Technical Justification for Low-Threat
Closure Scenarios for Petroleum Vapor Intrusion Pathway

1   EXECUTIVE SUMMARY

For petroleum-related volatile organic compounds (VOCs) at retail sites, current risk-based screening levels (such as the California Human Health Screening Levels [CHHSLs]) for evaluating risk from vapor intrusion at retail sites are extremely conservative. This conservatism is caused by excluding biodegradation in site screening and often drives further unnecessary site evaluation. Recent models and field studies show that bioattenuation of petroleum hydrocarbons at retail sites is significant. Petroleum VOCs (such as benzene, toluene, ethylbenzene and xylenes (BTEX)) concentrations can attenuate by 4 to 6 orders of magnitude within short vertical distances (e.g., < 2 m) in the unsaturated zone. The VOC attenuation increases by an additional order of magnitude (or more) if transport across the building foundation to indoor air is also considered. The sharp decrease in petroleum VOC concentrations within a short vertical distance of the unsaturated zone is amenable to use of exclusion distances as a site-screening methodology for vapor intrusion. Exclusion distances are defined as source (VOCs in soil or groundwater)-receptor (building) separation distances beyond which the risk of vapor intrusion is negligible. Exclusion distance criteria can be broadly defined for two types of sources: low-concentration and high-concentration sources which are defined below.

Recent modeling studies and evaluations of field (soil-gas) data from numerous retail sites and sampling locations demonstrate that biodegradation is sufficient to limit the potential for vapor intrusion at sites with "low concentration" hydrocarbon sources. For example, there is less than a 5% probability that benzene concentrations in soil gas would exceed a conservative screening level of 100 ug/m^3 at a distance of 5 feet above the source. (Note the CHHSL for benzene in soil gas is 83 ug/m^3.) The attenuation is predicted to increase with lateral displacement of the source from the building foundation. Vapor intrusion risks are thus expected to be rare to non-existent at sites with low-concentration sources.

At sites with "high concentration" volatile sources (unweathered residual LNAPL in soil and/or unweathered free-phase LNAPL on groundwater), transport modeling shows that hydrocarbons will attenuate in the unsaturated zone by approximately 6 orders of magnitude within 7 m (~20 ft) at sites. This result is achieved assuming reasonable approximations for source type and biodegradation rate. Analysis of soil-gas data collected from many retail sites with LNAPL sources indicate that the distance required to attenuate soil vapor concentrations to below typical screening levels are on the order of 8 – 13 ft. As with "low-concentration" sources (weathered residual LNAPL in soil and/or dissolved concentrations in groundwater), the bioattenuation is more significant for LNAPL sources separated laterally from building foundations (i.e. the soil gas concentrations would attenuate in even shorter distances).

The Stakeholder Group has proposed screening criteria for four basic scenarios that can be used to identify low-threat closure scenarios for vapor intrusion (VI). The purpose of this technical document is

to outline the intent of the Stakeholder Group for use of these screening criteria and to provide justification for the four scenarios below. These scenarios are:

Scenario 1: Unweathered LNAPL on groundwater
Scenario 2: Unweathered LNAPL in soil
Scenario 3: Dissolved phase benzene concentrations in groundwater
Scenario 4: Direct measurement of soil gas concentrations

For each of these scenarios, screening criteria have been proposed that, if met, would identify the site as a low-threat to human health from the vapor intrusion pathway.

It is important that the current state of the science as described herein be used to develop rational, technically defensible, approaches to address these potential vapor intrusion risk scenarios.   In addition, many of the cited exclusion criteria are based on analysis of soil-gas data collected from retail sites. The screening criteria may therefore not be applicable for non-retail (e.g., pipeline, manufacturing, and terminal) sites where significantly larger volume petroleum hydrocarbon releases may have occurred. If conditions at non-retail sites are significantly different than would be encountered at a typical retail site, they should be evaluated on a site-specific basis. The materials referenced in this technical justification are consistent with the technical material being used to develop guidance by US EPA's Office of Underground Storage Tanks (OUST)'s Task Force on Petroleum Vapor Intrusion.

2   INTRODUCTION

Biodegradation is the most critical process governing the potential for vapor intrusion at petroleum release sites. The significance of biodegradation depends largely on the demand for oxygen (O_2) and its availability. Key factors that affect the O_2 demand/availability include source strength/type (e.g., LNAPL or dissolved phase), source location (i.e., above or below the capillary zone), soil type (DeVaull, 2007), variable and/or high soil-moisture saturation, building foundation type/size (Patterson and Davis, 2009; DeVaull (in press) and surface cover.

At sites with "low-concentration" sources (weathered residual in soil and/or dissolved concentrations in groundwater), the significance of biodegradation is most notable because biodegradation conditions in the unsaturated zone generally remain aerobic. At these sites, O_2 availability in the unsaturated zone generally exceeds O_2 demand resulting from biodegradation. Biodegradation under aerobic conditions has been shown to be rapid resulting in the development of sharp attenuation fronts where BTEX concentrations decrease by several orders of magnitude over relatively short (e.g. <1 m) vertical distances (Fischer et al., 1996; Lahvis et al., 1999; DeVaull, 2007; Davis, 2009; and Hartman, 2010). The hydrocarbon reaction fronts (the point at which most of the degradation is occurring) tend to develop very near the water table at sites with dissolved-phase only sources in groundwater (e.g., benzene concentrations < 15 mg/L). At these sites, effects of soil type, building foundation and surface cover will tend to be limited. Evidence to support these assertions exists both in the theory (modeling) (DeVaull, 2007, Abreu et. al. 2009, API, 2009) and in the field (Lahvis and Baehr, 1996; API, 2009; Davis, 2009).

Further attenuation is predicted for dissolved-phase sources displaced laterally from the building foundation (Abreu and Johnson, 2005).

At sites with LNAPL on the groundwater, biodegradation can also be quite notable. Exclusion distances for benzene and total petroleum hydrocarbons (TPH) determined from analysis of soil-gas data primarily collected at retail sites have been estimated to be in the range of 8 to 15 feet (Davis, 2009; Hartman, 2010; Lahvis, 2011)[1]. The greater exclusion distance for LNAPL sites compared to dissolved-phase sites is in part related to the added demand for O_2 (noted above) for LNAPL sources and the tendency for LNAPL sources to be distributed above the capillary zone. For dissolved phase sources in groundwater, the capillary zone has been documented as an active zone for VOC attenuation (Lahvis and Baehr, 1996). Results from the analysis of the Davis (2010) soil-gas database are consistent with other large field studies (Lahvis, 2011). As noted above, the significance of bioattenuation is largely dependent on source type. Differentiation of residual-phase LNAPL (high concentration) sources from dissolved-phase (low concentration) sources can, however, be difficult. The following general rules of thumb could be used as indicators of residual-phase LNAPL sources in groundwater or in soil:

Presence of LNAPL

Direct evidence:

- sites with current or historical evidence of LNAPL in soil or LNAPL at the water table as evidenced in wells

Indirect evidence:

- chemicals of concern (COCs) approaching (> 0.2) effective solubilities (Bruce et al., 1991) in groundwater (e.g., benzene > 3 mg/L ; total benzene, toluene, ethylbenzene and xylenes (BTEX) > 20 mg/L; TPH diesel range organics (DRO) > 5 mg/L) and in soil (TPH gasoline range organics (GRO) > 100 - 200 mg/kg[(2)]; TPH DRO > 10 - 50 mg/kg) (see ASTM, 2006, Alaska DEC, 2011)[3]

- TPH vapor readings from a photo-ionization detector (PID) of > 1,000 ppm (recent gasoline release sites), > 100 ppm (recent diesel/historic gasoline release sites), and > 10 ppm (historic diesel sites) (Alaska DEC, 2011). Note weathered LNAPL typically has a significant reduction in the VOC content and therefore represents less of a concern for vapor intrusion.

The following rules-of-thumb for can be used to determine whether LNAPL is a concern for vapor intrusion risk:

Differentiating between Weathered and Unweathered LNAPL

- For groundwater impacted by LNAPL or where groundwater is in proximity to LNAPL, effective solubility is a key indicator for whether the LNAPL is depleted of VOCs. For

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[1] It is important to note, that the soil-gas data were collected primarily at retail sites. Approximately 16% of the soil-gas sampling locations were directly below building foundations (i.e., sub-slab).

[2] TPH (GRO) between 100 to 200 mg/kg may indicate there may be a slight amount of LNAPL. TPH (GRO) less than 100 mg/kg is a good indication that there is no LNAPL present.

[3] The primary driver for vapor intrusion is benzene. For petroleum-based fuels other than gasoline, benzene is not found at levels that would cause a vapor intrusion problem.

example, benzene's effective solubility is approximately 18 mg/L, if it constitutes 1% of gasoline. Therefore benzene concentrations < 1 mg/L are reasonable indicators that the LNAPL is weathered (depleted of VOCs).

- For soil sources, TPH (GRO) < 100 mg/kg is a good indication that there is a small or low concentration (VOC) source.

Naphthalene is currently considered a carcinogen via the inhalation exposure route and since it is also volatile, it can be considered a potential risk driver. The exclusion criteria defined for benzene are assumed to be conservative for naphthalene, which is also highly susceptible to biodegradation (Anderson et al., 2008; GSI, 2010). Naphthalene also has a much lower solubility value and Henry's Law coefficient (compared to benzene), thereby limiting the amount of naphthalene available to volatilize into the gas phase. For these reasons, the screening criteria described here, while developed for benzene, should also be protective of naphthalene vapor intrusion.

3   TECHNICAL BACKGROUND – Discussion of Biodegradation Effects

This section will present the results of model studies and field data that support the assumptions made in the vapor intrusion exclusion criteria. First, the results found at "low-concentration source" cases will be discussed followed by "high-concentration source" cases.

Lastly, it is important to note that once the groundwater concentrations are below effective solubility, the actual hydrocarbon concentrations in groundwater are not necessarily good predictors of vapor intrusion risk. Field site observations show that dissolved-phase hydrocarbon concentrations in shallow groundwater and soil gas concentrations overlying the water table are poorly correlated (Lahvis, 2011). The poor correlation at dissolved-phase only sites can be attributed to the inability to accurately measure hydrocarbon concentrations at the water table and to the considerable bioattenuation of hydrocarbon vapors between the water-table source and the soil-gas measurement location. At LNAPL (residual-phase) sites, soil-gas concentrations are also poorly correlated with groundwater concentrations because LNAPL sources are typically present above the water table. For these reasons, it is recommended to focus the development of screening criteria solely on the basis of source type (LNAPL and groundwater) rather than source (groundwater) concentration.

3.1   Low-Concentration Sources (weathered residual in soil and/or dissolved concentrations in groundwater)

For purposes of this technical justification, low concentration sources at hydrocarbon sites are defined as dissolved-phase concentrations. Low concentration sources will therefore be composed primarily of the more soluble (aromatic) LNAPL constituents, benzene, toluene, ethylbenzene, xylenes, and naphthalene. Of these constituents, benzene is the primary risk driver for vapor intrusion because of its relatively higher toxicity and vapor migration potential. Note, weathered LNAPL can behave like low-concentration sources because the LNAPL may be depleted of volatile chemicals.

3.1.1 Model Studies

Results from detailed numeric (3-dimensional) models (see Figure 3 from API below) indicate that complete attenuation of the hydrocarbons (approximately 10 orders of magnitude) is predicted between a relatively low concentration source (< 10 mg/L total hydrocarbon in soil gas) and indoor air where the source is separated from the receptor by > 3 meters (see API, 2009; Abreu et al., 2009)[4]. Note, the "hydrocarbon" modeled in these studies was assumed to have the same fate and transport properties as benzene. In addition, the simulations are based on assuming biodegradation takes place only in the aerobic portion of the unsaturated zone (i.e., when O_2 concentrations exceed 1%). An aerobic biodegradation rate of 0.79 hr^{-1} is assumed for the hydrocarbon (benzene) based on a mean of published rates (DeVaull, 2007). Note, while a degradation rate of 0.75 hr^{-1} may seem high, the model only allows degradation in the regions where there is enough O_2 to support it. The model cutoff for allowing degradation was 1% O_2. A 10 mg/L benzene vapor source is consistent with a dissolved-phase source of benzene (or BTEX) of around 40 mg/L assuming equilibrium partitioning between soil gas and groundwater and a Henry's law coefficient of 0.25 for benzene (or BTEX). The attenuation with distance is increased for the latter condition because diffusion of the hydrocarbons will tend to be vertically upwards (toward the soil surface) rather than laterally towards the receptor. Hence, there is little potential for vapor intrusion to occur at sites with dissolved-phase sources separated laterally from building foundations.

The following two figures from API (2009) show hydrocarbon and O_2 profiles predicted by transport modeling for low-concentration vapor sources varying between 0.1 mg/L hydrocarbon (0.4 mg/L dissolved-phase equivalent) and 10 mg/L hydrocarbon (40 mg/L dissolved-phase equivalent) and two different foundation configurations, basement and slab, respectively. Note, the "hydrocarbon" modeled in these studies was again assumed to have the same fate and transport properties as benzene. The source concentration was assumed to be equal to the combined concentrations of all of the BTEX. This approach was used because it was conservative to consider the increased O_2 demand from the additional VOCs present (all of the BTEX). Therefore, these modeling study results can be considered conservative for benzene.

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[4] A 10 mg/L hydrocarbon soil gas source would equate to a ~40 mg/L source of BTEX in groundwater assuming a vapor/aqueous phase partition coefficient of around 0.25 (Morrison, 1999) assuming the source were dissolved.
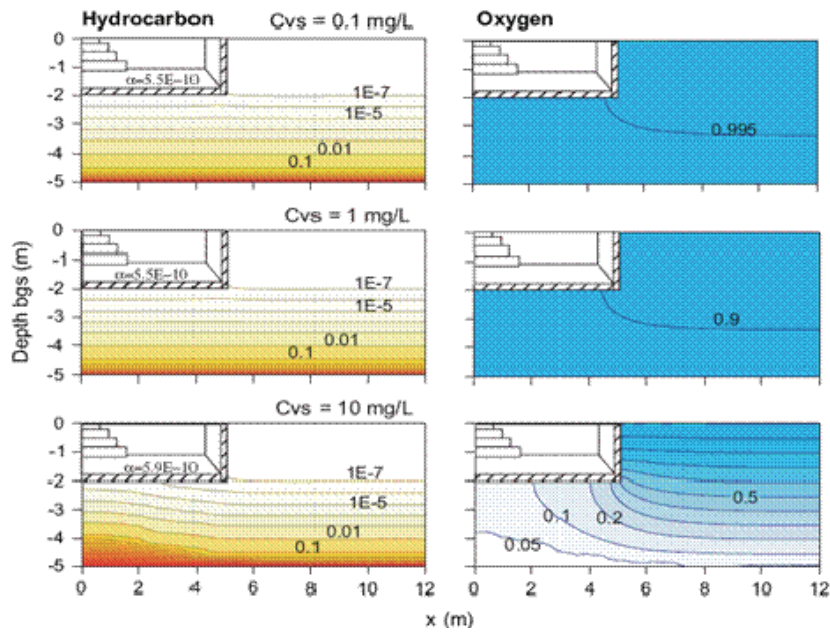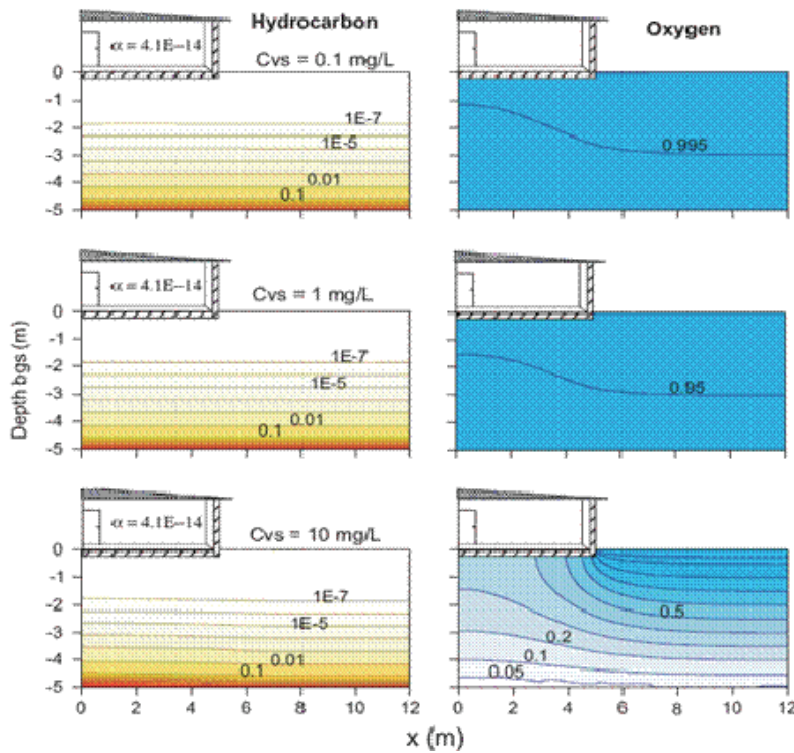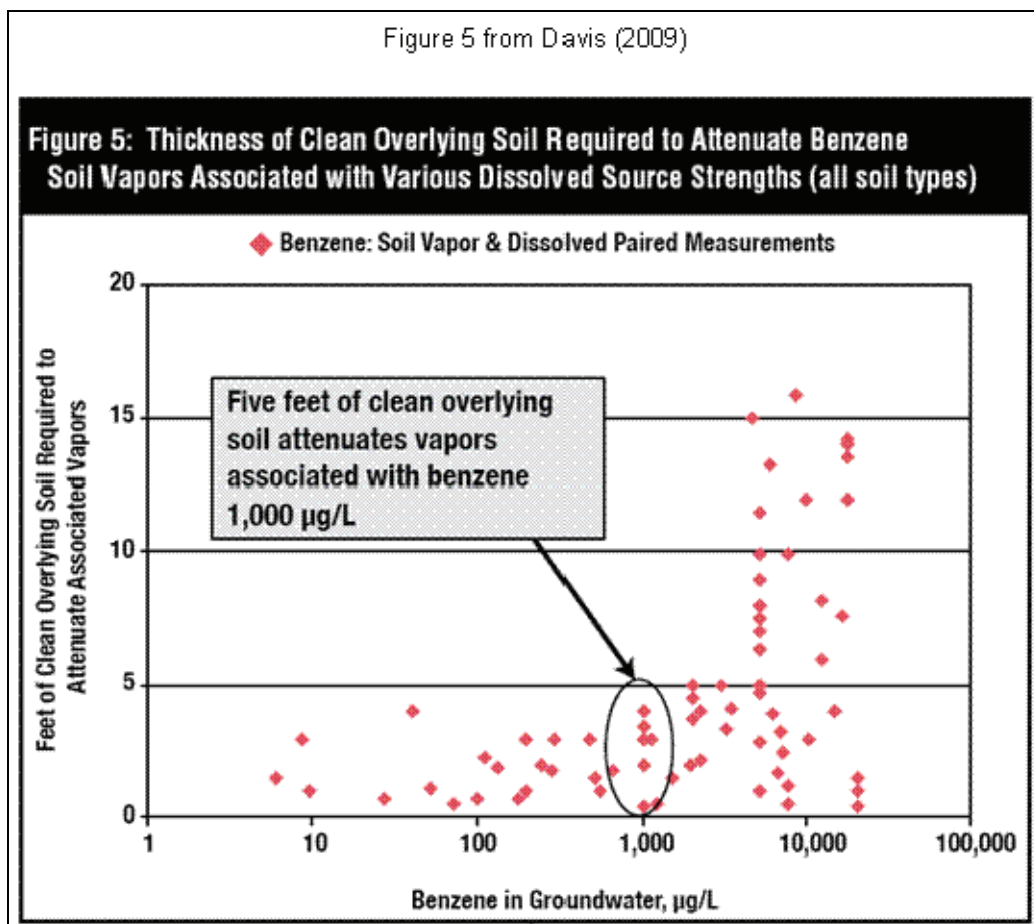
Figure 3. Effect of low vapor source concentration (Cvs) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79$ h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

Figure 4. Effect of low vapor source concentration (Cvs) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for slab-on-grade foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79$ h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

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3.1.2   Field Data

A soil-gas database has been developed by Robin Davis (Utah Department of Environmental Quality - DEQ). The database was compiled from numerous retail, distribution, and manufacturing sites across several states, including California. The soil-gas data were collected from locations on and off-site. Approximately 16% of the soil-gas data were collected directly below building foundations (i.e., subslab). The data **from retail sites** are being used to support the development of new state (see http://www.swrcb.ca.gov/ust/luft_manual.shtml) and federal (US EPA OUST) vapor intrusion guidance. Analyses of the soil-gas data are described in Davis (2009) and Hartman (2010). The data analyses support the model results discussed in the previous section. The analyses indicate that "dissolved-phase" sources < 6 mg/L benzene in groundwater (or ~24,000,000 ug/m^3 vapor phase equivalent[5]) are completely attenuated within distances of 5 ft. or less (see figure below from Davis, 2009).

Figure 5 from Davis (2009)

Figure 5: Thickness of Clean Overlying Soil Required to Attenuate Benzene Soil Vapors Associated with Various Dissolved Source Strengths (all soil types)
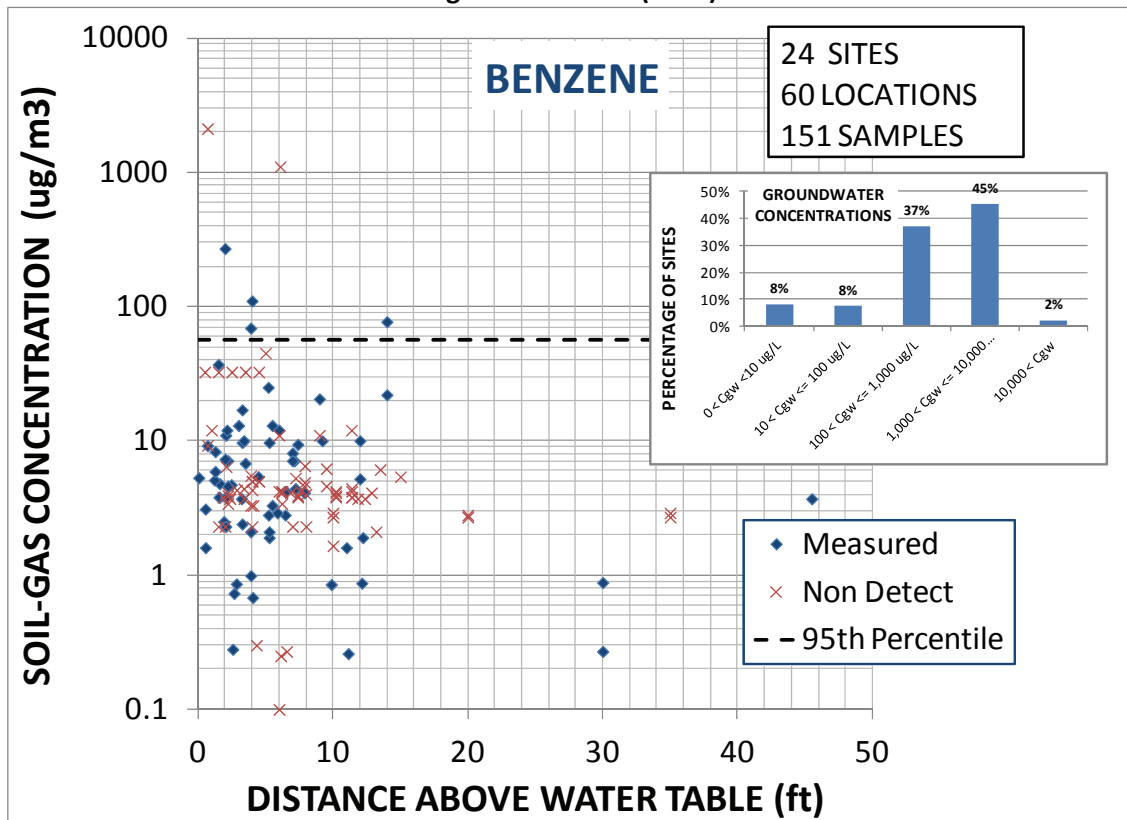
It is important to note, however, that the Davis (2009) analyses of thickness of clean overlying soil required to attenuate benzene vapors (or "exclusion distance") did not rigorously screen out potential residual LNAPL sources above the water table. These sites pose a similar risk for vapor intrusion as sites

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[5] Assuming a Henry's Law coefficient of 0.25 cm^3/cm^3 for benzene.

with free-phase LNAPL on groundwater (i.e., sites where LNAPL is observed in monitoring wells). The analysis shown in Figure 5 also includes data from "non-retail" locations. It is also important to note that the Davis (2009) results imply that the vapor intrusion risk is dependent on the source concentration in groundwater. Again, this dependence has not been observed at other sites and is not recommended to be used in developing groundwater concentration-based exclusion distances.
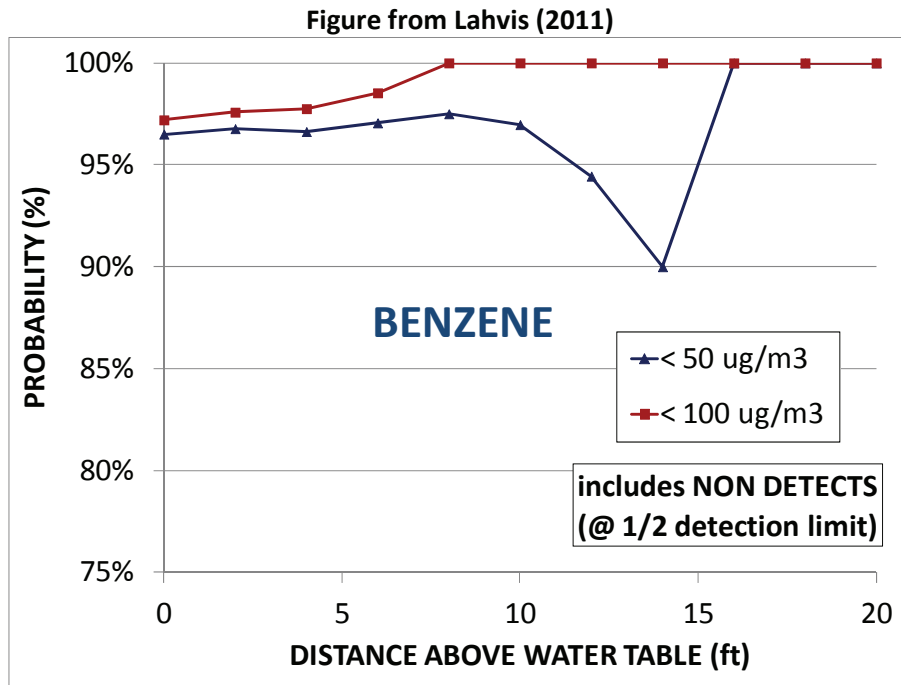
A slightly different analysis of the "**retail-only**" data from the Robin Davis database by Lahvis (2011) shows that benzene will be bioattenuated below a relatively conservative soil-gas screening level of 100 ug/m^{3} within 5 ft of the water table[6]. The analysis focused on identified sources of benzene in groundwater and filtered out sites with either direct evidence of LNAPL (current, historical) or indirect evidence of LNAPL (soil-gas measurements collected near potential sources (i.e., locations within 25 ft of USTs and dispensers), and also screened out sites with benzene concentrations in groundwater > 15 mg/L or BTEX > 75 mg/L). The vast majority (84%) of the soil-gas measurements were taken from sites with source concentrations of benzene in groundwater ranging from 0.1 mg/L (100 ug/L) to 15 mg/L.

Figure from Lavis (2011)

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[6] This value represents the attenuation between a benzene source in groundwater up to 15 mg/L (or 7,500,000 ug/m^{3} in soil-gas) and a conservative soil-gas screening level concentration of 100 ug/m^{3}. This concentration is representative of a screening-level concentration in soil gas (assuming an indoor air risk-based concentration of 2 ug/m^{3} and a slab attenuation factor of 0.02).

From a probability standpoint, the results from the scatter plot can be defined as follows (Lahvis, 2011):

Figure from Lahvis (2011)

The probability of having benzene vapor concentrations near the receptor that exceed a conservative screening level (i.e., 100 ug/m^3) at dissolved-phase (retail) sites is less than 5%. The water table would have to essentially be in contact with a building foundation for there to be a potential concern for vapor intrusion at low concentration sites.
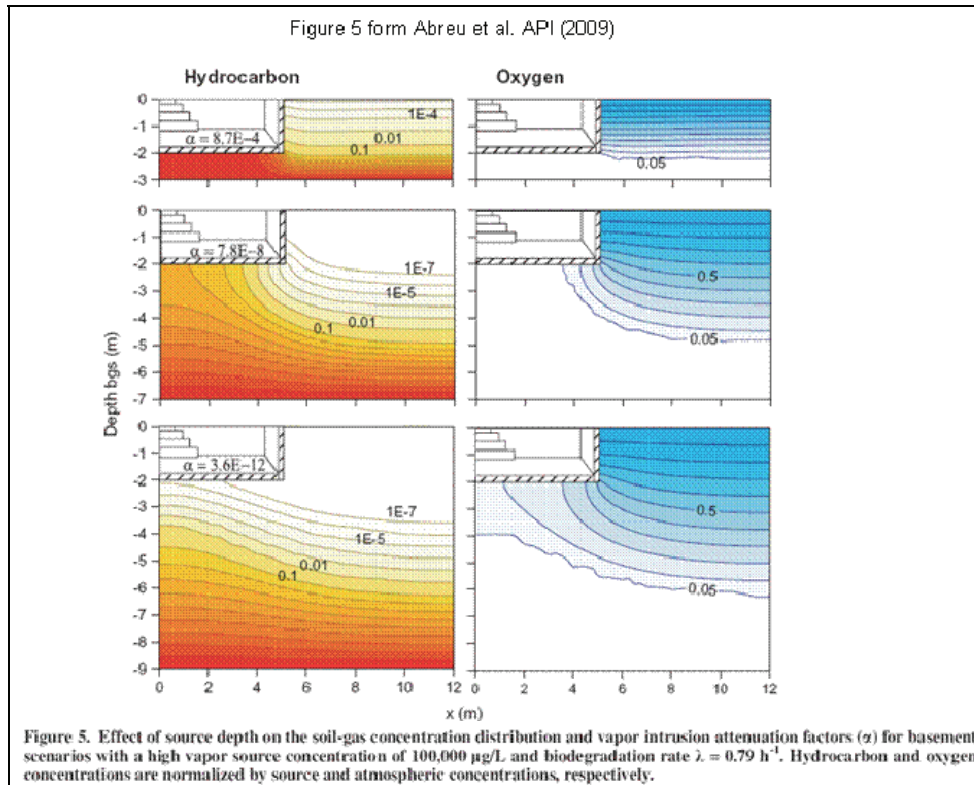
3.1.3   Summary of Low Concentration Sources

In summary, field data from retail sites shows that for low concentration (e.g., dissolved-phase only) sources, benzene will be attenuated to below screening levels within 5 ft above the water table. Vapor intrusion risks would be rare to non-existent at these retail sites provided the water table does not come in contact with the building foundation.

3.2   High-Concentration Sources (unweathered residual in soil and/or free-phase LNAPL on groundwater)

3.2.1   Model Studies

As shown in the attached figure from Abreu et al. (2009), hydrocarbons are predicted to completely attenuate in the unsaturated zone above an LNAPL source within ~ 7m of the source. Again, the model simulations use benzene as a surrogate for all of the TPH present. A mean biodegradation rate of 0.79 hr^{-1} was again assumed (DeVaull, 2007) in model regions where the O$_2$ level was sufficiently high enough to support aerobic biodegradation.

Figure 5. Effect of source depth on the soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement scenarios with a high vapor source concentration of 100,000 μg/L and biodegradation rate λ = 0.79 h⁻¹. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.
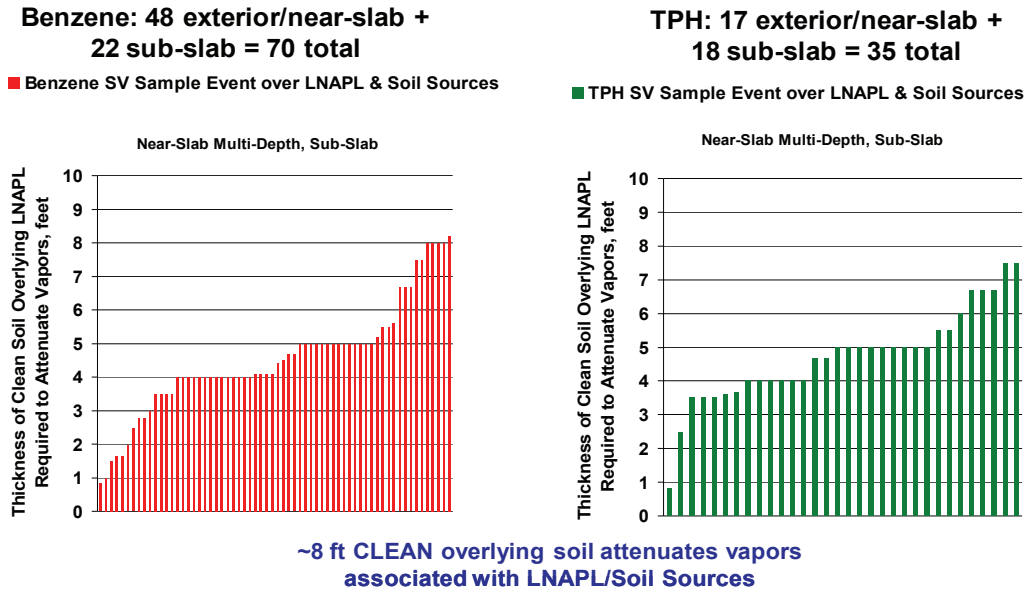
Again, the attenuation is expected to increase for NAPL sources displaced laterally from the basement foundation (see Abreu and Johnson, 2005).

3.2.2 Field Data

A more recent analysis of the soil-gas database by Davis (2010) indicates that the model predicted bioattenuation is conservative. Exclusion distances of only 8 ft. were found to be sufficient to attenuate LNAPL sources. This analysis takes into account residual LNAPL sources in the unsaturated zone (see the following figure from Davis (2010)).
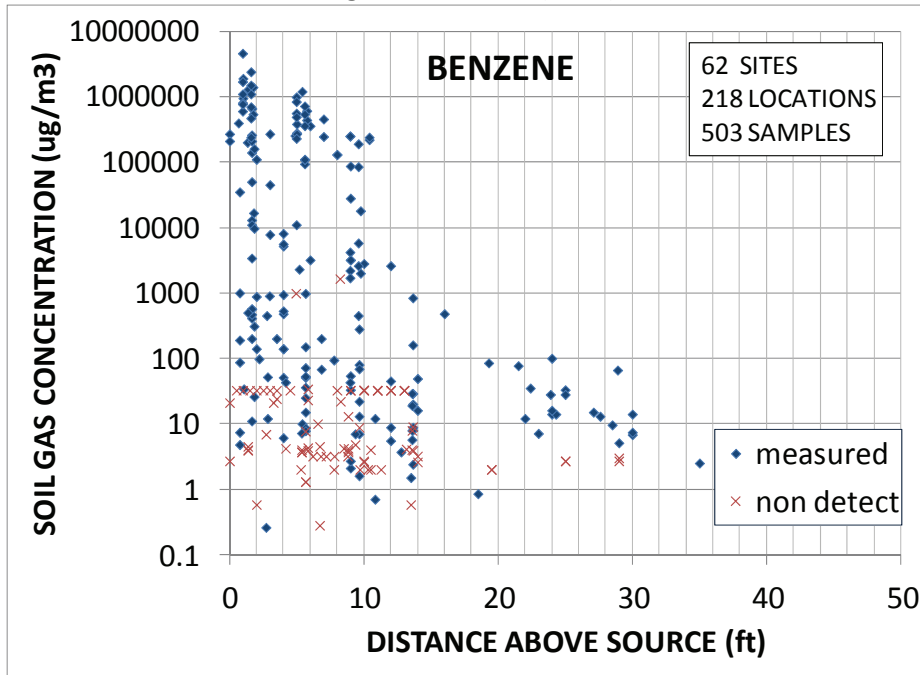
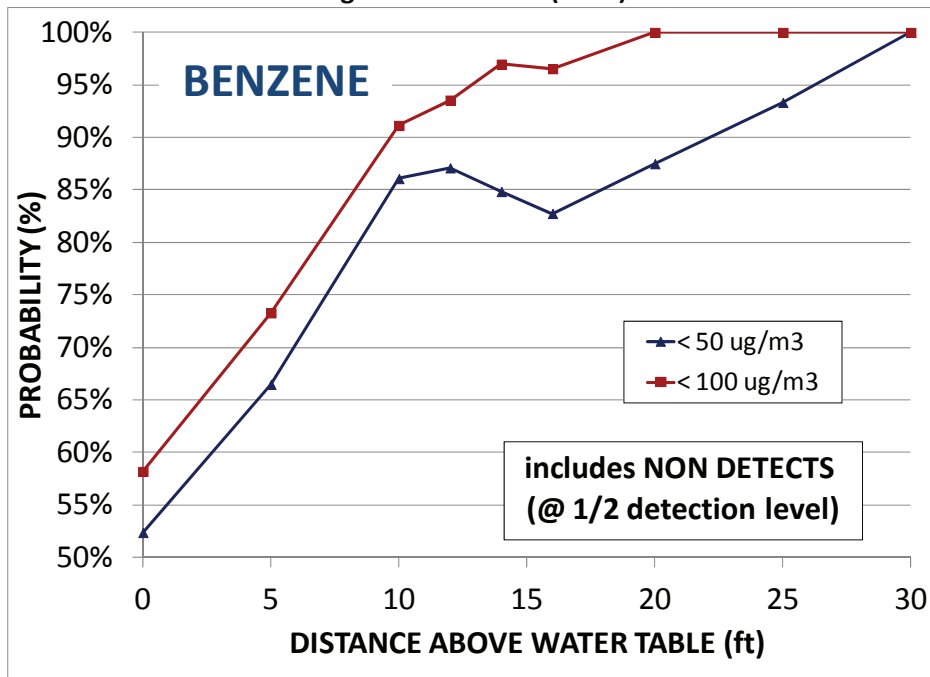Figure from Davis (2010)

LNAPL & Soil Sources

Benzene: 48 exterior/near-slab + 22 sub-slab = 70 total

■ Benzene SV Sample Event over LNAPL & Soil Sources

TPH: 17 exterior/near-slab + 18 sub-slab = 35 total

■ TPH SV Sample Event over LNAPL & Soil Sources

Near-Slab Multi-Depth, Sub-Slab

Near-Slab Multi-Depth, Sub-Slab

~8 ft CLEAN overlying soil attenuates vapors associated with LNAPL/Soil Sources

Lahvis (2011) has interpreted the soil-gas database compiled by Davis slightly differently. The next figure shows benzene concentrations in soil gas from retail-only sites plotted as a function of distance above the water table) (see following figure):

Figure from Lavis (2011)

As shown, benzene concentrations in soil gas generally attenuate by more than 4 orders of magnitude with at a source separation distance of > 12 ft from the source at LNAPL sites. The attenuation is most significant at distances > 12 ft above the source. A statistical analysis of these data shows a > 95% probability of encountering benzene concentration below 100 ug/m3 in soil gas at distances >~ 13 ft above the source.

Figure from Lahvis (2011)

The lateral separation exclusion distances would be expected to be less than the vertical exclusion distances for the reasons previously explained.

3.2.2   Summary

Most recent field data analyses indicate that 8 to 13 ft of clean soil (soil with no LNAPL present) are sufficient to limit the risk for vapor intrusion at sites with LNAPL sources in either soil or groundwater.

3.3   Technical Background Conclusions

Low-concentration sources have been shown to attenuate up to 6 orders of magnitude in the unsaturated zone within short vertical distances (e.g., < 5 ft) due to biodegradation. Biodegradation is sufficient to essentially eliminate these sites from further vapor intrusion consideration.

At sites with unweathered LNAPL sources ("high-concentration sources"), 8 to 13 ft of clean soil are required to fully attenuate the hydrocarbon vapors. The attenuation due to biodegradation would be equally or more significant for LNAPL sources separated laterally from building foundations (i.e. a shorter distance would be required for attenuation). It is important that the current state of the science as described here be used in the development of more rational, technically defensible, approaches to vapor intrusion risk assessment.

4   THE FOUR LOW-THREAT VAPOR INTRUSION SCREENING SCENARIOS

The Stakeholder Group that was assembled by the Cal-EPA/SWRCB examined the available current and relevant scientific information and recommends the following low-threat guideline to manage the petroleum vapor intrusion pathway incorporating additional safety factors to protect human health in a state-wide policy document.   The Stakeholder Group developed four basic scenarios for decision-making purposes and they are respectively:

    Scenario 1: Unweathered LNAPL on groundwater
    Scenario 2: Unweathered LNAPL in soil
    Scenario 3: Dissolved phase benzene concentrations in groundwater
    Scenario 4: Direct measurement of soil gas concentrations

Scenarios 1 and 2 are essentially "high-concentration sources", while scenarios 3 and 4 are "low-concentration sources". The following section details the specific justification(s) for each of the sets of exclusion criteria outlined in these four scenarios. Benzene is assumed to be the primary risk driver for vapor intrusion from petroleum hydrocarbon sites. Although naphthalene is not present in gasoline at levels as high as typical benzene levels, and is potentially present at very low concentrations (mass fraction of 0.0026) in diesel (TPHCWG, 1998), it is another volatile carcinogenic chemical, and could potentially be considered as an additional risk driver. Also, naphthalene has similar (if not, higher (GSI, 2010)) degradation rates as benzene and much lower aqueous solubility. The discussions below focus on benzene attenuation.

4.1   Scenario 1: Unweathered LNAPL on Groundwater

- **30 ft vertical bioattenuation zone between a unweathered LNAPL (residual or free-phase) source and a building foundation.**

The proposed 30 ft exclusion distance[7] is conservative based on:

- Model theory shows full attenuation within 7 m (~ 21 ft) of the source assuming reasonable approximations of the biodegradation rate (see figures below from Abreu et al., 2009).
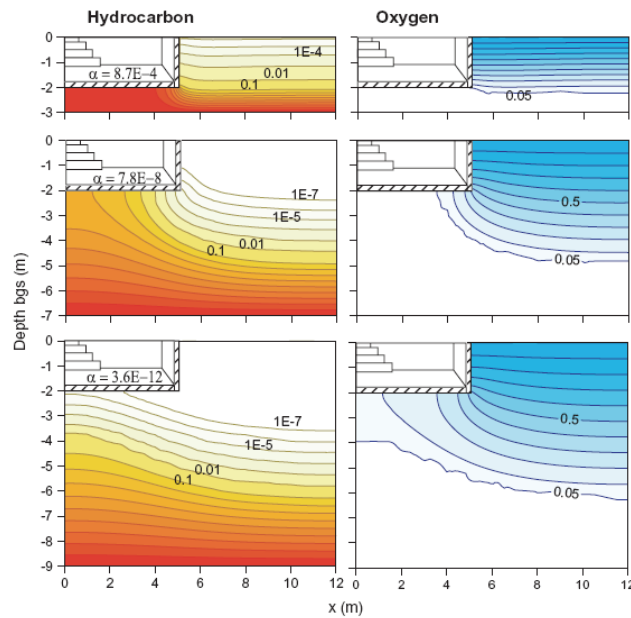
Figure from Abreu et al. (2009)

Figure 5. Effect of source depth on the soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement scenarios with a high vapor source concentration of 100,000 μg/L and biodegradation rate $\lambda = 0.79$ h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

Abreu et al. (GWMR - 2009)

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[7] The top of the residual-phase source can generally be assumed to be consistent with the historic high water-table elevation.
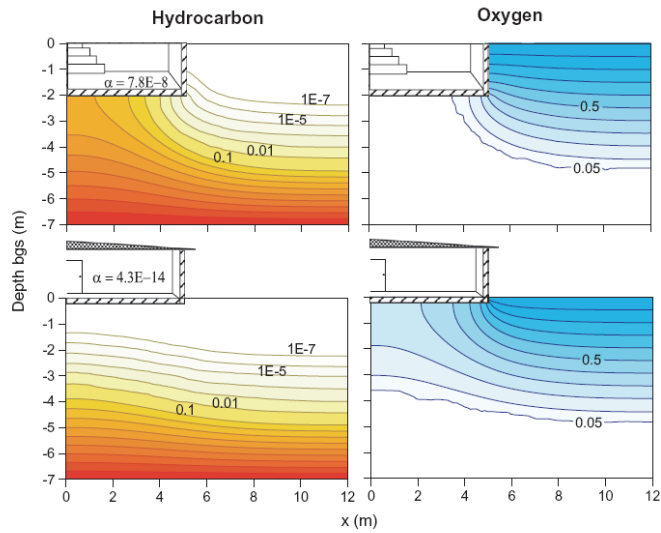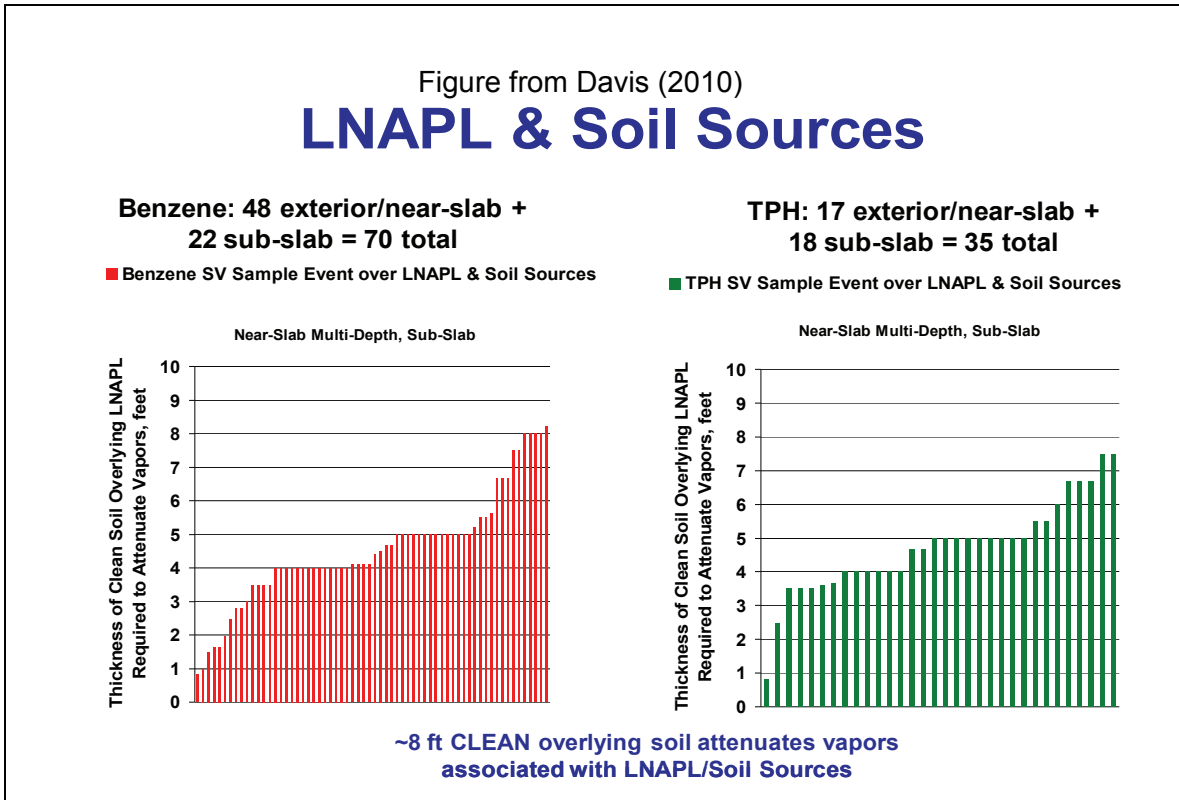
Figure from Abreu et al. (2009)

Figure 7. Effect of building type on soil-gas concentration distribution for high vapor source concentration (100,000 μg/L) and bio-degradation rate λ = 0.79 h⁻¹. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

- Field soil-gas data show full attenuation within 8 ft of the source (see figure, below, from R. Davis (2010) – also published in Hartman (2010)).

Figure from Davis (2010)
LNAPL & Soil Sources

Benzene: 48 exterior/near-slab + 22 sub-slab = 70 total

■ Benzene SV Sample Event over LNAPL & Soil Sources

TPH: 17 exterior/near-slab + 18 sub-slab = 35 total

■ TPH SV Sample Event over LNAPL & Soil Sources

~8 ft CLEAN overlying soil attenuates vapors associated with LNAPL/Soil Sources

- Analysis of the same soil-gas data by Lahvis (2011) that shows benzene is attenuated to concentrations in soil gas < 100 ug/m³ (a conservative risk-based screening level) at distances more than 13 ft from a LNAPL (residual or free-phase) source benzene (probability = 95%).
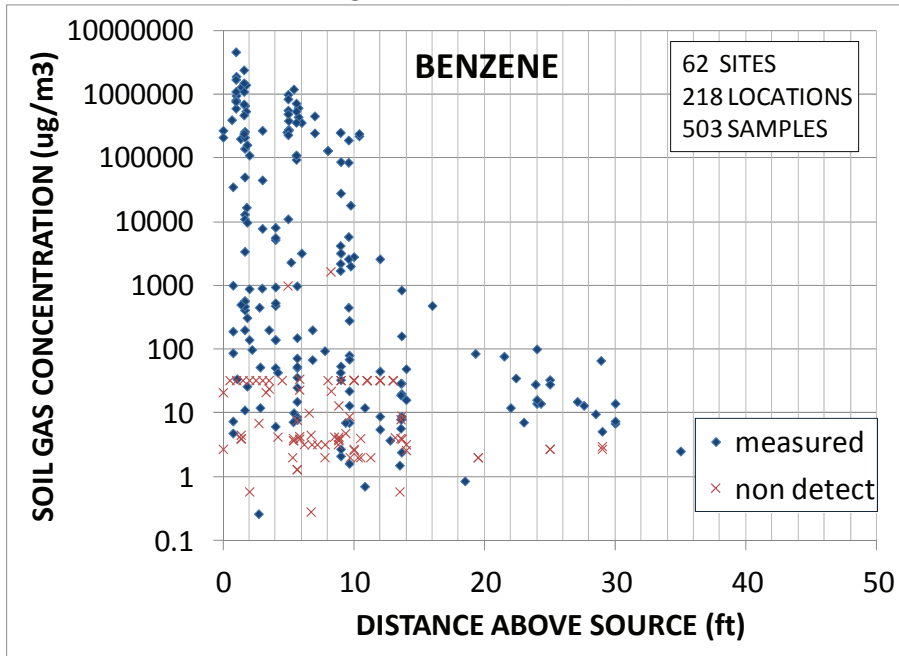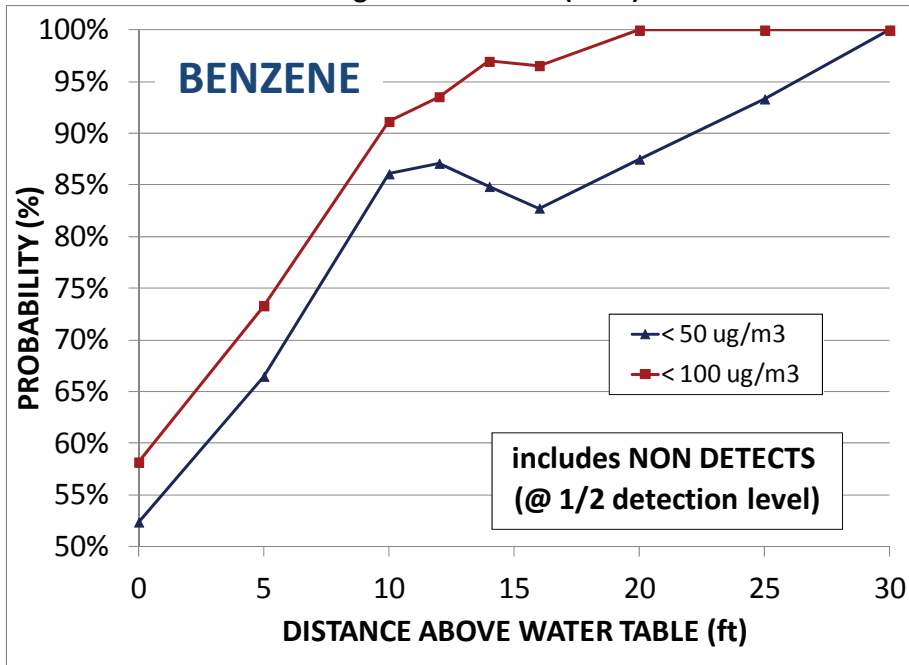
Figure from Lahvis (2011)

Figure from Lahvis (2011)

4.2   Scenario 2: Unweathered LNAPL in Soil

- **30 ft lateral and vertical separation distance between a unweathered LNAPL (residual or free-phase) source in soil and a building foundation.**

The same technical justification provided for Scenario 1 applies to Scenario 2. The proposed 30 ft. lateral off-set distance is even more conservative for sources displaced laterally as shown in the following figure from Abreu and Johnson (2005). For example, an additional order of magnitude of attenuation is predicted for plume centerlines displaced 10 m (~30 ft). The attenuation would be significantly greater (e.g., several orders of magnitude) in cases where the plume (dissolved-phase) boundary was separated by 30 ft.
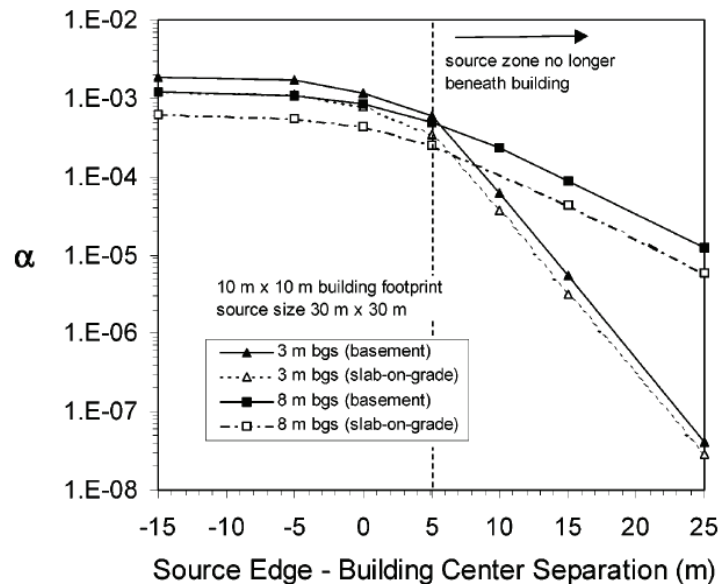
Figure from Abreu and Johnson (2005)

FIGURE 9. Changes in vapor attenuation coefficient (α) with vapor source—building separation and vapor source depth for basement and slab-on-grade foundation scenarios.

As discussed in the technical background section 3.2.2, 13 ft. is more than adequate to fully attenuate LNAPL sources in soil and groundwater, therefore assuming a 30' separation is very conservative.

4.3   Scenario 3: Dissolved Phase Benzene Concentrations in Groundwater

- **No Oxygen Measurements - 5 ft. vertical separation distance between a dissolved-phase source < 100 ug/L benzene and a building foundation; 10 ft. vertical exclusion distance for a dissolved-phase source < 1,000 ug/L benzene.**
- **With Oxygen > 4% – 5 ft. vertical separation distance between a dissolved-phase source < 1,000 ug/L and a building foundation.**

These separation distances are conservative with respect to protecting human health based on the following:

- Model theory shows 9 orders of magnitude (i.e., complete) attenuation (for reasonable approximations of the biodegradation rate) within a source/building separation distance of L=3 m (10 ft) for benzene vapor sources < 10 mg/L (or 40 mg/L dissolved phase concentration in groundwater assuming Henry's Law coefficient of 0.25) (see attached figure from Abreu et al., 2009). The attenuation is complete regardless of the dissolved-phase concentration (up to ~ 40 mg/L benzene in groundwater) for sources located 3 meters or more from a building foundation. The dissolved phase concentrations (especially) and required bioattenuation zone thickness specified in this scenario are therefore very conservative.
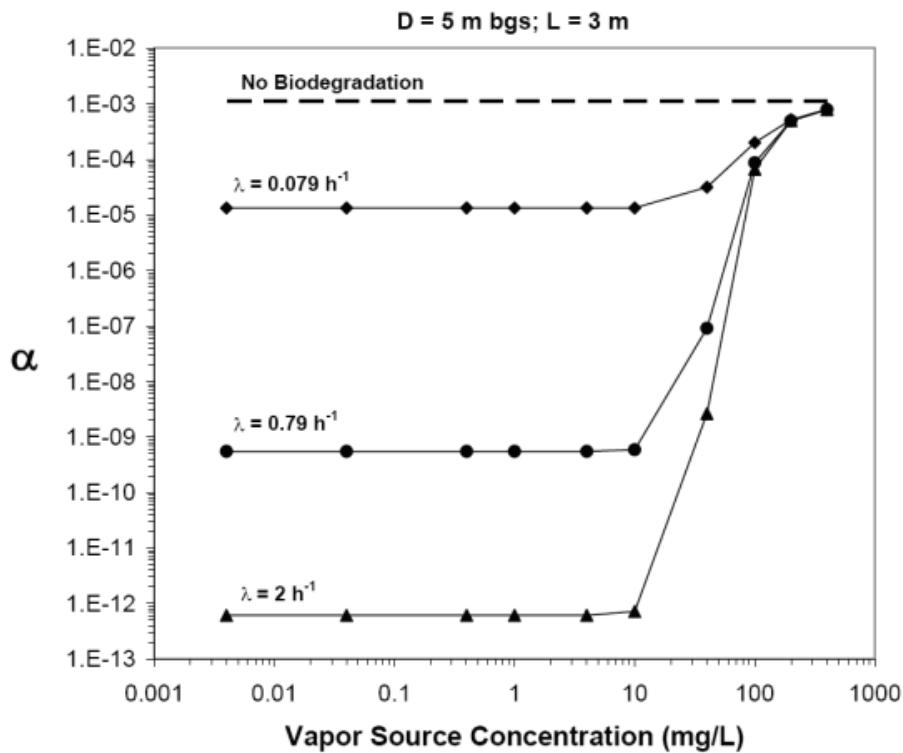
Figure from Abreu et al. (2009)

Figure 5—Influence of soil vapor source concentration and first-order biodegradation rates (λ) on vapor intrusion attenuation factors (α) for basement scenarios, homogeneous sand soil and source depth (D) of 5 m bgs (source-foundation separation L = 3 m).

- The attenuation is shown to be complete within 2 m (6 ft.) for a soil gas source of benzene < 10 mg/L (or 40 mg/L dissolved phase concentration in groundwater assuming Henry's Law coefficient of 0.25) (see attached figure from API (2009)).
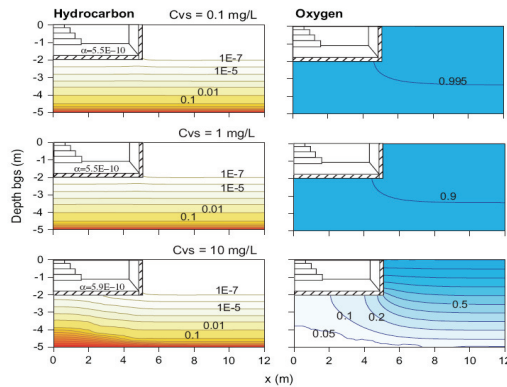
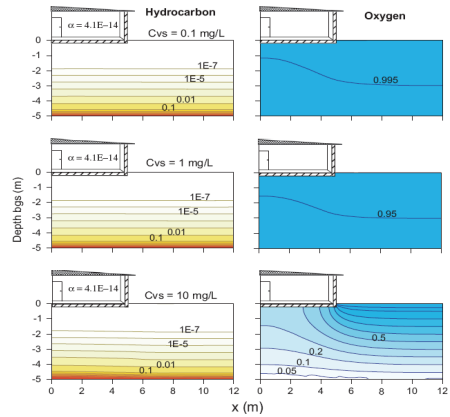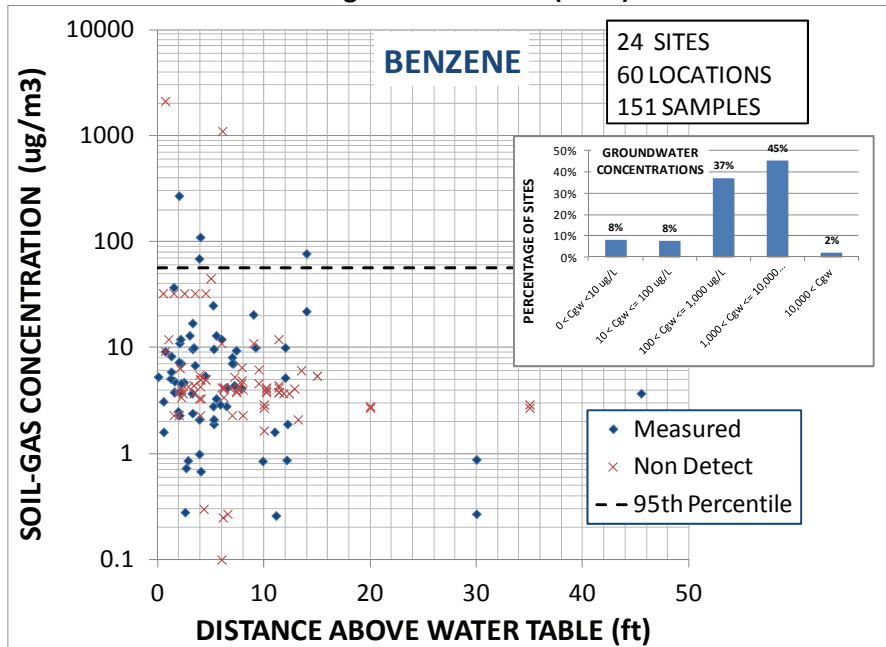Version date: June 30, 2011

Figure from API (2009)

Figure 3 API

Figure 4 API

Figure 3. Effect of low vapor source concentration (Cvs) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79$ h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

Figure 4. Effect of low vapor source concentration (Cvs) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for slab-on-grade foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79$ h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.
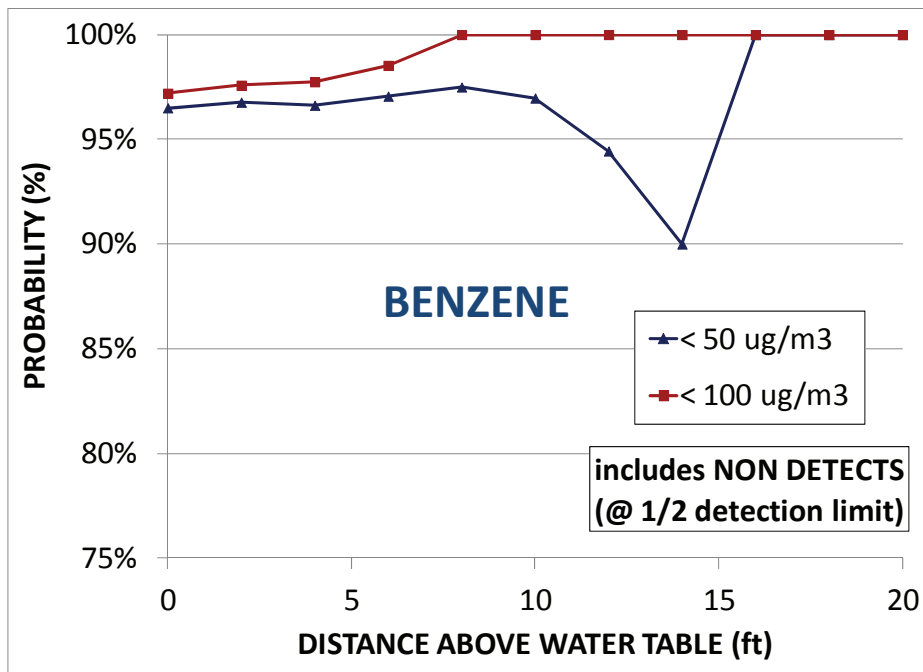
- Field soil-gas data from Robin Davis collected at retail sites (Lahvis, 2011) that show the proposed exclusion distances and groundwater concentrations are highly conservative. The data imply that the potential risk of vapor intrusion from dissolved-phase sources (up to 15 mg/L benzene in groundwater) is minimal unless groundwater is essentially in contact with the building foundation.

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Figure from Lahvis (2011)

- From a probability standpoint, the soil-gas data show a > 95% probability of detecting benzene in soil gas at concentrations < 100 ug/m^3 @ dissolved-phase sites; conversely, there is less than a 5% probability that benzene soil gas concentrations will exceed 100 ug/m^3 (a conservative risk-based screening number for soil gas, Lahvis (2011)).

Figure from Lahvis (2011)

4.4   Scenario 4: Direct Measurement of Soil Gas Concentrations

-    **Application of a bioattenuation (additional attenuation) factor of 1000x to risk-based soil-gas criteria (i.e., vapor sources) located within 5 ft. of a building foundation.**

- Model theory predicts that bioattenuation is significant for LNAPL sources provided vapor concentrations are < 0.1 (1/10th) of a TPH vapor source of 100,000 ug/L (or 10,000,000 ug/m^3). Therefore the proposed vapor screening criteria of 5,000 ug/m^3 for benzene is very conservative.   (See the following figures from Abreu et al. 2009.)
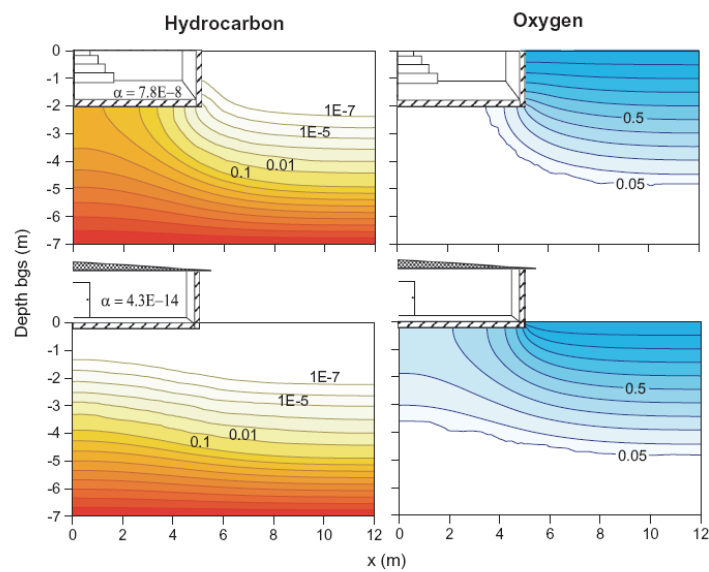
Figure from Abreu et al. 2009

Figure 7. Effect of building type on soil-gas concentration distribution for high vapor source concentration (100,000 µg/L) and bio-degradation rate λ = 0.79 h^{-1}. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.
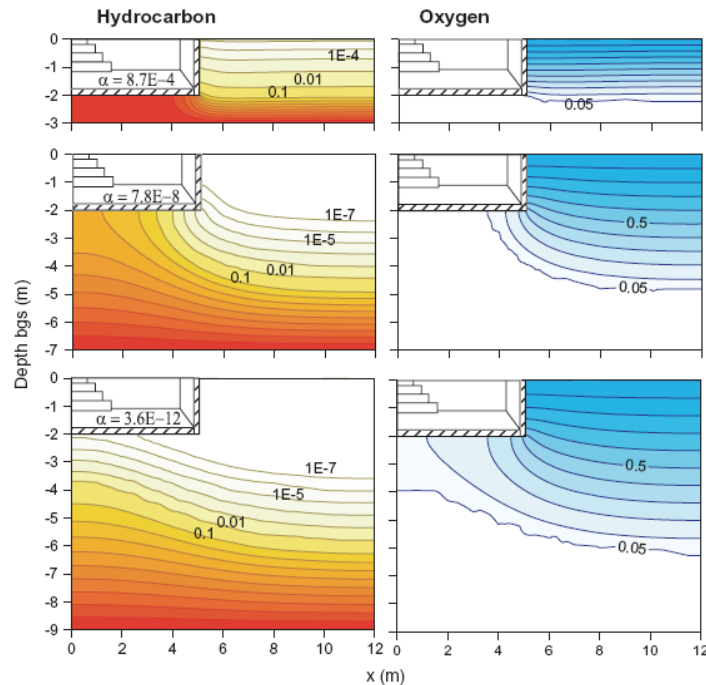
Figure from Abreu et al. 2009

Figure 5. Effect of source depth on the soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement scenarios with a high vapor source concentration of 100,000 µg/L and biodegradation rate λ = 0.79 h⁻¹. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

Abreu et al. (GWMR - 2009)

- The 4% oxygen requirement in this scenario is also a very conservative level for biodegradation to occur. The numeric models used 1% as a conservative estimate.

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