result in lower attenuation factors.

4.3 Potential Receptors

Buildings or enclosed spaces located directly above the contaminated area are obvious candidates to be investigated for VI; however, regulatory agencies generally require to extend the area to be investigated with a certain margin to ensure that receptors located close to the impacted area are also screened. This additional margin is called “Lateral Inclusion Zone (LIZ)” and its objective is to define a distance considered to be “safe” for receptors located close to the contaminated area.

In addition to the lateral spreading of the soil gas plume, the “Vertical Separation Distance (VSD)” between the impacts and the receptor is also a factor to be assessed during the elaboration of the CSM. The vadose zone is generally an oxygen rich area, and compounds that can biodegrade under aerobic conditions (such as PHC) will show a higher degree of attenuation within the soil column, limiting the transport of vapors from the source to the receptor and the potential VI effects associated with it (ITRC, 2014).

Figure 10 (ITRC, 2014) illustrates the VSD concept in areas impacted by NAPL or dissolved plumes.

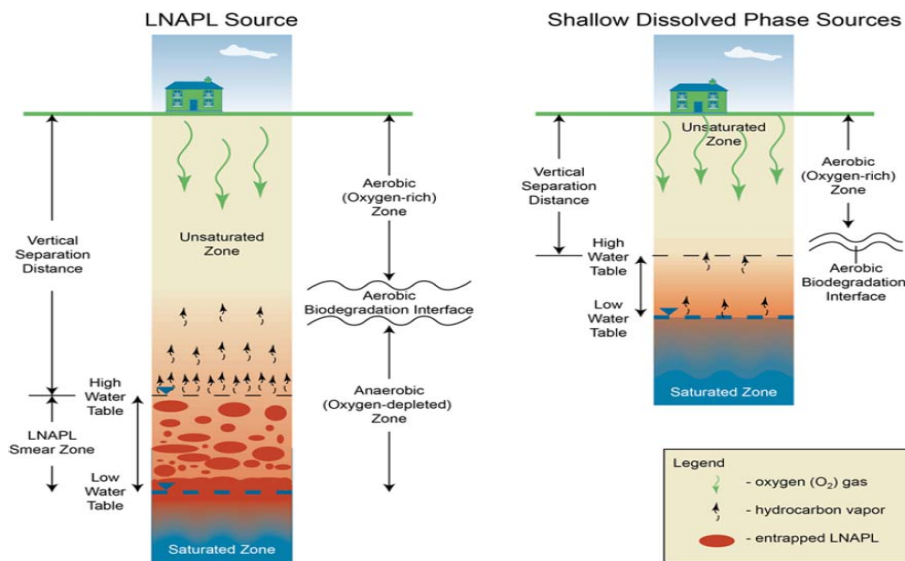


Figure 10. Vertical separation distance between the impacted zone and the potential receptor (ITRC, 2014)

Some VI regulatory guidelines recommend inclusion distances (LIZ and VSD) for certain groups of contaminants (e.g. chlorinated solvents, PHC), and receptors that are located outside the recommended inclusion distances generally do not need to be investigated for VI. Most guidelines suggest LIZ distances of 10 meters for PHC and 30 meters for chlorinated solvents, and VSD distances between 2 and 5 meters for PHC (up to 10 meters if LNAPL¹⁰ is present), and 30 meters for chlorinated solvents (Eklund et al., 2018).

These proposed inclusion distances are based on technical data evaluated from many sites and seem appropriate based on the attenuation processes occurring in subsurface. However, contaminated groundwater or soil gas can enter sewer lines or piping conduits and affect receptors located outside the recommended inclusion distances and in rather unexpected areas (e.g. upgradient from the plume). Therefore, the applicability of recommended inclusion distances in a given project should always be confirmed and justified during the elaboration of the CSM. If the CSM identifies specific conditions (e.g. large building foundations) or preferential pathways (e.g. sewer lines, pipes or cable conduits, elevator shafts) that could limit

¹⁰ LNAPL – Light Non-Aqueous Phase Liquid

biodegradation processes or facilitate vapor migration (either horizontally or vertically), the list of potential receptors should be reassessed to include also buildings located within the zone of influence of the identified preferential pathway(s). Figure 11 (Friedrich A et. al, 2018) illustrates a project case in US where such situation was observed.

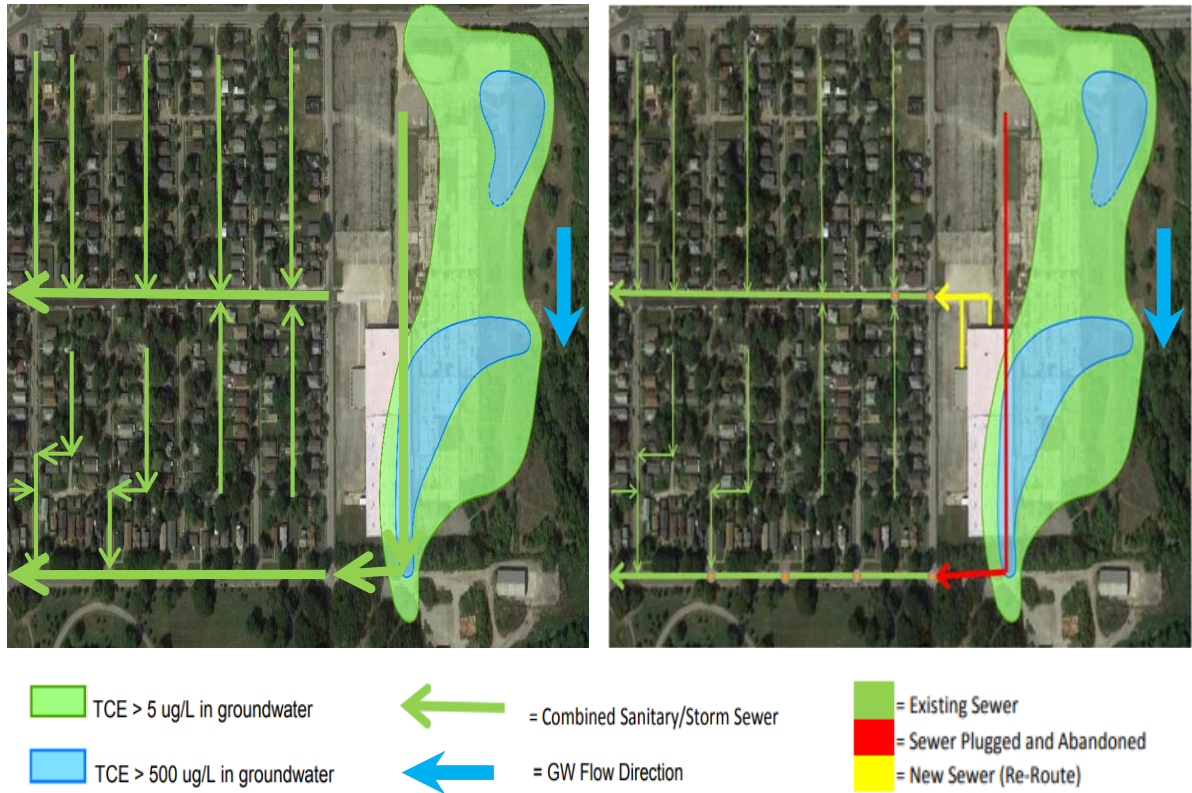


Figure 11. Preferential pathways affecting the zone of influence of Vapor Intrusion (Friedrich A et al., 2018.)

At this case study, a shallow TCE plume in groundwater entered a combined sanitary/storm water sewer via cracks in the pipes, and TCE vapors originating from the impacted groundwater were transported via the sewer lines to multiple residential properties located outside the expected zone of influence of the groundwater plume (residential area located west of the TCE plume). VI impacts were observed in multiple properties in the residential area, and VI mitigation efforts required plugging and abandoning a section of the existing Site sewer line (indicated in red in Figure 11), and other receptor-focused mitigation actions (e.g. plumbing corrections, installation of Sub-Slab Depressurization (SSD) systems). This case study by Friedrich A et. al, (2018) demonstrates how complex the VI pathway can be, and underpins the importance of building a robust CSM that incorporates elements such as building characteristics and preferential pathways located underneath or in the vicinity of the potential receptors.

5. DISCUSSION

The first step in VI investigations, both in Europe as well as in US, is generally performed during the delineation phase and includes using conservative modeling and risk assessment tools to predict if the impacts in subsurface are posing a health risk to occupants/users of a given building (Gouvea Junior et.al, 2018). Concentrations of the COCs in soil and groundwater samples collected underneath (or near) the building of interest are used to simulate the attenuation processes occurring from the source to the receptor(s), and to estimate sub-slab soil gas and indoor air concentrations. When the soil gas or indoor air concentrations are below the applicable screening values, no risk to the receptors are anticipated and no further actions are generally required. However, if the modeling results suggest a potential inhalation risk (by exceeding soil gas or indoor air screening values), additional investigations are needed to confirm the potential vapor intrusion risk and to define if remedial actions are required.

Modelling vapor intrusion impacts often rely on one- or two-dimensional analytical solutions consisting of 2 parts – one focusing in the vapor transport processes occurring in the vadose zone, and the other simulating the entry of the vapors into the building (Yao and Suuberg, 2013). The transport processes occurring in the vadose zone are well understood and can be reasonably simulated using vapor flow equations and site-specific data collected during the delineation of the impacts (or conservative default data defined by regulatory agencies in the absence of site data). However, modeling the entry of vapors into the building can be a considerably more challenging exercise. According to Yao and Suuberg (2013), even some of the most sophisticated three-dimensional VI models are not able to model accurately the different migration pathways and variable conditions associated with VI in order to estimate correctly indoor air concentrations. Therefore, regulators and VI practitioners tend to consider modeling tools as a conservative first step in VI assessments used to screen-out low-risk sites that would not require further VI investigations.

When the modeling and risk assessment approach suggests that VI is posing a health risk to occupants/users of a given receptor, regulatory guidelines generally require collecting samples at the receptors to confirm if vapor intrusion is indeed occurring and if remedial actions or mitigation measures are needed. Although many regulatory guidelines encourage using the MLE approach to assess if the VI pathway is complete, the decision to implement vapor mitigation measures is often based on the results of paired sub-slab soil gas and indoor air sampling campaigns.

Similar to sampling programs for other environmental media (e.g. soil, sediments, groundwater), soil gas and ambient air sampling also require following specific protocols to ensure that reliable data is collected. Factors such as the location where the samples will be collected, the number and type of samples that will be collected in each receptor, their frequency (e.g. every quarter, twice per year), and the methods to collect the samples (e.g. canisters or multi-bed sorbent tubes, short or long term sampling) can influence greatly the outcome of the VI assessment. Regulatory and technical guidelines are essential to structure this process and to define the boundaries of what is acceptable during a VI assessment. The lack of guidelines can lead to inconsistencies in the way the VI assessment is performed, potentially resulting in incorrect decisions that enforces mitigation at receptors not affected by VI, or that does not recognize VI impacts when present due to inadequate sampling strategies or practices.

Table 5.1 below presents data from two residences located downgradient of an industrial property where chlorinated solvents were released into subsurface and impacted both soil and groundwater (Valle P, 2011).

Table 5.1 Vapor Intrusion Assessment Results – Residential Area

Location Sample	Unit	Screening Value (1,2-DCA)	Results for 1,2-Dichloroethane (1,2-DCA)	
			Home 1 ^A	Home 2
Living Floor	µg/m ³	0.40	1.42	0.388
Basement ^B	µg/m ³	0.40	-	0.121
Crawl Space ^C	µg/m ³	*	< 0.081	< 0.081
Soil Gas ^D	µg/m ³	*	< 1.70	< 1.70
Shallow Groundwater ^E	µg/L	30	0.47	< 0.10

Notes: (A) Residence without a basement.

(B) Not used as living space, only as storage room.

(C) Crawl space covered with very thin and highly permeable concrete layer.

(D) Soil gas samples collected just above the water table (conservative approach).

(E) Water table depth in the area ranging between 2.0 and 3.0 meters below ground level (m-bgl).

(*) Not available.

(-) Not sampled.

The residences were located approx. 500 meters downgradient of the site, and the main COCs present in groundwater were degradation products. Traces of 1,2-Dichloroethane (1,2-DCA) were detected in a few monitoring wells installed in the residential area, however always below the applicable regulatory value for groundwater (30 µg/L). As the potential VI source

was the impacted shallow groundwater, the following samples were included in the VI characterization campaign of each receptor: shallow groundwater, soil gas, crawl space, basement (when present), living floors, and outdoor air.

As indicated above, 1,2-DCA was detected in the indoor air of both homes in concentration just below (Home 2 – 0.388 $\mu\text{g}/\text{m}^3$) or above (Home 1 – 1.42 $\mu\text{g}/\text{m}^3$) the regulatory guidelines for indoor air (0.40 $\mu\text{g}/\text{m}^3$). However, the groundwater sample collected underneath Home 1 detected only traces of 1,2-DCA, and both the soil gas sample collected just above the water table as well as the ambient air sample collected in the crawl-space area reported 1,2-DCA below detection limits. In Home 2, the groundwater sample, the soil gas sample, and the sample collected in the crawl-space area reported 1,2-DCA below detection limits. However, 1,2-DCA was detected in both the sample collected in the living area as well as in the sample collected in the basement. Given that the 1,2-DCA concentration observed in the living area was higher than in the basement, the indoor air source of the 1,2-DCA impacts was expected to be located in the living area of the house.

The sampling strategies implemented in this case study were designed based on the CSM prepared for each receptor, and the results obtained illustrate the value of collecting combined data sets when assessing the VI pathway.

5.1 Conceptual Site Models (CSM)

Elaborating a Conceptual Site Model (CSM) that represents accurately the processes occurring in the subsurface and the exposure pathways associated with the impacts is a key step for designing effective VI characterization strategies. Multiple US and European VI guidelines include extensive chapters on the elaboration of CSMs and the importance of incorporating characteristics of the potentially affected buildings into the site models (USEPA 2001, 2002, 2012, 2015; ITRC 2007, 2014; OVAM 2019; RIVM 2007). The type of building structures present in the area will affect the spatial distribution of the contaminants in the subsurface, and specific building conditions may influence the temporal variability of soil gas and indoor air concentrations (USEPA, 2012).

ITRC (2014) recommends the use of a Vapor Intrusion CSM checklist when developing conceptual models in sites impacted by petroleum hydrocarbons. Although prepared as part of the ITRC Petroleum Vapor Intrusion (PVI) document, the vast majority of the elements included in the checklist are relevant for the screening of VI receptors in sites impacted by other

COCs as well. Factors such as type and extent of the source of impacts, migration mechanisms between the source and the receptor, detailed characterization of receptors, and information on preferential pathways, are highlighted in the checklist from a VI assessment perspective, facilitating and structuring the CSM elaboration process. In addition to the use of a checklist, ITRC (2007) also recommends performing a building inspection survey in order to identify the main factors that will govern the entering of vapors into the building, as well as elements that could influence the sampling results (e.g. indoor vapor sources). Annex 1 provides a copy of the checklist (ITRC, 2014), and Annex 2 of the building survey (ITRC, 2007) that ITRC proposes to use to gather information on the receptors during VI assessments.

Table 5.2 below provides a brief summary of building information that should be incorporated into a Vapor Intrusion Conceptual Site Model (VICSM).

Table 5.2 Vapor Intrusion Conceptual Site Model – Building Information

Location and Type	Location of existing or future buildings and spatial distance to the source of VI impacts (vertical and horizontal).
	Type, use and occupancy of the building (e.g. residential, commercial, industrial).
Preferential Pathways	Location of potential preferential pathways (e.g. sewer or storm water drains, utility or cable lines, dewatering sumps, elevator shafts) that could facilitate the migration of vapors from the source to the receptor, or increase its zone of influence, affecting buildings located outside of the applicable inclusion zones.
Construction Details	Date of construction, building structure and materials (e.g. wooden frame, pre-fab concrete blocks), number of floors and connections between floors, location and connection between enclosed spaces, presence of building openings such as windows or doors, and presence of HVAC systems. The objective is to obtain information on construction features or operating systems that could influence airflow within the building, either increasing or limiting indoor air exchange rates in certain areas of the building, or in the building as a whole.
	Mapping of any potential vapor entry points that could facilitate the migration of vapors present underneath the slab into the building. Description of the building foundations should include type of floor (e.g. impermeable, concrete, dirt), thickness, and presence of drainages, penetrations, or cracks.

Potential Indoor Air Sources	Mapping of potential indoor air sources of pollution that could interfere with the indoor air sampling results.
-------------------------------------	---

Gathering information on the elements listed above will facilitate the elaboration of an adequate VI sampling strategy for each receptor and provide valuable insights during the interpretation of the results.

5.2 Screening Values & Attenuation Factors

Screening values are chemical concentrations intended to be protective of human health and/or the environment and that below which no additional regulatory attention is required (ITRC, 2005). The use of soil gas screening values in VI assessments is a well-accepted approach by many state regulators in US. According to Eklund et al. (2018), approximately 70% of the US states providing screening values in their guidelines include shallow or deep soil gas screening values.

Vapor Intrusion Screening Levels (VISL) are generally defined considering the expected attenuation between the impacts present in subsurface and the indoor air. The conditions favoring or impeding VI tend to be unique for every single building/potential receptor, and to vary over time. As a result, attenuation factors will vary between buildings, or even between different enclosed spaces in the same building. Although defining attenuation factors for each building/enclosed space would be a more technically sound approach, this methodology is not seen by the author as a cost effective and realistic solution in many project Sites.

Given the complexity associated with the characterization of the vapor intrusion pathway, more specifically on the attenuation process occurring between the soil gas underneath the slab and the indoor air, soil gas screening values calculated based on empirical data sets and statistical analysis can provide a first cost-effective step in the VI screening of low risk receptors. However, given the strong influence that hydrogeological settings, climate patterns and building conditions can have in the attenuation process occurring from source to the receptor, the use of empirical data sets that reflect the local conditions is advisable.

If the soil gas screening values are set too conservatively, costly investigations may need to be carried in properties where vapor intrusion is not occurring. Conversely, if the screening values are too permissive, buildings where the VI pathway is likely complete may be screened out too early in the process based on limited or inconclusive data. CETESB currently applies

for both residential and non-residential buildings a soil gas screening value based upon the Sub-Slab-to-Indoor-Air Attenuation Factor (SSAF) proposed by the USEPA (0.03 – USEPA, 2015). Given the considerably different climate patterns and building conditions observed across the different regions in Brazil, the author believes that the empirical attenuation factor proposed by the USEPA may be overly conservative to many sites located in Brazil. Therefore, CETESB and other state regulatory agencies in Brazil should develop a database for residential and non-residential buildings in order to define empirical attenuation factors and soil gas screening values that are applicable for sites in their states.

5.3 *Characterization Strategies*

Defining the appropriate characterization strategies to be adopted in each receptor, as well as how the samples should be collected and the data evaluated, are key elements that need to be incorporated in VI guidelines. As the risk associated with the VI pathway is defined by the concentrations of the COCs present in the indoor air in the buildings, indoor air samples are often the most important element considered in VI assessments.

The most common approach for characterizing indoor air quality in buildings consists of using canisters or multi-bed sorbent tubes to collect short-period indoor air samples (24h in residential buildings, and 8h in commercial/industrial settings), and repeating the sampling effort over multiple campaigns (e.g. every quarter, winter and summer) to account for seasonal variability. The number and location of samples should be defined based on the VICSM and the findings of the building survey. However, many regulatory guidelines provide information on the expected minimum number of sub-slab and indoor air samples to be collected in order to characterize a certain building.

Figure 12 (Eklund et al., 2012) summarizes the minimum number of sub-slab soil gas and indoor air samples that should be collected in each receptor in different US states. The data present is from 2012, therefore does not necessarily reflect the current recommendations of the different USEPA state agencies; however, it does illustrate the following aspects:

- 1) The number of samples generally increases with the size and complexity of the building;
- 2) The number of rounds can be site specific or seasonally bound (up to quarterly campaigns); and
- 3) For indoor air samples, most guidelines recommend short-sampling durations of 24h in residential buildings, and 8h in commercial/industrial settings.

State	Sub-slab		Indoor Air			
	No. of Samples	No. of Rounds	No. of Rounds	Sampling Duration (hr)	No. Samples (1st Floor)	No. of Samples (Basement)
Alaska	-	-	2	24	1 per 1,000 ft ²	1 per 1,000 ft ²
Arizona	-	-	-	-	-	-
California	2	2	2	24 (8 for nonres)	1	1
Colorado	1	1-2	multiple	24 (8 for nonres)	site-dependent	site-dependent
Delaware	-	-	-	-	-	-
Idaho	1	-	2	-	-	-
Indiana	per EPA VI guidance	-	>1	24	1-2	1-2
Kansas	1	-	site-specific	24	1	1
Louisiana	-	-	-	-	-	-
Maine	-	2	2	-	1	1
Massachusetts	2-4	1-2	2-3	24 (8 for nonres)	1	1
Michigan	-	-	-	12	-	-
Minnesota	1 per 1,000 ft ²	2	2	24	1	1
Missouri	4	2	-	-	-	-
Montana	3	site-by-site basis	1-2	24 (8 for nonres)	1	1
New Hampshire	3	site-by-site basis	multiple rounds	24 (8 for nonres)	-	-
New Jersey	2	site-specific	1	24 (8 for nonres)	site-specific	1
New York	1 per area	>1	>1	24 (8 for nonres)	1	1
North Carolina	1	1 or more	1 or more	2	1 per story	1 per story
Ohio	2	up to quarterly	up to quarterly	24 (8 for nonres)	-	-
Oregon	2	2	2	24 (8 for nonres)	-	-
Pennsylvania	-	-	-	-	-	-
Vermont	-	>1	>1	-	1	1
Virginia	-	-	-	-	-	-
Washington	>1	>1	1 or more	24 (8 for nonres)	-	1
Wisconsin	3	1 or more	1 or more	24 (8 for nonres)	1	1

Figure 12. Summary of US State Sampling Guidance for Indoor Air (as of 2012)
(Eklund et al., 2012)

Similar recommendations are included in many European guidelines (DRF, 2007; OVAM 2019), with sampling strategies to be designed based on the VICSM and the potential VI scenarios present. The VI scenarios generally take in consideration the location and type of VI sources, the distance between the source and the receptor, the characteristics of the receptor, and the presence of preferential pathways in the area of influence of the impacts.

Given that indoor air concentrations will vary over time as a response to changes in weather conditions, variations in indoor air exchange rates, and different vapor entry rates (Brewer et al, 2014), many VI practitioners question the reliability of short-term samples for characterizing the occurrence of Vapor Intrusion.

According to Kram et al. (2020), collecting samples at random times may result in false negative determinations of reasonable maximum exposure risks, if the samples were collected during moments where the building conditions were not favorable for vapor intrusion. Favorable conditions for vapor intrusion occur when the pressure differential between the subsurface (just beneath the building slab) and the building indoors is positive, reflecting a higher pressure in the subsurface relative to indoors. Higher pressure in the subsurface will facilitate upward advective soil gas transport and may result in higher COC concentrations in

the indoor air. Figure 13 (Kram et al., 2020) displays the evolution over time of TCE concentration versus pressure differential in the Women's Restroom of a project site located in San Diego, California.

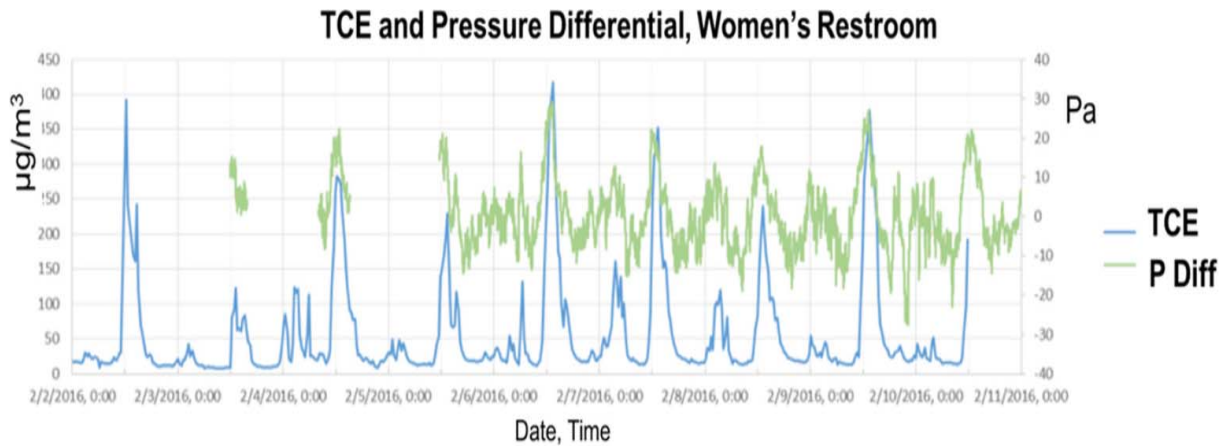


Figure 13. Evolution over time of TCE concentration versus pressure differential (Kram et al., 2020)

As illustrated above, the highest TCE concentration values corresponded to the positive pressure differential peaks, and according to Kram et al. (2020), similar temporal correlations were observed in other monitoring locations in the building.

Therefore, as important as sampling at the right locations and using the right methods, collecting the samples at the right moment is also an important element to be considered when elaborating sampling strategies. Real-Time monitoring of the pressure difference between the subsurface just beneath the building and a paired indoors location is a cost effective way to assess the building VI conditions and to define the most representative moment to collect short-term indoor air samples.

High-resolution techniques such as Real-Time monitoring systems and Compound Specific Isotope Analysis (CSIA) can also be used to differentiate indoor sources from the subsurface impacts, identify vapor intrusion entry points, and assess the variability of the concentrations in indoor air over time. These tools are available in most countries (including Brazil), and its use as part of vapor intrusion assessments adds great value in understanding the VI pathway, the design of sampling campaigns, and the implementation of effective vapor mitigation systems when required.

6. CONCLUSION

The outcome of a VI assessment can be a decisive factor in defining the risk management strategy for a contaminated area. The general VI approach involves using predictive modeling and risk assessment tools to evaluate, in a conservative way, if vapor intrusion is occurring, and sampling campaigns tailored to the different receptors to confirm if the VI pathway is complete and if mitigation measures are required.

Characterizing the VI pathway can be a complex and somewhat laborious process. Despite of the considerable technical progress reached in the past few years and the growing technical awareness of the processes governing VI, there are still countries without guidelines to structure the VI assessment and decision-making process (Brazil as an example).

The purpose of this essay was to contribute to the ongoing technical discussions taking place in Brazil regarding the management of VI risks in areas with soil and groundwater pollution. The author hopes that the information summarized in this essay will contribute to the development of a specific protocol to investigate and mitigate VI in sites in Brazil.

Table 6.1 below summarizes elements that, in the view of the author, could be considered in the elaboration of a vapor intrusion guideline document for contaminated sites in Brazil.

Table 6.1 Proposed Elements for a Vapor Intrusion Guideline for Sites Located in Brazil

Topic	Comments
Conceptual Site Models (CSM)	<ul style="list-style-type: none"> Building a CSM that represents accurately the processes occurring in subsurface and in the receptor is key to assess the VI pathway. Since the construction details and the use & occupancy of receptors tend to vary widely, specific Vapor Intrusion Conceptual Site Models (VICSM) should be elaborated for the different receptors that need to be investigated. The VI sampling strategy to be implemented in each receptor should be based on its VICSM and agreed upfront with all stakeholders involved.
	<ul style="list-style-type: none"> Preferential pathways can facilitate the migration of vapors from the source to the receptor, and transport vapors to areas located outside its anticipated zone of influence. The presence of preferential pathways such as sewer or storm water drains, utility or cable lines, dewatering sumps or elevator shafts, should be always thoroughly investigated and incorporated into the VICSMs prepared for the project

Topic	Comments
Conceptual Site Models (CSM)	<ul style="list-style-type: none"> The construction characteristics and specific conditions present in each receptor can vary over time and will affect greatly the outcome of the vapor intrusion assessment. Therefore performing Building Surveys should be a mandatory step during the elaboration of the VICSM and the design of a VI sampling strategy for a given receptor. During periodical VI monitoring campaigns, a Building Survey should be performed prior to each sampling event, and the sampling strategy should be reassessed if the survey indicates any change in conditions (both structural or operational) in the building related to previous sampling events.
Screening Values & Attenuation Factors	<ul style="list-style-type: none"> The use of screening values and soil-gas-to-indoor-air attenuation factors as a first step in the screening of low risk receptors is a well-accepted approach by regulators in US and in Europe. Therefore applying a similar strategy for sites located in Brazil seems an adequate approach.
	<ul style="list-style-type: none"> Given the complexity associated with the characterization of the vapor intrusion pathway, more specifically on the attenuation process occurring between soil gas and indoor air, the use of conservative screening values and attenuation factors as a first step of a VI assessment is advisable.
	<ul style="list-style-type: none"> The use of empirical data sets and statistical analysis seems to be a cost-effective approach to calculate attenuation factors and define soil gas screening values that are protective of human-health. However, given the strong influence that hydrogeological settings, climate patterns and building conditions can have in the attenuation process occurring from source to the receptor, the use of empirical data sets that reflect the local conditions is advisable.
	<ul style="list-style-type: none"> Regulatory agencies in Brazil should develop a database for residential and non-residential buildings in order to define soil gas screening values that are protective of human-health for sites in Brazil. While the Brazilian database is being developed, the author believes that the following sub-slab-to-indoor-air attenuation factors (SSAF) could be applied for residential and non-residential buildings located in Brazil: <ul style="list-style-type: none"> Residential Buildings – <u>0.03</u> (Source: USEPA database) Non-Residential Buildings – <u>0.001</u> (Source: DoD database) The proposed SSAF for residential buildings should also be used for commercial properties that are in fact converted residential buildings (USEPA, 2015). The characterization of the type of building and the applicable SSAF to be used should be part of the building survey process, and incorporated into the VICSM of the receptor.

Topic	Comments
Characterization Strategies	<ul style="list-style-type: none"> Characterization strategies should be designed based on the VICSM, and take into consideration the location and type of vapor intrusion sources, the distance between the source and the receptor, the specific characteristics of each receptor, and the presence of preferential pathways in the area of influence of the impacts.
	<ul style="list-style-type: none"> Lateral Inclusion Zones (LIZ) of 10 m for PHC and 30 m for chlorinated solvents, and Vertical Separation Distances (VSD) of 5 meters for PHC (up to 10 meters if LNAPL is present), and 30 meters for chlorinated solvents could be considered as initial inclusion distance reference for sites in Brazil. However, the applicability of any given inclusion distance should always be confirmed and justified during the elaboration of the CSM.
	<ul style="list-style-type: none"> The pressure differential between the building indoors and the subsurface is an important element to be considered when elaborating sampling strategies. Monitoring of the pressure difference between the subsurface just beneath the building and paired indoors locations is a cost effective way to define the most representative moment to collect short-term indoor air samples.
	<ul style="list-style-type: none"> High-resolution techniques such as Real-Time monitoring systems and CSIA can be used to differentiate indoor sources from the subsurface impacts, identify vapor intrusion entry points, and assess the variability of the concentrations in indoor air over time. These tools can add great value in understanding the VI pathway and ensuring that VI samples are collected in representative moments.
	<ul style="list-style-type: none"> Sampling strategies should include the collection of combined data sets (e.g. groundwater, soil gas, sub-slab, indoor air), and decisions should be made based on the execution of multiple sampling events.

The thoughts presented above reflect the opinion of the author based on the document review performed as part of this essay, as well as the author’s professional experience gathered during the execution of multiple vapor intrusion assessments performed across Europe.

The author made his best effort to summarize the key information presented in the documents that were reviewed, but it is possible that some of the information has been incorrectly translated or misunderstood. Therefore the author encourages the readers to consult the actual documents when reviewing specific policies and procedures listed in this essay.

7. REFERENCES

Brewer R, Nagashima J, Rigby M, Schmidt M, O’Neill H. Estimation of Generic Subslab Attenuation Factors for Vapor Intrusion Investigations. NGWA, Groundwater Monitoring & Remediation 34, no. 4: 79–92. December 2014.

CETESB - COMPANHIA DE TECNOLOGIA E SANEAMENTO AMBIENTAL DO ESTADO DE SÃO PAULO. *Manual de Gerenciamento de Áreas Contaminadas.* São Paulo, 2021. Available at: < <https://cetesb.sp.gov.br/areas-contaminadas/documentacao/manual-de-gerenciamento-de-areas-contaminadas/informacoes-gerais/apresentacao/> > Accessed 18 Dec 2021.

CETESB - COMPANHIA DE TECNOLOGIA E SANEAMENTO AMBIENTAL DO ESTADO DE SÃO PAULO. *Decisão de Diretoria Nº 125/2021/E, de 09 de Dezembro de 2021 – Dispõe sobre a Aprovação da Atualização da Lista de Valores Orientadores para Solo e Água Subterrânea.* São Paulo, 2021. Available at: < <https://cetesb.sp.gov.br/wp-content/uploads/2021/12/DD-125-2021-E-Atualizacao-dos-Valores-Orientadores-paa-solo-e-aguas-subterraneas.pdf> > Accessed 18 Dec 2021.

CETESB - COMPANHIA DE TECNOLOGIA E SANEAMENTO AMBIENTAL DO ESTADO DE SÃO PAULO. *Relatório de Áreas Contaminadas e Rehabilitadas no Estado de São Paulo 2020.* São Paulo, 2020. Available at: < <https://cetesb.sp.gov.br/areas-contaminadas/wp-content/uploads/sites/17/2021/03/TEXTO-EXPLICATIVO-2020.pdf> > Final Report.

Eklund B, Beckley L, Yates V, McHugh TE. – Overview of state approaches to vapor intrusion. Remediation. 2012 Autumn; 7–20.

Eklund B, Beckley L, Rago R. – Overview of state approaches to vapor intrusion: 2018. Remediation. 2018;28:23–35. <https://doi.org/10.1002/rem.21573>

Ferreira S M, Oliveira E de, & Duarte U. – *Comparação Entre a Espessura Real e Aparente da Gasolina com Etanol e da Gasolina Pura em Colunas de Laboratório.* (2003). Available at: < <https://aguassubterraneas.abas.org/asubterraneas/article/view/23973> >

Fetter, CW. Applied Hydrogeology 3rd edition. New York. 1994.

Friedrich A, Wallace A. The Autobahn of Vapor Intrusion – Pathway Evaluation from a Sole Source Impacted Subsurface Sewer. 2018 Battelle Chlorinated Conference Proceedings, Session G3 Vapor Intrusion Preferential Pathways. US, Palm Springs, 2018. Available at: < https://www.battelle.org/docs/default-source/conferences/chlorinated-conference/proceedings/2018-chlorinated-conference-proceedings/g3-vapor-intrusion-preferential-pathways/g3_0940_-1126_friedrich.pdf?sfvrsn=29008088_0 >

Geoprobe Systems. Direct Push Installation of Devices for Active Soil Gas Sampling & Monitoring. Technical Bulletin No.MK3098. May 2006.

Gouvêa Júnior J, Bertolo R, Hart T. – *Intrusão de Vapores do Solo: Breve Histórico sobre Desenvolvimento da Tecnologia, Cenário Brasileiro e Avanços Recentes.* 2018. Instituto de Geociências da Universidade de São Paulo - Centro de Pesquisas de Águas Subterrâneas. DOI: <http://dx.doi.org/10.14295/holos.v18i2.12307>

Hallberg KE, Levy LC, Gonzalez-Abraham R, Lutes CC, Lund LG, Caldwell D. 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, 1148-1158. June 2021.
<https://doi.org/10.1080/10962247.2021.1930286>

Holton, CW. Dissertation “Evaluation of Vapor Intrusion Pathway Assessment Through Long-Term Monitoring Studies”, Arizona State University. May 2015. Available at < <https://core.ac.uk/download/pdf/79576406.pdf> >

ITRC – THE INTERSTATE TECHNOLOGY & REGULATORY COUNCIL. White Paper Examination of Risk-Based Screening Values and Approaches of Selected States. Prepared by The ITRC Risk Assessment Resources Team. December 2005.

ITRC – THE INTERSTATE TECHNOLOGY & REGULATORY COUNCIL. Vapor Intrusion Pathway: A Practical Guideline – ITRC Technical & Regulatory Guidance Publication – January 2007.

ITRC – THE INTERSTATE TECHNOLOGY & REGULATORY COUNCIL. Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios – Technical & Regulatory Guidance Publication. January 2007.

ITRC – THE INTERSTATE TECHNOLOGY & REGULATORY COUNCIL. Petroleum Vapor Intrusion Guideline: Fundamentals of Screening, Investigation, and Management. Technical & Regulatory Guidance Publication. October 2014.

ITRC – THE INTERSTATE TECHNOLOGY & REGULATORY COUNCIL. Implementing Advanced Site Characterization Tools. Published by the ITRC Implementing Advanced Site Characterization Tools Team in December 2019. Available at: < <https://asct-1.itrcweb.org/> > Accessed 30 Dec 2021.

Kram M, Hartman B, Frescura C, Negro P, Egelton D. Vapor intrusion risk evaluation using automated continuous chemical and physical parameter monitoring. *Remediation Journal*, Volume 30, Issue3, Pages 65-74. June 2020.

Lutes CC, Holton CW, Truesdale R, Zimmerman JH, Schumacher B. Key Design Elements of Building Pressure Cycling for Evaluating Vapor Intrusion – A Literature Review. *Groundwater Monitoring & Remediation* 39. February 2019.

NICOLE BRASIL - Network For Industrially Contaminated Land in Latin America. Gouvêa Júnior, José Carlos Rocha et al. *White Paper Intrusão de Vapores em Ambientes Fechados: Conceitos Básicos, Avaliação e Gerenciamento de Áreas Contaminadas no Brasil. Grupo Técnico de Intrusão de Vapores.* São Paulo, 2016.

OVAM – OPENBARE VLAAMSE AFVALSTOFFENMAATSCHAPPIJ. Code van Goede Praktijk: Evaluatie van uitdampingsrisico's in het kader van bodem- en grondwaterverontreinigingen. OVAM Report. March 2019.

Pankow JF, Cherry JA. Dense Chlorinated Solvents and Other DNAPLs in Groundwater: History, Behavior, and Remediation. Waterloo Press, Ontario. 1996.

Ramlal M, Broekman M, Schols E. *Notitie advies luchtmetingen van vinylchloride - Bijlage bij brief 135/12 LER JL/md, 041012.* October 2012.

RIVM – *RIJKSINSTITUUT VOOR VOLKSGEZONDHEID EN MILIEU*. *Richtlijn voor luchtmetingen voor de risicobeoordeling van bodemverontreiniging* – RIVM Report 711701048/2007. July 2007.

RIVM – *RIJKSINSTITUUT VOOR VOLKSGEZONDHEID EN MILIEU*. *Grip op vluchtige verbindingen*. RIVM Information Sheet. 2015.

Schwarzenbach RP, Gschwend PM, Imboden D M. *Environmental Organic Chemistry*. New York: Wiley. 1993.

Sitolini, Tatiana Penteado. *Integração de métodos de investigação de Áreas Contaminadas, com ênfase na caracterização de etenos clorados em aquíferos granulares – Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de Brownfields)*. Escola Politécnica da USP, Departamento de Engenharia Química, São Paulo. 2020.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. Draft Supplemental Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway (Vapor Intrusion Guidance). EPA RCRA Report. December 2001.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance). EPA Report 530-D-02-004. November 2002.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. Conceptual Model Scenarios for the Vapor Intrusion Pathway. EPA Report 530-R-10-003. February 2012.

USEPA – UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air. EPA OSWER Publication 9200.2-154. June 2015.

Valle, P. Data collected as part of a Vapor Intrusion Assessment performed in a residential area. Project performed by ERM in Western Europe, Confidential Site. April 2011.

Yao Y, Suuberg EM. A Review of Vapor Intrusion Models. *Environ Sci Technol*, 47(6): 2457–2470. March 2013. <https://doi.org/10.1021/es302714g>.

Annex 1. Building Survey – Indoor Air Sampling Questionnaire
(ITRC, 2007)

Indoor Air Sampling Questionnaire

**NEW YORK STATE DEPARTMENT OF HEALTH
INDOOR AIR QUALITY QUESTIONNAIRE AND BUILDING INVENTORY
CENTER FOR ENVIRONMENTAL HEALTH**

This form must be completed for each residence involved in indoor air testing.

Preparer's Name _____ Date/Time Prepared _____

Preparer's Affiliation _____ Phone No. _____

Purpose of Investigation _____

1. OCCUPANT:

Interviewed: Y / N

Last Name: _____ First Name: _____

Address: _____

County: _____

Home Phone: _____ Office Phone: _____

Number of Occupants/persons at this location _____ Age of Occupants _____

2. OWNER OR LANDLORD: (Check if same as occupant ___)

Interviewed: Y / N

Last Name: _____ First Name: _____

Address: _____

County: _____

Home Phone: _____ Office Phone: _____

3. BUILDING CHARACTERISTICS

Type of Building: (Circle appropriate response)

Residential
Industrial

School
Church

Commercial/Multi-use
Other: _____

If the property is residential, type? (Circle appropriate response)

Ranch	2-Family	3-Family
Raised Ranch	Split Level	Colonial
Cape Cod	Contemporary	Mobile Home
Duplex	Apartment House	Townhouses/Condos
Modular	Log Home	Other: _____

If multiple units, how many? _____

If the property is commercial, type?

Business Type(s) _____

Does it include residences (i.e., multi-use)? Y / N If yes, how many? _____

Other characteristics:

Number of floors _____ Building age _____

Is the building insulated? Y / N How air tight? Tight / Average / Not Tight

4. AIRFLOW

Use air current tubes or tracer smoke to evaluate airflow patterns and qualitatively describe:

Airflow between floors

Airflow near source

Outdoor air infiltration

Infiltration into air ducts

5. BASEMENT AND CONSTRUCTION CHARACTERISTICS (Circle all that apply)

- a. Above grade construction: wood frame concrete stone brick
- b. Basement type: full crawlspace slab other _____
- c. Basement floor: concrete dirt stone other _____
- d. Basement floor: uncovered covered covered with _____
- e. Concrete floor: unsealed sealed sealed with _____
- f. Foundation walls: poured block stone other _____
- g. Foundation walls: unsealed sealed sealed with _____
- h. The basement is: wet damp dry moldy
- i. The basement is: finished unfinished partially finished
- j. Sump present? Y / N
- k. Water in sump? Y / N / not applicable

Basement/Lowest level depth below grade: _____(feet)

Identify potential soil vapor entry points and approximate size (e.g., cracks, utility ports, drains)

6. HEATING, VENTING and AIR CONDITIONING (Circle all that apply)

Type of heating system(s) used in this building: (circle all that apply – note primary)

- | | | | |
|---------------------|------------------|---------------------|-------------|
| Hot air circulation | Heat pump | Hot water baseboard | |
| Space Heaters | Stream radiation | Radiant floor | |
| Electric baseboard | Wood stove | Outdoor wood boiler | Other _____ |

The primary type of fuel used is:

- | | | |
|-------------|----------|----------|
| Natural Gas | Fuel Oil | Kerosene |
| Electric | Propane | Solar |
| Wood | Coal | |

Domestic hot water tank fueled by: _____

Boiler/furnace located in: Basement Outdoors Main Floor Other _____

Air conditioning: Central Air Window units Open Windows None

Are there air distribution ducts present? Y / N

Describe the supply and cold air return ductwork, and its condition where visible, including whether there is a cold air return and the tightness of duct joints. Indicate the locations on the floor plan diagram.

7. OCCUPANCY

Is basement/lowest level occupied? Full-time Occasionally Seldom Almost Never

Level General Use of Each Floor (e.g., familyroom, bedroom, laundry, workshop, storage)

Basement	_____
1 st Floor	_____
2 nd Floor	_____
3 rd Floor	_____
4 th Floor	_____

8. FACTORS THAT MAY INFLUENCE INDOOR AIR QUALITY

- a. Is there an attached garage? Y / N
- b. Does the garage have a separate heating unit? Y / N / NA
- c. Are petroleum-powered machines or vehicles stored in the garage (e.g., lawnmower, atv, car) Y / N / NA
Please specify _____
- d. Has the building ever had a fire? Y / N When? _____
- e. Is a kerosene or unvented gas space heater present? Y / N Where? _____
- f. Is there a workshop or hobby/craft area? Y / N Where & Type? _____
- g. Is there smoking in the building? Y / N How frequently? _____
- h. Have cleaning products been used recently? Y / N When & Type? _____
- i. Have cosmetic products been used recently? Y / N When & Type? _____

- j. Has painting/staining been done in the last 6 months? Y / N Where & When? _____
- k. Is there new carpet, drapes or other textiles? Y / N Where & When? _____
- l. Have air fresheners been used recently? Y / N When & Type? _____
- m. Is there a kitchen exhaust fan? Y / N If yes, where vented? _____
- n. Is there a bathroom exhaust fan? Y / N If yes, where vented? _____
- o. Is there a clothes dryer? Y / N If yes, is it vented outside? Y / N
- p. Has there been a pesticide application? Y / N When & Type? _____

Are there odors in the building? Y / N
 If yes, please describe: _____

Do any of the building occupants use solvents at work? Y / N
 (e.g., chemical manufacturing or laboratory, auto mechanic or auto body shop, painting, fuel oil delivery, boiler mechanic, pesticide application, cosmetologist)

If yes, what types of solvents are used? _____

If yes, are their clothes washed at work? Y / N

Do any of the building occupants regularly use or work at a dry-cleaning service? (Circle appropriate response)

- | | |
|--|---------|
| Yes, use dry-cleaning regularly (weekly) | No |
| Yes, use dry-cleaning infrequently (monthly or less) | Unknown |
| Yes, work at a dry-cleaning service | |

Is there a radon mitigation system for the building/structure? Y / N Date of Installation: _____
 Is the system active or passive? Active/Passive

9. WATER AND SEWAGE

Water Supply: Public Water Drilled Well Driven Well Dug Well Other: _____
 Sewage Disposal: Public Sewer Septic Tank Leach Field Dry Well Other: _____

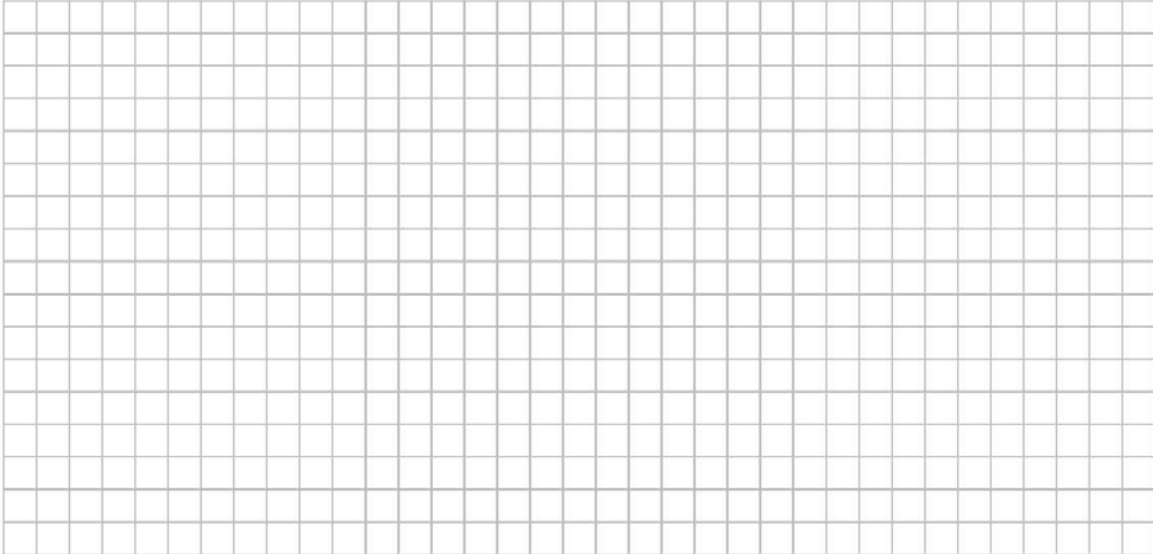
10. RELOCATION INFORMATION (for oil spill residential emergency)

- a. Provide reasons why relocation is recommended: _____
- b. Residents choose to: remain in home relocate to friends/family relocate to hotel/motel
- c. Responsibility for costs associated with reimbursement explained? Y / N
- d. Relocation package provided and explained to residents? Y / N

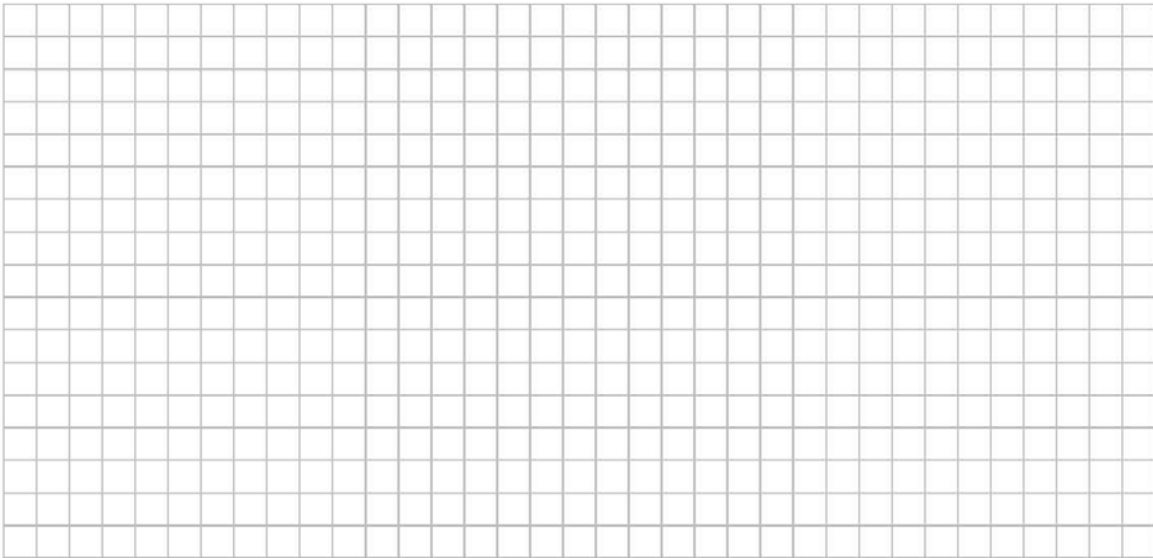
11. FLOOR PLANS

Draw a plan view sketch of the basement and first floor of the building. Indicate air sampling locations, possible indoor air pollution sources and PID meter readings. If the building does not have a basement, please note.

Basement:



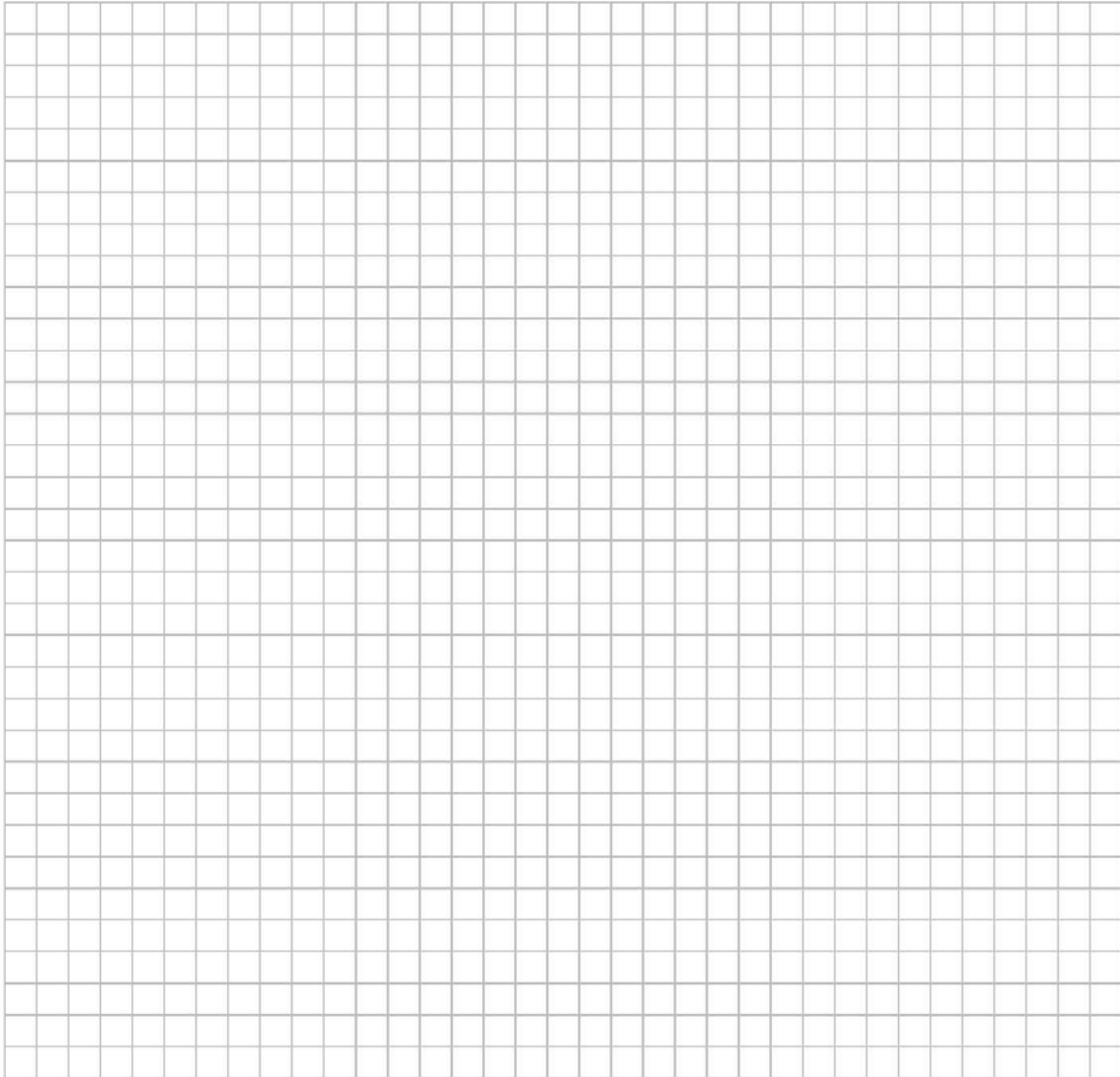
First Floor:



12. OUTDOOR PLOT

Draw a sketch of the area surrounding the building being sampled. If applicable, provide information on spill locations, potential air contamination sources (industries, gas stations, repair shops, landfills, etc.), outdoor air sampling location(s) and PID meter readings.

Also indicate compass direction, wind direction and speed during sampling, the locations of the well and septic system, if applicable, and a qualifying statement to help locate the site on a topographic map.



Annex 2. Petroleum Vapor Intrusion Conceptual Site Model Checklist
(ITRC, 2014)



PETROLEUM VAPOR INTRUSION CONCEPTUAL SITE MODEL CHECKLIST

The information included in this checklist may be useful for developing the site-specific conceptual migration model and in planning the soil gas sampling. You can use this checklist to compile information for each site.

Site ID/Name: _____

Address/Location: _____

Site Owner/Operator: _____

Released Product(s) & Volume(s): _____

Release Date: _____

Type of Petroleum Site

(Identification of indicator petroleum hydrocarbon compounds and release sources)

- Gasoline and/or diesel UST locations
- Commercial and home heating oil locations
- Refineries
- Bulk storage facilities
- Pipelines and transportation
- Oil exploration and production sites
- Former manufactured gas plants
- Creosote (wood treating) facilities
- Dry cleaners using petroleum solvents (such as Stoddard solvent)
- Other, describe:

(Required for screening evaluation)**Source(s)**

- Identify affected media
 - LNAPL
 - Dissolved
 - Sorbed
 - Vapor
- Define magnitude and extent of affected media
- Indicators for screening (state-specific)
- Indicators/COPCs for investigation (state-specific)
- Nonpetroleum VOCs
 - Indications of an ongoing release?
 - Describe source stability (stable, increasing, decreasing)
 - Have petroleum odors been reported or documented in buildings?

Migration

- Define lateral separation distance between source and receptor.
- Define the thickness of unaffected (“biologically active” or “relatively clean”) soil between the source(s) and the building foundation.
- Describe biodegradation indicators, including O₂, CO₂, methane, total organic carbon (TOC) content, moisture, temperature, and pH at depths specified.
- Describe vadose zone lithology.

Buildings (Receptors)

- Identify and denote on site plan existing and potential future buildings.
- Identify the occupancy and use of the buildings, for example residential, commercial, or industrial (may need to interview occupants to obtain this information).
- Describe the construction of the building including materials (such as wood frame or block), openings (windows, doors), and height (one-story, two-story, multiple-story); identify any elevator shafts present in the building (if applicable).
- Describe the foundation construction including:

- Type (basement, crawl space, slab on grade)
 - Floor construction (such as concrete or dirt)
 - Depth below grade/ground surface
 - Describe foundation drainage or penetrations if they exist (French drains, sumps, cracks, or other)
- Describe the HVAC system in the building including:
- Furnace/air conditioning type (forced air, radiant)
 - Furnace/air conditioning location (basement, crawl space, utility closet, attic, roof)
 - Source of return air (inside air, outside air, combination)
 - System design considerations relating to indoor air pressure (positive pressure is often the case for commercial buildings).
- Describe subslab ventilation systems or moisture barriers present on existing buildings, or identify building and fire code requirements for subslab ventilation systems (such as for methane) or moisture barriers below foundations.
- Identify occupancy and use of off-site buildings affected or potentially affect by site sources. Assess the need for public communication plan.

Engineered Preferential Pathways—Utilities, Process Piping, Sumps

- Locate and denote on site plan all underground utilities near the soil or groundwater impacts; note utilities that connect affected areas to occupied buildings including depths and entry points.
- Locate and denote on site plan all underground process piping near the soil or groundwater impacts.
- Locate and denote on site plan building basement dewatering sumps.

Source Area

- Identify and denote on site plan the sources and their locations contributing to vapor-phase contaminants related to the subsurface VI pathway (LNAPL, dissolved plume, contaminated soil, soil gas). Estimate mass of LNAPL, dissolved plume size, affected soil volume.
- Describe and denote on site plan the presence, distribution, and composition (gasoline and ethanol content, diesel, and fuel oil) of LNAPL at the site.
- Identify and denote on site plan any presence of comingled chlorinated hydrocarbon plume.
- Identify the vapor-phase contaminants (based on volatility and toxicity) that are to be considered for the subsurface VI pathway (benzene).

- Describe the status and results for the delineation of contamination in environmental media, specifically soil and groundwater, between the source area and the potential affected buildings.
- Describe the environmental media (soil, groundwater, both) containing contaminants.
- Describe the depth to source area (LNAPL, dissolved plume, unsaturated soil, soil gas).
- Describe the potential migration characteristics (stable, increasing, decreasing) for the distribution of contaminants.
- Describe contaminant transport mechanisms (diffusion in vadose zone or through capillary zone, advective flows, movement through preferential pathways).
- Describe remedial actions completed to date.

Geology/Hydrogeology

- Describe regional geology (especially important in fractured rock or karst areas).
- Review all boring logs, monitoring well construction, and soil sampling data to understand the following: depth of vadose zone, capillary fringe and the phreatic (saturated) zone
 - Note any seasonal water table fluctuations and seasonal flow direction changes (hydraulic gradient).
 - Note the depth interval between the vapor source and the ground surface.
 - Note the presence and thickness of a biologically active layer to support biodegradation.
 - Note the presence of any perched aquifers.
 - Note where the water table intersect well screen interval or note the presence of submerged screen.

Biological Indicators

- Describe biological indicators.
 - O₂ concentrations to support aerobic PHC biodegradation, note presence of large building footprint that may limit atmospheric oxygen transport beneath center area of building
 - CO₂ concentrations
 - Methane concentrations (generation under anaerobic biodegradation of PHC because of high concentrations at plume interior or presence of LNAPL, or because of high-ethanol gasoline), potential for concentrations in explosive range (especially in confined areas), increased O₂ demand because of aerobic biodegradation of methane
 - Organic soil (such as peat) with low O₂ that limits potential for aerobic PHC degradation

Describe distinct strata and characteristics (soil type, temperature, moisture content, porosity, bulk density, organic content).

Identify the depth to groundwater.

Describe groundwater characteristics (seasonal fluctuation, temperature, hydraulic gradient: vertical and horizontal; natural versus induced, flow directions).

Site Characteristics & Considerations

Estimate and denote on site plan the lateral extent of and the distance from edge of groundwater plume to building.

Identify groundwater beneficial use (potable or nonpotable).

Identify nearby potential contaminant sources.

Estimate vertical separation distance from vapor source to building foundation and denote on subsurface cross-sections.

Describe the surface cover between the vapor source area and the potentially affected building.

Identify presence of continuous pavement that may result in unimpeded migration of vapor in the subgrade layer to building foundation.

Describe surface water/precipitation infiltration in unpaved areas, serving as a pathway for transport of dissolved O₂ to vadose zone for aerobic PHC degradation.

Describe background contributions and concentrations of volatile contaminants to indoor air (both ambient/outdoor and indoor sources).

Describe data quality for VI assessment (sample collection methods, laboratory detection levels, sufficiency of sample numbers and events, and representative sample locations).

Describe rationale for determination of VI exposure pathways and any exclusion.