

Attachment 5

Technical Justification for Groundwater Media-Specific Criteria 11-7-11

The purpose of this document is to provide technical justification for the four classes of low-threat groundwater plumes that are described in the Groundwater section of the Low-Threat UST Closure Policy (Policy). The fifth plume class is a site-specific evaluation.

Various researchers have conducted multi-site studies of groundwater plume lengths at petroleum release sites across the United States. These studies considered sites where active remediation was performed and sites where no active remediation was performed. Many studies focused on benzene plumes (Rice, et al. 1995; Rice et al. 1997; Busheck et al. 1996; Mace, et al. 1997; Groundwater Services, Inc. 1997; API 1998); other researchers (Dahlen et al. 2004; Shih et al. 2004) studied both benzene and oxygenate plumes, including MTBE. Many of these plume characteristic studies are discussed in greater detail in the Fate and Transport chapter of the California LUFT Manual (SWRCB, 2010). Many of the researchers recognized benzene, MTBE, and TPHg as key indicator constituents for groundwater plume lengths. Researchers' technical justification for using these three constituents as key indicators relied on the facts that (1) benzene has the greatest toxicity of the soluble petroleum constituents, (2) MTBE typically has the greatest plume lengths, and (3) TPHg represents the additional dissolved hydrocarbons that may be present resulting from a typical petroleum release.

The peer-reviewed study of plume lengths at 500 petroleum UST sites in the Los Angeles area is widely accepted as representative of plume lengths at California UST sites (Shih et. al., 2004). *Shih* reports benzene, MTBE and TPHg plume characteristics as follows:

Constituent (and plume limit concentration)	Average Plume Length (feet)	90 th Percentile Plume Length (feet)	Maximum Plume Length (feet)
Benzene (5 µg/l)	198	350	554
MTBE (5 µg/l)	317	545	1,046
TPHg (100 µg/l)	248	413	855

Note: plume lengths were measured from the source area.

Although the California MCL for benzene is 1 µg/l, the *Shih et al.* study used a benzene concentration of 5 µg/l to determine plume length because of the statistical uncertainty

associated with concentrations near the 0.5 µg/l laboratory reporting limit. Benzene plume lengths measured at a 1.0 µg/l concentration limit could be expected to be slightly longer than those tabulated above.

Ruiz-Aguilar et al. (2003) studied releases of ethanol-amended gasoline (10% ethanol by volume) at UST release sites in the Midwest. Ruiz-Aguilar et al. found that benzene plume lengths may increase by 40% to 70% when gasoline is formulated with 10% ethanol substituting for MTBE. Ethanol preferentially biodegrades prior to benzene, which results in a longer benzene plume.

Biodegradation/natural attenuation of petroleum hydrocarbon and oxygenate plumes has been documented by many researchers since the 1990s. This body of work demonstrates that biodegradation/natural attenuation of petroleum hydrocarbons and MTBE occurs under both aerobic and anaerobic conditions (Howard, 1990). The rate of degradation/attenuation depends on the constituent and the plume bio/geochemical conditions.

TBA is an intermediate byproduct of the biodegradation of MTBE. TBA concentrations may therefore initially increase in the anaerobic portion of a degrading plume. With respect to the natural attenuation of TBA, Kamath et al. (in press) recently studied benzene, MTBE and TBA plumes at 48 UST sites (30 sites in California) and found that (1) 68% of the TBA plumes were stable or decreasing in size, and (2) in the stabilized plumes, the median attenuation rate for TBA was similar to the rates for MTBE and benzene.

Diesel

Researchers do not consider TPHd to be a key indicator of plume lengths largely because the hydrocarbons in the TPHd carbon range are of low solubility and therefore create plumes which are usually shorter than those associated with gasoline releases. Most of the TPHd carbon range (approximately C12 to C22) is greater than the carbon range of the most common solubility-limited hydrocarbons (i.e. those less than or equal to C14).

It is well documented that effective solubility limits the concentrations of hydrocarbons that will dissolve into groundwater from petroleum fuel releases (including gasoline, kerosene, jet fuel, diesel or heavier fuels). Dissolved petroleum constituents are commonly limited to light aliphatic hydrocarbons less than C7 and aromatics less than C14 (e.g., Shiu et al. 1990; Coleman et al. 1984). The C15 and larger hydrocarbons have very low effective solubilities and are not often found in the dissolved phase of a petroleum fuel release. The concentrations of dissolved hydrocarbons in groundwater

whose carbon range is less than or equal to C14 is effectively measured by the TPHg method, which quantifies the concentration of hydrocarbons in the range of approximately C5 to C12. Therefore, a TPHg analysis should be sufficient to quantify dissolved hydrocarbons that may be present in addition to benzene and MTBE from the most common types of petroleum UST releases. Oxygenates other than MTBE were not included as indicator constituents because Shih et al. (2004) documented that MTBE had the longest plume length of any of the oxygenates (MTBE, TBA, DIPE, TAME, ETBE) at any percentile. Therefore, MTBE can be used as a conservative plume length benchmark for all fuel oxygenates, including TBA. However, if a plume resulting from a petroleum release contains petroleum constituents other than TPHg, benzene, or MTBE (e.g. TBA, toluene, ethylbenzene, etc.) in concentrations greater than water quality objectives, and the plume length exceeds the limiting plume length of the scenario for which it would otherwise qualify, the site should be considered to display “unique site attributes” that disqualify it for consideration of low-threat closure.

Researchers recommend applying silica gel cleanup to groundwater samples prior to analyzing them for dissolved hydrocarbons quantified as TPHd. If SGC is not used, the reported TPHd concentration may include polar non-hydrocarbon compounds (e.g., Zemo and Foote 2003) derived from various sources. These sources often include petroleum biodegradation metabolites (primarily alcohols and organic acids, with possible phenols, aldehydes and ketones), but may also include decay products of naturally occurring organic matter. In some cases researchers have demonstrated that without performing SGC the majority of organics quantified as TPHd are polar compounds and not dissolved hydrocarbons. The San Francisco Bay RWQCB recognized that non-SCG laboratory-quantified TPHd concentrations may include polar compounds. The SFRWQCB issued a guidance memorandum recommending that SGC be routinely used so that “..... decisions could be made based on analytical data that represents dissolved petroleum.” (SFRWQCB 1999).

Some regulatory agencies have expressed concern that SGC also removes some fraction of the dissolved hydrocarbons from groundwater samples. Lundegard and Sweeney (2004) concluded that SGC does not remove the dissolved hydrocarbons in a sample. Further, the potential for removal of hydrocarbons by SGC is always evaluated during routine laboratory quality assurance/quality control (QA/QC) procedures. These procedures include analyzing laboratory control samples spiked with a hydrocarbon surrogate, performing SGC, measuring surrogate recovery, and reporting whether the result is within acceptable ranges.

Low-Threat Groundwater Classes

Based on the plume studies, a total separation distance from the source area to the receptor of about 500 feet should be protective for 90% of plumes from UST sites, and a total separation distance from the source area to the receptor of about 1,000 feet should be protective for virtually all plumes from UST sites. Additionally, “low-threat classes” require a known maximum stabilized plume length, which reduces uncertainty as to how long the plume might become in the future. The draft low-threat policy addresses the potential for longer plumes of ethanol-enhanced gasoline by applying separation distance safety factors of 100% to 400%.

The use of separation distances is consistent with other State and local practices regarding impacts to groundwater caused by other anthropogenic releases. For example, State and local agencies establish required separation distances or “setbacks” between water supply wells and septic system leach fields (typically 100 feet), and sanitary sewers (typically 50 feet; [DWR 1981]).

The following paragraphs present and discuss the key rationales for low-threat plume lengths, maximum concentrations, and separation distances for each low-threat class. Note that the specified concentrations are maximums, and typically occur in source area monitoring wells; the average concentrations in the plume would be lower. These groundwater plume class criteria (concentrations, plume lengths and separation distances) are only one component of the overall evaluation of site conditions that must be satisfied to be considered for closure as a low-threat site under the Policy.

Class 1: The “short” stabilized plume length (<100 feet) is indicative of a small or depleted source and/or very high natural attenuation rate. The 250 feet distance to a receptor from the edge of the plume represents an additional 250% “plume length” safety factor in the event that some additional unanticipated plume migration was to occur.

Class 2: The “moderate” stabilized plume length (<250 feet) approximates the average benzene plume length from the cited studies. The maximum concentrations of benzene (3,000 µg/l) and MTBE (1,000 µg/l) are conservative indicators that a free product source is not present. These concentrations are approximately 10% and 0.02%, respectively, of the typical effective solubility of benzene and MTBE in unweathered gasoline. The potential for vapor intrusion from impacted groundwater must be evaluated separately as per the vapor intrusion section of the Policy. The 1,000 feet distance to the receptor from the edge of the plume is an additional 400% “plume

length” safety factor in the event that some additional unanticipated plume migration was to occur. Also note that California Health and Safety Code §25292.5 requires that UST owners and operators implement enhanced leak detection for all USTs within 1,000 feet of a drinking water well. In establishing the 1,000 feet separation requirement the legislature acknowledged that 1,000 feet was a sufficient distance to establish a protective setback between operating petroleum USTs and drinking water wells in the event of an unauthorized release.

Class 3: The “moderate” stabilized plume length (<250 feet) approximates the average benzene plume length from the cited studies. The on-site free product and/or high dissolved concentrations in the plume remaining after source removal to the extent practicable (as per the General Criteria in the Policy) require five years of monitoring to validate plume stability/natural attenuation (i.e., to confirm that the rate of natural attenuation exceeds the rate of NAPL dissolution and dissolved-phase migration). The potential for vapor intrusion from free product or impacted groundwater must be evaluated separately as per the vapor intrusion section of the Policy. The 1,000 feet distance to the receptor from the edge of the plume is an additional 400% “plume length” safety factor in the event that some additional unanticipated plume migration was to occur, and is consistent with H&S Code §25292.5 as discussed above.

Class 4: The “long” stabilized plume length (<1,000 feet) approximates the maximum MTBE plume length from Shih et al. (2004). The potential for vapor intrusion from impacted groundwater must be evaluated separately as per the vapor intrusion section of the Policy. The 1,000 feet distance to the receptor from the edge of the plume is an additional 100% “plume length” safety factor in the event that some additional unanticipated plume migration was to occur, and is consistent with H&S Code §25292.5 as discussed above.

Free Product Removal

State regulation (CCR Title 23, Division 3, Chapter 16, Section 2655) requires that “responsible parties“.... remove free product to the maximum extent practicable, as determined by the local agency...” (Section 2655a) “.... in a manner that minimizes the spread of contamination into previously uncontaminated zones”... (Section 2655b), and that “[a]batement of free product migration shall be the predominant objective in the design of the free product removal system” (Section 2655c). Over the years there has been debate on the meaning of the terms “free product” and “maximum extent practicable”. Product (light non-aqueous phase liquid [LNAPL]) can exist in three conditions in the subsurface: residual or immobile LNAPL (LNAPL that is trapped in the soil pore spaces by capillary forces and is not mobile), mobile LNAPL (enough LNAPL

is present in the soil pore spaces to overcome capillary forces so that the LNAPL can move) and migrating LNAPL (mobile LNAPL that is migrating because of a driving head). “Residual LNAPL”, “mobile LNAPL” and “migrating LNAPL” are described in detail in several peer-reviewed technical documents, including the 2009 Interstate Technology Regulatory Council (ITRC) Technical/Regulatory Guidance “Evaluating LNAPL Remedial Technologies for Achieving Project Goals”. Given the predominant objective of abatement of migration, the term “free product” in the State regulation is primarily equivalent to “migrating LNAPL” (which is a subset of “mobile LNAPL”), and secondarily equivalent to “mobile LNAPL”. Whether LNAPL is mobile (and therefore could potentially migrate) or not is usually tested by observing recharge of LNAPL after removing LNAPL from a monitoring well. Whether LNAPL is migrating or not is tested by monitoring the extent of the LNAPL body (usually using the apparent product thickness in monitoring wells) at a certain water level elevation over time. If the extent at that water level elevation does not expand, then the LNAPL is not migrating. Therefore, LNAPL must be removed to the point that its migration is stopped, and the LNAPL extent is stable. Further removal of non-migrating but mobile LNAPL is required to the extent practicable at the discretion of the local agency. Removal of mobile LNAPL from the subsurface is technically complicated, and the definition of “extent practicable” is based on site-specific factors and includes a combination of objectives for the LNAPL removal (such as whether the mobile LNAPL is a significant “source” of dissolved constituents to groundwater or volatile constituents to soil vapor, or whether there is a high likelihood that hydrogeologic conditions would change significantly in the future which may allow the mobile LNAPL to migrate) and technical limitations. The typical objectives for LNAPL removal, technologies for LNAPL removal and technical limitations of LNAPL removal are discussed in several peer-reviewed technical documents including the 2009 ITRC Guidance (see especially Section 4 “Considerations/Factors Affecting LNAPL Remedial Objectives and Remedial Technology Selection”, Table 4.1 [Example Performance Metrics], Table 5-1 [Overview of LNAPL Remedial Technologies], and Table 6-1 [Preliminary Screening Matrix]).

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Attachment 6

Technical Justification for Vapor Intrusion Media-Specific Criteria

11/22/11

1 EXECUTIVE SUMMARY

For petroleum-related volatile organic compounds (VOCs), current risk-based screening levels (such as the California Human Health Screening Levels [CHHSLs]) for evaluating risk from vapor intrusion at underground storage tank (UST) sites are extremely conservative. This conservatism is caused by not considering biodegradation in site screening which generally drives further unnecessary site evaluation. Recent models and field studies show that bioattenuation of petroleum hydrocarbons at retail sites is significant (Abreu et al., 2009; API, 2009; Davis, 2009; Lahvis, 2011). Petroleum hydrocarbon VOCs (such as, benzene, toluene, ethylbenzene and xylenes -BTEX) concentrations have been shown to attenuate by several orders of magnitude within short vertical distances (e.g., < 2-3 m) in the unsaturated zone due to biodegradation. The hydrocarbon VOC attenuation generally increases by an additional order of magnitude (or more) when transport across a building foundation to indoor air is also considered (U.S. EPA, 2008). The characteristic occurrence of rapid hydrocarbon attenuation in the unsaturated zone is amenable to a site-screening methodology for vapor intrusion based on exclusion distances. Exclusion distances are defined as VOC source-receptor (building) separation distances beyond which the risk of vapor intrusion is assumed negligible. Note the source may be located in soil and/or groundwater. Exclusion distances can be broadly defined for two types of sources: low-concentration (e.g., dissolved-phase) and high-concentration (e.g., light non-aqueous-phase liquid – LNAPL) sources as described below.

Recent modeling studies and evaluations of field (soil-gas) data from numerous UST sites and sampling locations demonstrate that biodegradation is sufficient to limit the potential for vapor intrusion at sites with “low-concentration” (dissolved-phase) hydrocarbon sources (Abreu et al., 2009; Davis, 2009; Davis, 2010; Lahvis, 2011). For example, there is less than a 5% probability that benzene concentrations in soil gas would exceed a low screening-level for vapor intrusion (50 ug/m^3) at distances of 5 ft (~2 m) or more above a dissolved-phase benzene concentration in groundwater < 1,000 ug/L. (Note, for comparison, the CHHSL for benzene in soil gas is 83 ug/m^3 for buildings on engineered fill.) Additional attenuation (i.e., a shorter exclusion distance) is predicted to occur by transport modeling for dissolved-phase sources displaced laterally from the building foundation (Abreu and Johnson, 2005). Vapor intrusion risks are thus expected to be rare to non-existent at sites with low-concentration sources.

At sites with “high concentration” hydrocarbon sources (unweathered residual light non-aqueous phase liquid (LNAPL) in soil and/or unweathered free-phase LNAPL on groundwater), transport modeling shows that hydrocarbon VOCs will attenuate below levels of concern in the unsaturated zone within a

distance of approximately 20 ft (~7 m) of the source. The transport modeling is based on assuming reasonable approximations of source concentration and transport within the unsaturated zone (including biodegradation rate). Soil-gas data collected at numerous retail, terminal, and manufacturing sites with LNAPL sources would suggest that the model predicted attenuation above LNAPL sources is conservative. Analysis of the field data at these types of sites shows that hydrocarbon VOCs are attenuated below screening-level concentrations within 8 – 13 ft (~3 - 4 m). Biodegradation accounts for more than 1,000x additional attenuation within 5 ft vertical distances of benzene sources in soil-gas up to 10,000,000 ug/m³. Again, the attenuation is predicted to increase further for high (e.g., LNAPL) sources displaced laterally from building foundations (i.e. the soil gas concentrations would attenuate in even shorter distances).

The purpose of this document is to provide a technical justification for the proposed low-threat vapor intrusion scenarios. The justification is based on current, state-of-the-art science on separation distances between source and receptor that are human-health protective. A few of the most recent studies cited below are awaiting publication (but are available for review). All cited studies should be considered in the development of a rational, technically defensible approach to vapor intrusion screening.

The four scenarios presented in the *Low-Threat UST Closure Policy* are:

Scenario 1: Unweathered LNAPL on groundwater

30 ft vertical source/building separation (exclusion) distance for unweathered (residual or free-phase) LNAPL on groundwater

Scenario 2: Unweathered LNAPL in soil

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

Scenario 3: Dissolved phase benzene concentrations in groundwater

- 5 ft. vertical separation distance between a dissolved-phase source < 100 ug/L benzene and a building foundation (no oxygen (O₂) measurement)
- 10 ft. vertical exclusion distance for a dissolved-phase source < 1,000 ug/L benzene (no O₂ measurement)
- 5 ft. vertical separation distance between a dissolved-phase source < 1,000 ug/L and a building foundation (measured O₂ in soil gas ≥ 4%)

Scenario 4: Direct measurement of soil gas concentrations

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

For each of these scenarios, screening criteria have been proposed that if met will identify the site as posing a low human health threat resulting from the vapor intrusion pathway. The screening criteria and low-risk scenarios are based on the science presented in this document; additional safety factors were incorporated as a policy decision. For the two unweathered LNAPL scenarios (Scenarios 1 and 2), the current science indicates that soil vapors above an LNAPL source will attenuate within a distance of 20 feet or less. However the two LNAPL scenarios include an additional safety factor of 10 feet so that

the exclusion criteria for these cases are set to 30 feet. Likewise, in Scenario 3, the scientific studies and field data indicate that the risk of vapor intrusion is negligible for building foundations located more than 5 feet above plumes with much higher benzene concentrations (up to 15,000 ug/L in groundwater). Again, the proposed screening criteria incorporate additional safety factors. In Scenario 4, research indicates that soil gas concentrations will attenuate by more than 3 orders of magnitude within a vertical distance of 5 feet. However, the “bioattenuation factor” applied in Scenario 4 is conservatively defined at 3 orders of magnitude (1000-fold attenuation). The proposed bioattenuation factor (in Scenarios 3 and 4) also requires that measured O₂ concentrations in soil gas are greater than or equal to 4%. Biodegradation has been shown to be significant at concentrations well below this O₂ threshold (Borden and Bedient, 1996; Roggemans et al. 2001). In conclusion, each of the scenarios, by design, had safety factors included and therefore the exclusion criteria will appear to be more conservative than would be otherwise indicated if only basing the results on the modeling results and field data presented in this document.

2 INTRODUCTION

It is well recognized that petroleum hydrocarbons rapidly biodegrade in the presence of O₂ (i.e., when conditions in the unsaturated zone are aerobic¹). The degree of biodegradation depends largely on O₂ availability of and the O₂ demand created by the biodegradation reaction. One of the critical factors affecting O₂ demand is source strength/type (e.g., LNAPL or dissolved phase).

Various researchers (Fischer et al., 1996; Lahvis et al., 1999; DeVaul, 2007; Davis, 2009; and Hartman, (2010) have shown that conditions in the unsaturated zone are aerobic, and that for “low-concentration” sources (weathered residual in soil and/or dissolved concentrations in groundwater), the degree of biodegradation is significant. . At these sites, the demand for O₂ resulting from biodegradation generally exceeds O₂ availability. The hydrocarbon concentrations (mainly BTEX) decrease by several orders of magnitude over relatively short (e.g. <2 m) vertical distances. For low concentration hydrocarbon sources, the attenuation will tend to be significant very near the water table (i.e., capillary zone). These assertions are supported both by theory (modeling) (DeVaul, 2007, Abreu et. al. 2009, API, 2009) and by field observation (Lahvis and Baehr, 1996; API, 2009; Davis, 2009). Work by Abreu and Johnson (2005) predicts a greater degree of vapor attenuation at sites where the source is displaced laterally from the building foundation.

Researchers have also documented rapid biodegradation of petroleum vapors at sites underlain by LNAPL sources. At such UST sites, exclusion distances determined by analyzing benzene concentrations in soil gas have been estimated to be in the range of 8 to 15 feet (Davis, 2009; Hartman, 2010; Lahvis, 2011). The greater exclusion distance for LNAPL sources compared to dissolved-phase sources is largely related to the additional demand for O₂ (noted above) created by LNAPL sources and the tendency for LNAPL sources to be distributed above the capillary zone. Lahvis and Baehr (1996) showed the capillary zone to be an active zone of biodegradation and hydrocarbon attenuation). The presence of residual-phase LNAPL can, however, be difficult to identify because LNAPL may not readily appear in

¹ Borden and Bedient (1986) and Roggemans et al. (2001) define minimum thresholds for aerobic biodegradation of 100 ug/L-water (0.24%) and 2%, respectively.

groundwater monitoring wells. In such cases, one may rely on general LNAPL indicator “rules of thumb”, including:

Presence of LNAPL

Direct evidence:

- current or historical evidence of LNAPL in soil (known release area) or at the water table (visible/reported in nearby groundwater monitoring wells)

Indirect evidence:

- hydrocarbon VOC concentrations in groundwater approaching (> 0.2) effective solubilities (Bruce et al., 1991) (e.g., benzene > 3 mg/L; BTEX or TPH gasoline range organics (GRO) > 20 mg/L; TPH diesel range organics (DRO) > 5 mg/L)
- total hydrocarbon VOC concentrations in soil of TPH 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 releases), > 100 ppm (recent diesel/historic gasoline releases), and > 10 ppm (historic diesel releases) (Alaska DEC, 2011). Note that weathered LNAPL typically has a significantly reduced VOC content and therefore represents a lesser vapor intrusion risk than unweathered NAPL.
- proximity (e.g., < 20 ft to a known release area)

It is important to note that although hydrocarbon VOC concentrations approaching effective solubility limits in groundwater can be used as an indirect indicator of residual-phase LNAPL, dissolved-phase hydrocarbon concentrations are not necessarily good metrics for the development of screening criteria (i.e., separation distances) or assessing the vapor intrusion risk potential. Benzene concentrations in soil-gas have shown to be poorly correlated with benzene concentrations in shallow groundwater (Lahvis, 2011). The poor correlation can be attributed to 1) the inability to accurately measure water-table concentrations using monitoring wells screened across the water table and 2) bioattenuation of hydrocarbon vapors in the capillary zone. Hydrocarbon VOC concentrations in soil gas are also expected to be poorly correlated with VOC concentrations in groundwater in cases where residual-phase LNAPL sources are present above the water table. Screening (exclusion) distances should therefore be defined on the basis of source type (LNAPL and groundwater) rather than source (groundwater) concentration.

Lastly, the exclusion criteria defined for benzene are assumed to be conservative for naphthalene, which is currently considered a carcinogen via the inhalation exposure route and, in certain cases, a potential risk driver. This assertion is based on fact that naphthalene is relatively less volatile than benzene (i.e., has a much lower solubility value and Henry’s Law coefficient than benzene) and is also highly

² TPH (GRO) between 100 to 200 mg/kg may indicate the presence 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.

susceptible to biodegradation (Anderson et al., 2008; GSI, 2010). The screening criteria described here, while developed for benzene, are therefore assumed to be protective of naphthalene vapor intrusion.

3 TECHNICAL BACKGROUND – Discussion of Biodegradation Effects

This section presents the results of model studies and field data that support the proposed vapor intrusion exclusion criteria. The results are discussed first for “low-concentration” source cases followed by “high-concentration” sources cases.

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 petroleum UST sites are defined as dissolved-phase hydrocarbon concentrations. Low concentration sources are therefore composed primarily of the more soluble (aromatic) VOC 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 is analogous to low-concentration sources in cases where the LNAPL is depleted of VOCs.

3.1.1 Model Studies

Results from numerical (3-dimensional) models (see Figures 3, 4 and 10 below [Abreu et al., 2009]) indicate essentially complete attenuation of benzene soil gas concentrations (between 7 and 14 orders of magnitude – expressed as attenuation factors $\alpha < 1E-07$) within 2 m to 3 m away from a relatively low (< 10 mg/L) benzene source concentration in an unsaturated sand.⁴ The simulations also assumed biodegradation occurred only in the aerobic portion of the unsaturated zone (i.e., where O₂ concentrations exceed 1%). This threshold for aerobic biodegradation contrasts with the 0.24% O₂ threshold defined by Borden and Bedient (1996). An aerobic biodegradation rate of 0.79 hr⁻¹ was assumed for benzene, which is consistent with the mean of published rates defined by DeVaul (2007). Note that while this degradation rate may seem high, the model only simulates biodegradation in the portion of the unsaturated zone where there is sufficient O₂ (> 1 %) to support biodegradation. The modeled hydrocarbon vapor source concentration, < 10 mg/L, is assumed to be consistent with a dissolved-phase source (see Abreu et al. [2009] – Figure 10). Lastly, the attenuation is expected to increase for a similar range of source concentrations and degradation rates in lower permeability soils (e.g., silty clay) (see Figure 19 from API, 2009) and for sources displaced laterally from building foundations (see Figure 9 from Abreu and Johnson, 2005). The attenuation increases for the latter scenario because hydrocarbon transport tends 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 where the dissolved-phase source is separated laterally from a building foundation.

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.

The following figures show the results of the modeling studies:

- The figures from Abreu et al. (2009) (Figures 3 and 4) show benzene and O₂ profiles predicted by transport modeling for low-concentration vapor sources and two different foundation configurations (basement and slab, respectively) in a sand unsaturated zone for a reasonable approximation of the hydrocarbon biodegradation rate ($\lambda = 0.79 \text{ hr}^{-1}$).

Figure 3 from Abreu et al (2009).

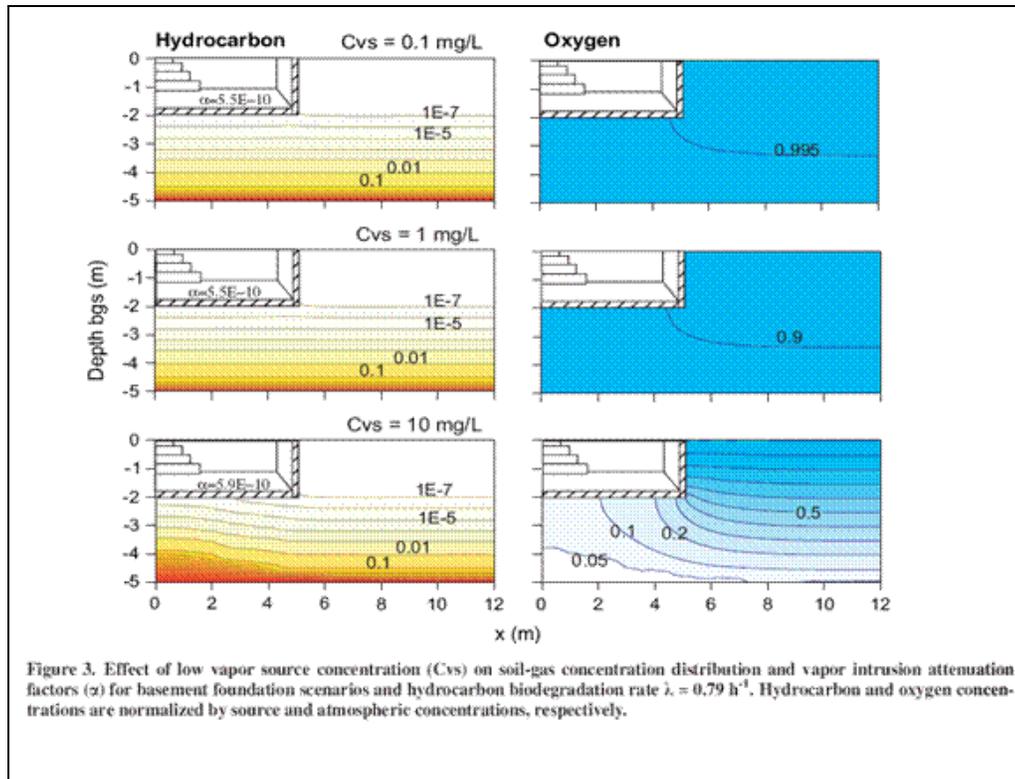


Figure 4 (Abreu et al., 2009)

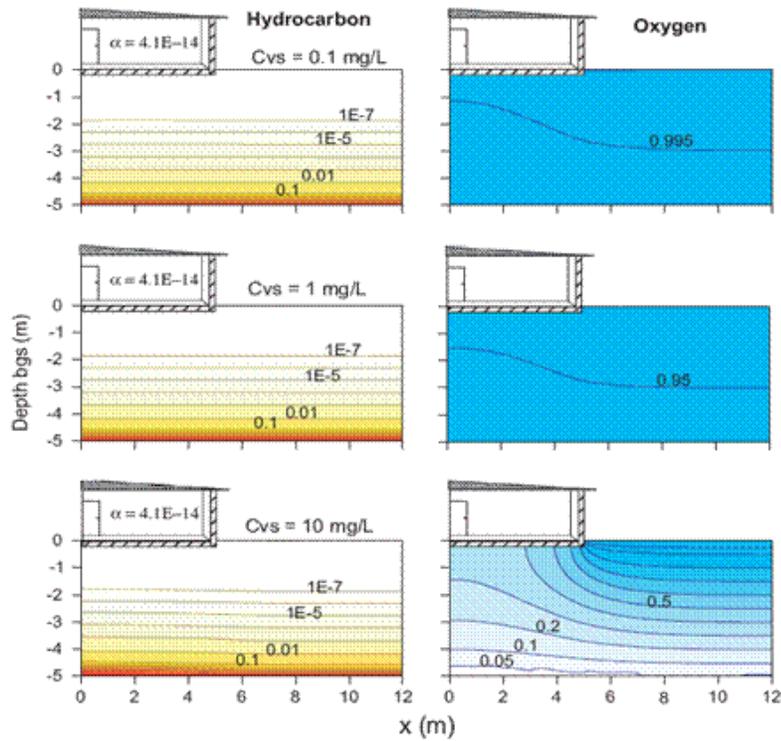


Figure 4. Effect of low vapor source concentration (C_{vs}) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for slab-on-grade foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations are normalized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

- Figure 10 from Abreu et al. (2009) is a plot of the hydrocarbon (benzene) attenuation factor in the unsaturated zone versus source vapor concentration for a range of source/building foundation separation distances assuming a representative biodegradation rate ($\lambda = 0.79 \text{ hr}^{-1}$) and a sand unsaturated zone:

Figure 10 from Abreu et al. (2009)

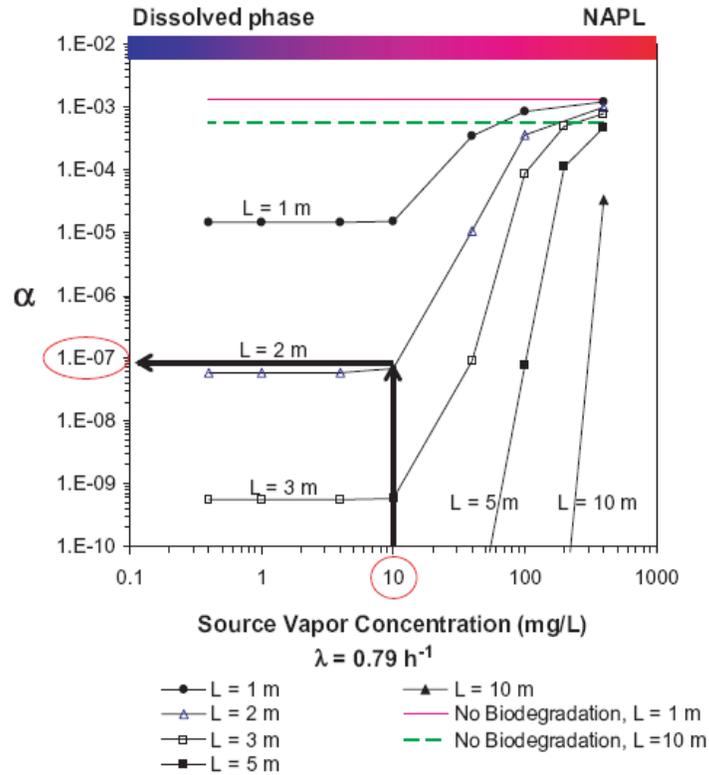


Figure 10. Use of the chart to select a semi-site-specific attenuation factor. For a source concentration of 10,000 $\mu\text{g/L}$ and a source-building separation of 2 m, the attenuation factor would be about $1\text{E-}7$.

- Figure 19 from API (2009) is a plot of the hydrocarbon (TPH-gasoline) attenuation factor in the unsaturated zone versus source vapor concentration for a range of source/building foundation separation distances assuming a representative biodegradation rate and two soil types, a sand and a silty-clay:

Figure 19 from API (2009)

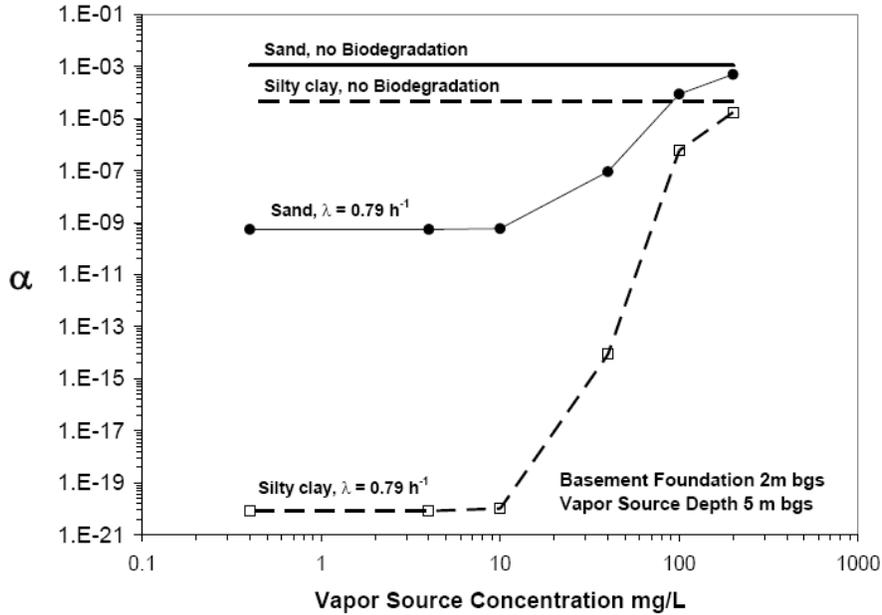


Figure 19—Attenuation factors as a function of soil type and vapor source concentration for a source located at 5 m bgs (3 m below a basement foundation). The graph present results for no biodegradation scenarios and biodegradation scenarios with a first-order biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Q_s (sand) = 3.7 L/min and Q_s (silty clay) = 0.05 L/min.

- Figure 9 from Abreu and Johnson (2005) is a plot of the attenuation factor in the unsaturated zone versus source edge–building separation distance predicted in a sand unsaturated zone for a slab-on-grade building foundation. Biodegradation was not considered in the model analysis.

Figure 9 from Abreu and Johnson (2005)

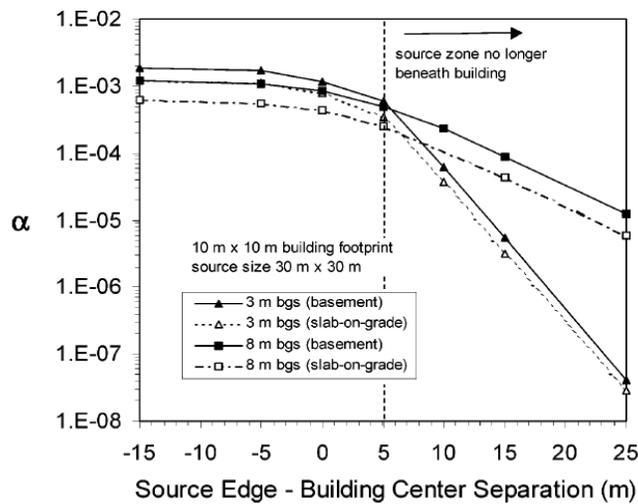
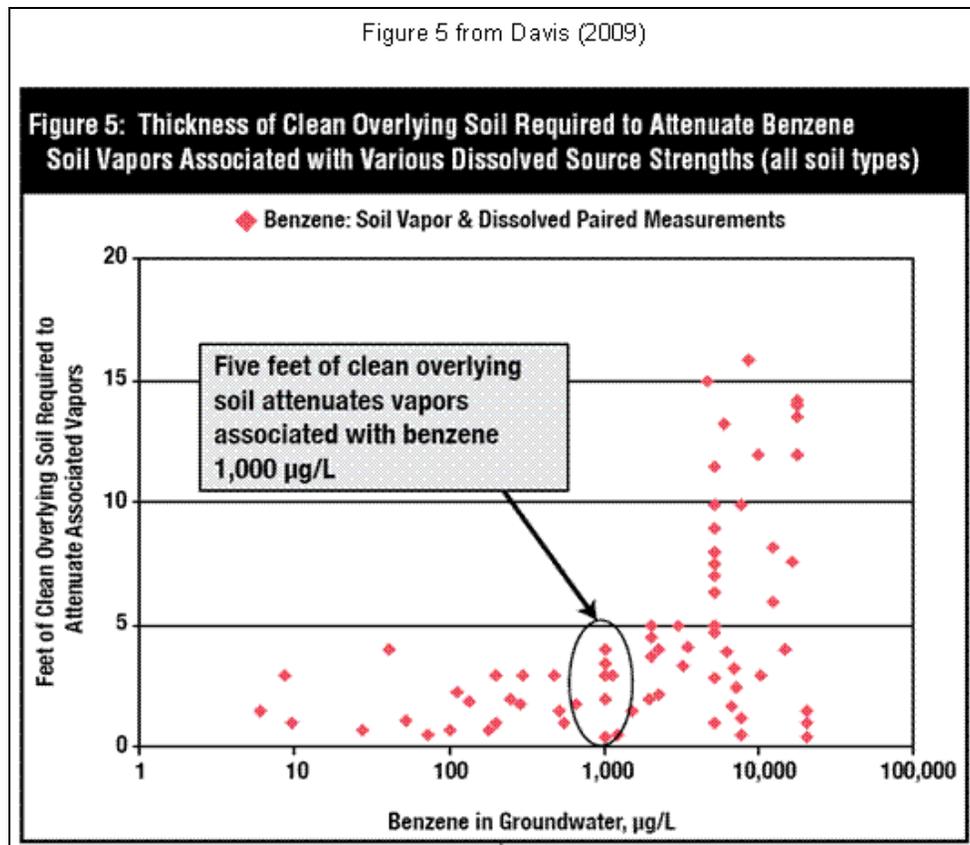


FIGURE 9. Changes in vapor attenuation coefficient (α) with vapor source–building separation and vapor source depth for basement and slab-on-grade foundation scenarios.

3.1.2 Field Data

Two hydrocarbon soil-gas databases were used to support the development of exclusion distance criteria. One was compiled by Robin Davis (Davis, 2009) and the other by Jackie Wright (Wright, 2011). The Davis (2009) database is 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. The cited databases are publically available. Davis (2009) compiled the database from measurements at 58 retail, distribution, and manufacturing sites across several states, including California. Wright's 2011 database includes soil-gas data collected from 124 additional retail, distribution, and manufacturing sites in Australia. Both databases include soil-gas data collected from on and off-site locations. Approximately 16% of the soil-gas data are measurements taken directly below building foundations (i.e., sub-slab). The field data support the model results discussed in the previous section. An analysis by Davis (2009) indicates that benzene concentrations in soil gas are completely attenuated within 5 feet or less of groundwater containing up to 6 mg/L (or ~1,500,000 ug/m³ vapor phase equivalent⁵) benzene (see Figure 5 below from Davis, 2009). The analysis includes data from "non-retail" locations.



It is important to note in Figure 5, that the exclusion distance (and vapor intrusion risk potential) is relatively independent of the benzene source concentration over the approximate range of dissolved

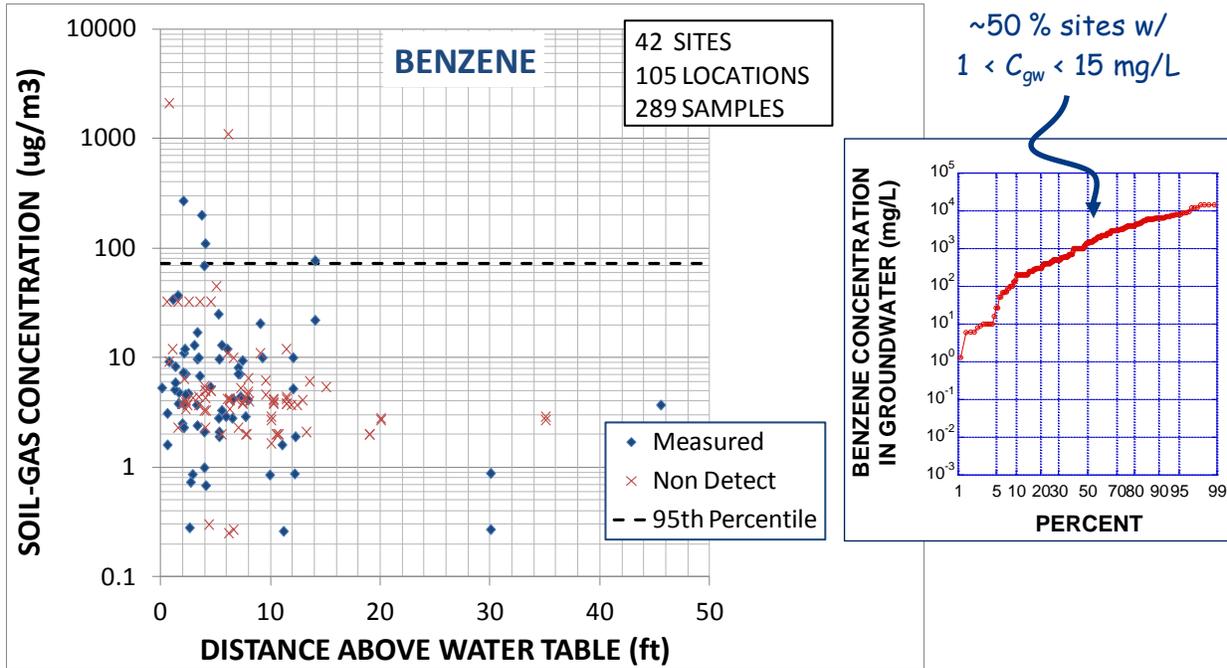
⁵ Assuming equilibrium partitioning between soil-gas and groundwater and a Henry's Law coefficient of 0.25 m³/m³ for benzene.

phase concentrations up to 6,000 ug/L. The development of more conservative groundwater concentration-based exclusion distances (e.g., specific exclusion distance criteria for 100 ug/L and 1,000 ug/L sources) was a policy decision.

Davis (2009) did not screen out sites with potential residual LNAPL sources above the water table (i.e. LNAPL in soil). Note that residual LNAPL in soil and free-phase LNAPL on groundwater will pose similar vapor-intrusion risks. The latter are sites where LNAPL is observed in groundwater monitoring wells located in the source area. However, Davis (2009) found that the thickness of “clean” soil required to fully attenuate vapors to health-protective concentrations (i.e., the exclusion distance) decreased from ~15 feet (Figure 5) to 8 feet when considering LNAPL sources in soil in the absence of free-phase LNAPL on groundwater (Davis 2010 – see Figure from Davis in Section 3.2.2).

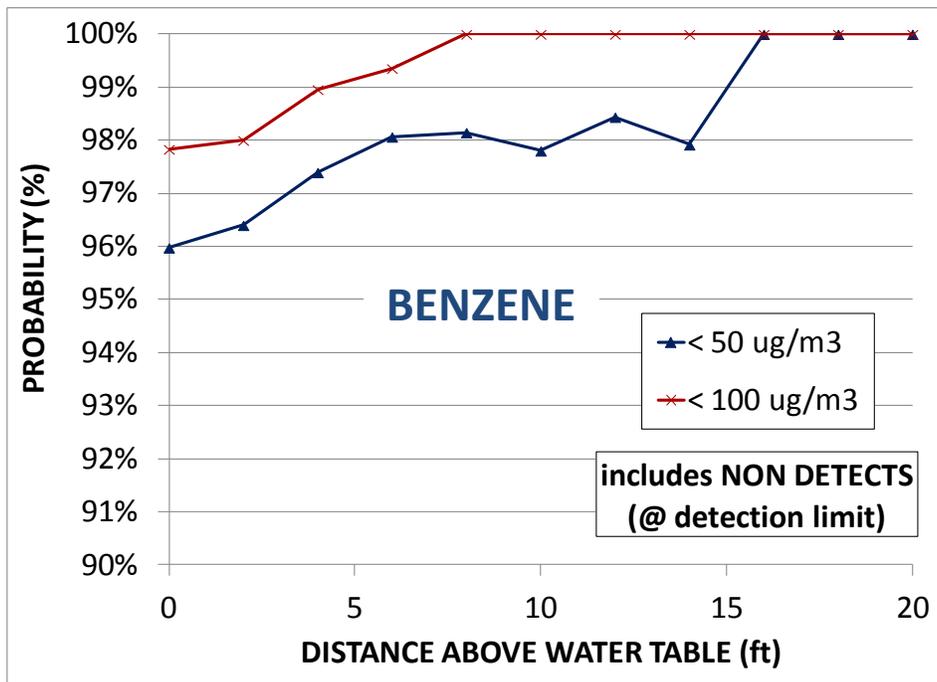
Lahvis (2011) analyzed soil-gas data collected above dissolved-phase sources where efforts were taken to identify and screen out sites with LNAPL above the water table (i.e LNAPL in soil). The analysis filtered out sites with either direct evidence of LNAPL (current, historical) or indirect evidence of LNAPL (soil-gas measurements collected near potential sources (i.e., locations within 25 ft of USTs and dispensers). . The analysis did, however, include soil-gas data from sites with dissolved-phase (source) concentrations up to 15 mg/L benzene and 75 mg/L BTEX. Lahvis (2011) included these additional data to assess an “upper bound” on exclusion distances for dissolved-phase sources, realizing that dissolved-phase concentrations greater than 3 mg/L benzene and 20 mg/L BTEX may potentially indicate the presence of a residual-phase LNAPL source (Bruce et al. , 1991). In other words, Lahvis (2011) included soil-gas data from sites with potential LNAPL sources to be conservative in estimating the exclusion distances for dissolved-phase sources. The Lahvis study included soil-gas data from both Davis (2009) and Wright (2011). This study shows that benzene in soil vapor is attenuated below a relatively conservative soil-gas screening level of 50 ug/m³ when the dissolved benzene source is 5 vertical feet or greater from the receptor. Note that more than half of the soil-gas measurements were taken from sites with source concentrations of benzene dissolved in groundwater ranging from 1 to 15 mg/L.

Figure from Lahvis (2011)



The results shown in the figure from Lahvis (2011) were then used by to define exclusion distance criteria based on a conditional probability assessment as shown in the following figure:

Figure from Lahvis (2011)



The results indicate that the probability of observing benzene vapor concentrations in excess of a conservative screening level (i.e. 100 ug/m³) at distances greater than 5 ft above the dissolved phase source at retail sites is less than 5%. The water table would have to be essentially in contact with a building foundation for there to be a potential concern for vapor intrusion for this class of low concentration sites.

3.1.3 Summary of Low Concentration Sources

In summary, field data from UST petroleum release sites shows minimal vapor-intrusion-to-indoor air risk above dissolved-phase only hydrocarbon sources. At low-concentration sites, benzene, the primary risk driver for vapor intrusion, will be attenuated below conservative soil-gas screening limits within 5 feet above the water table.

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 figures (Figures 5 and 7 from Abreu et al. [2009]), benzene is predicted to completely attenuate in the unsaturated zone above an LNAPL source within ~ 7m (20 ft) of the source⁶. Abreu et al (2009) used benzene to represent the greatest potential risk posed by soil vapor from an unweathered LNAPL vapor source. This LNAPL source will primarily consist of aliphatic hydrocarbons. The model is assumed to be conservative when considering benzene biodegradation assumptions (see note 7 below.).

⁶ Note Figures 5 and 7 from Abreu et al. (2009) were slightly modified to highlight the technical justification.

Figure 5 (modified) from Abreu et al. (2009)

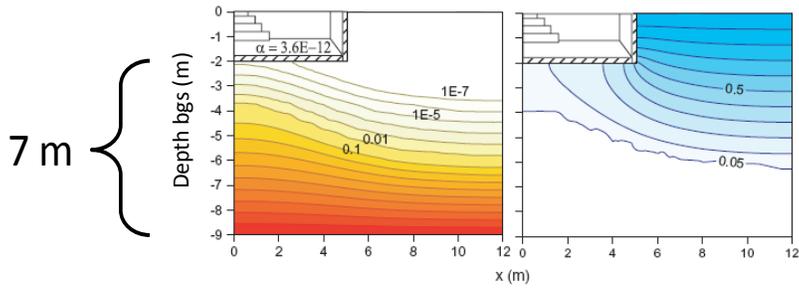


Figure 5. Effect of source depth on the soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement scenarios with a high vapor source concentration of 100,000 $\mu\text{g/L}$ and biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations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

Figure 7 (modified) from Abreu et al. (2009)

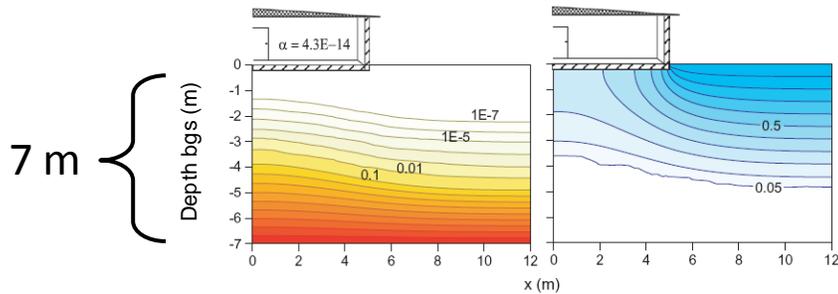


Figure 7. Effect of building type on soil-gas concentration distribution for high vapor source concentration (100,000 $\mu\text{g/L}$) and biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

Vapor attenuation is predicted to increase for LNAPL sources displaced laterally from the basement foundation (Abreu and Johnson, 2005).

3.2.2 Field Data

A recent analysis of a soil-gas database by Davis (2010) indicates that the model-predicted attenuation cited above is conservative. Davis (2010) found source-receptor separation distances of only 8 ft. attenuated soil-gas vapors associated with benzene and TPH from LNAPL sources to below health-risk screening criteria (see the following figure from Davis [2010]). The Davis (2010) analysis includes residual LNAPL sources in the unsaturated zone.

Figure from Davis (2010)

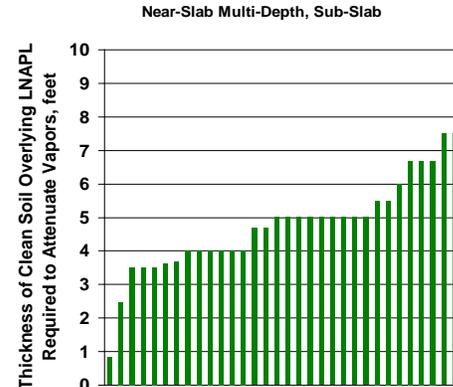
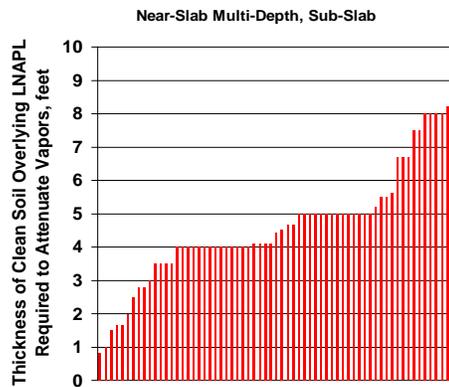
LNAPL & Soil Sources

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

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

■ Benzene SV Sample Event over LNAPL & Soil Sources

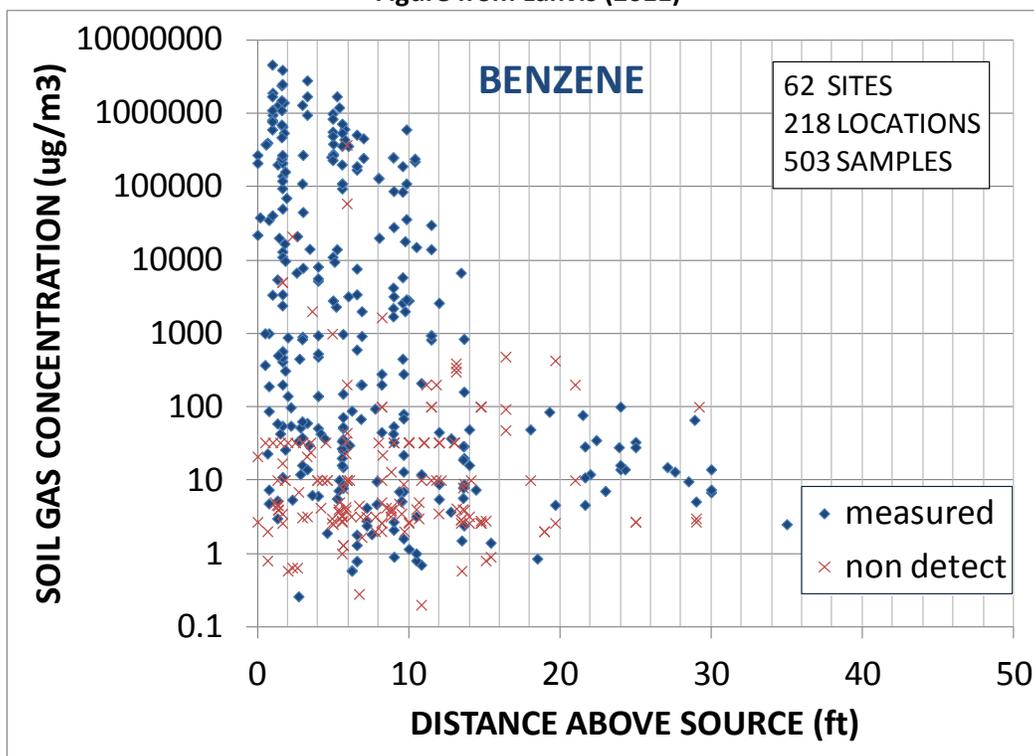
■ TPH SV Sample Event over LNAPL & Soil Sources



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

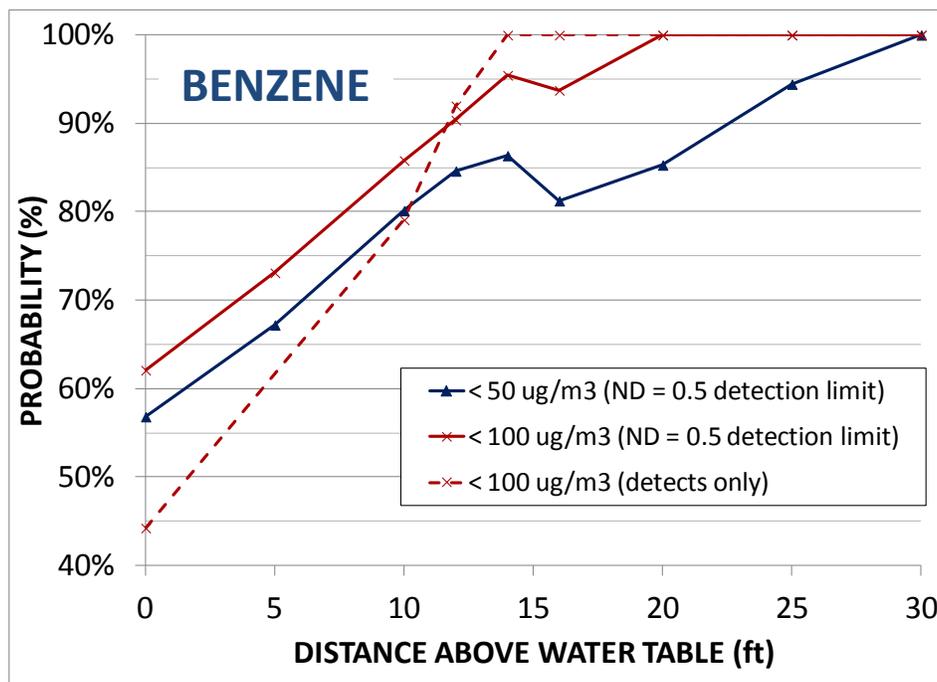
In addition, Lahvis (2011) demonstrates in the following figure that benzene concentrations in soil gas generally decrease by more than 4 orders of magnitude at source-receptor separation distances of > 13 feet at LNAPL sites:

Figure from Lahvis (2011)



From a conditional probability standpoint, benzene concentrations in soil gas will attenuate below 50 and 100 ug/m³ at distances of > ~25 ft and >~ 13 ft above the source in greater than 95% of cases, respectively.

Figure from Lahvis (2011)



Again, lateral separation exclusion distances would be expected to be less than the vertical exclusion distances for the reasons previously presented.

3.2.2 Summary

Most recent field data analyses indicate that 8 to 13 feet of clean soil (soil with no LNAPL present) between source and receptor is sufficient to reduce soil-vapor concentrations to below health-protective levels for the vapor-intrusion-to-indoor air pathway at sites with LNAPL sources in either soil or groundwater.

3.3 Technical Background Conclusions

Researchers have demonstrated that soil-vapor benzene concentrations above low-concentration sources 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 high concentration sources (e.g., unweathered LNAPL sources), 8 to 13 feet of clean soil (i.e. TPH <100 mg/kg) are required to fully attenuate hydrocarbon vapors to health-protective concentrations for the vapor-intrusion-to-indoor air pathway. 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 to health-protective concentrations). Some of the referenced studies have been accepted for publication, but are awaiting the respective Journal publication dates. They are available for review. It is important to consider these “state of the science”

results in the development of rational, technically defensible, approaches to vapor intrusion risk assessment.

Please note that the Stakeholder Group that developed the Low-Threat UST Policy Petroleum considered the cited technical sources when developing the vapor-intrusion scenarios and associated risk criteria presented in the Low-Threat Policy. In addition, *as a statewide policy consideration*, the Stakeholder Group applied source-to-receptor separation distance and source concentration safety factors that make the proposed vapor-intrusion-to-indoor-air screening criteria *more conservative* than they would otherwise be if considering the scientific literature alone. These safety factors include greater separation distances and lower threshold concentrations than those found by researchers to be health protective.

4 THE FOUR LOW-THREAT VAPOR INTRUSION SCREENING SCENARIOS

The Stakeholder Group convened by the SWRCB considered the available current and relevant scientific studies when developing the following low-threat vapor-intrusion-to-indoor air criteria. The four basic vapor-intrusion scenarios are:

Scenario 1: Unweathered LNAPL on groundwater

30 ft vertical source/building separation (exclusion) distance for unweathered (residual or free-phase) LNAPL on groundwater

Scenario 2: Unweathered LNAPL in soil

30 ft lateral and vertical source/building separation (exclusion) distance for an unweathered LNAPL (residual or free-phase) LNAPL source in soil and a building foundation

Scenario 3: Dissolved phase benzene concentrations in groundwater

- 5 feet vertical separation distance between a dissolved-phase source < 100 ug/L benzene and a building foundation (no oxygen [O₂] measurement)
- 10 feet vertical exclusion distance for a dissolved-phase source < 1,000 ug/L benzene (no O₂ measurement)
- 5 ft. vertical separation distance between a dissolved-phase source < 1,000 ug/L and a building foundation (measured O₂ in soil gas > 4%)

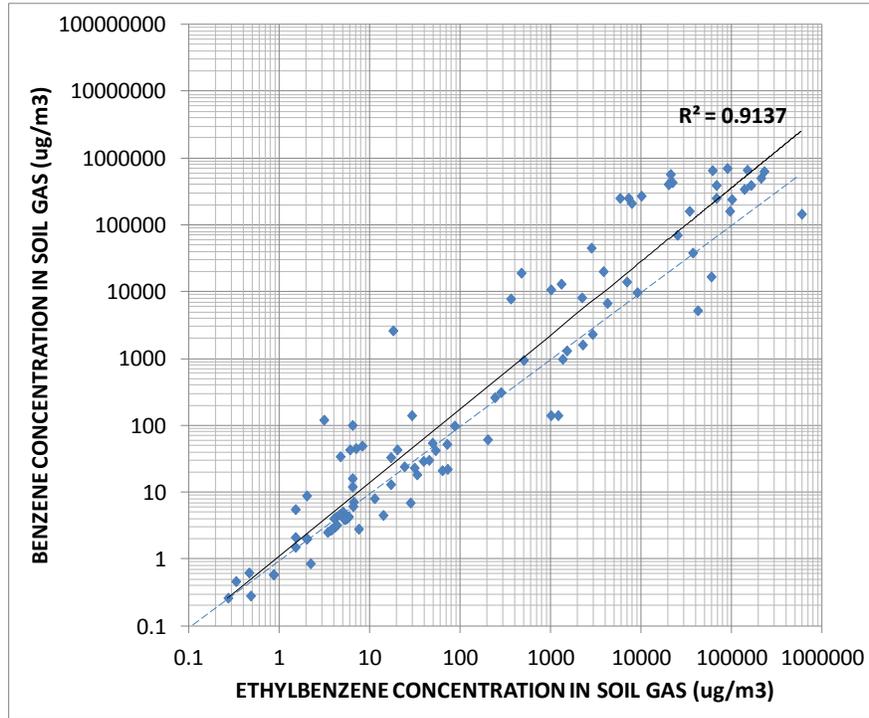
Scenario 4: Direct measurement of soil gas concentrations

Application of an additional thousand-fold biodegradation attenuation factor to risk-based soil-gas concentration criteria (CHHSLs) when the source is located more than 5 feet from a building foundation

Scenarios 1 and 2 are will usually be associated with “high”-concentration sources. Scenario 3 is associated with a “low” concentration source, and Scenario 4 may be associated with either “low” or “high” concentration sources. The following section details the technical justification(s) for each of the sets of low-threat exclusion criteria expressed in the four scenarios. Benzene is assumed to be the primary risk driver for vapor intrusion at petroleum hydrocarbon sites. The vapor-intrusion exclusion distance criteria determined for benzene are assumed to be health-protective for other potential hydrocarbon VOCs such as ethylbenzene and naphthalene. For ethylbenzene, this assumption is based on 1) ethylbenzene is expected to have similar source concentrations and fate and transport properties

as benzene (Abreu et al., 2009), and 2) soil-gas concentrations from UST petroleum release sites show a strong correlation between benzene and ethylbenzene concentrations in soil-gas measured concurrently from the same soil-gas probe (see following figure from Lahvis [written communication]):

Figure from Lahvis (written communication)



The exclusion distance criteria determined for benzene are assumed to be conservative for naphthalene because 1) naphthalene is typically present in gasoline at lower fractions as benzene, 2) naphthalene is likely present at very low concentrations (mass fraction of 0.0026) in diesel (Potter and Simmons, 1998), and 3) naphthalene is less volatile, and has similar (if not, higher) degradation rates as benzene (GSI, 2010).

4.1 Scenario 1: Unweathered LNAPL on Groundwater

30 ft vertical source/building separation (exclusion) distance for unweathered (residual or free-phase) LNAPL on groundwater

The proposed 30 feet exclusion distance⁷ is conservative based on:

- Model theory shows full attenuation within 7 m (~ 20 ft) of a high concentration LNAPL source assuming reasonable approximations of the biodegradation rate (see Figures 5 and 7 below from Abreu et al., 2009)⁸. The use of benzene to represent an unweathered LNAPL vapor source (which will primarily consist of aliphatic hydrocarbons) is assumed to be conservative with respect to benzene biodegradation assumptions (linked to O₂ availability)⁹.

⁷ The top of the residual-phase source can generally be assumed to be consistent with the historic high water-table elevation.

⁸ Note Figures 5 and 7 from Abreu et al. (2009) were slightly modified to highlight the technical justification

⁹ In this model, biodegradation is linked to O₂ availability. Biodegradation is not simulated when O₂ concentrations in the unsaturated zone fall below 1%. Relative to benzene, aliphatic hydrocarbons are less susceptible to biodegradation because they partition less to the aqueous phase (pore water) where biodegradation takes place. Simulating LNAPL with a single benzene source will thus be conservative with respect to O₂ demand (and benzene biodegradation) compared to simulating LNAPL using a primarily aliphatic hydrocarbons.

Figure 5 (modified) from Abreu et al. (2009)

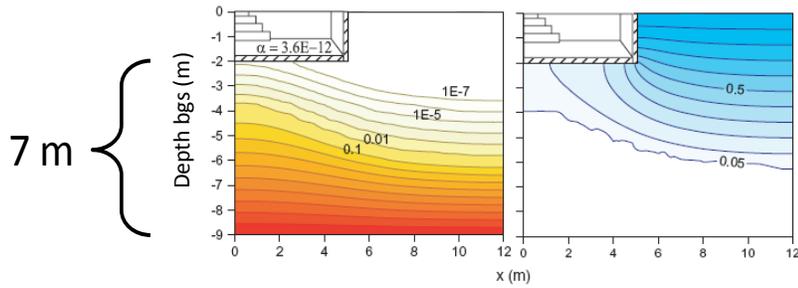


Figure 5. Effect of source depth on the soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement scenarios with a high vapor source concentration of 100,000 $\mu\text{g/L}$ and biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations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

Figure 7 (modified) from Abreu et al. (2009)

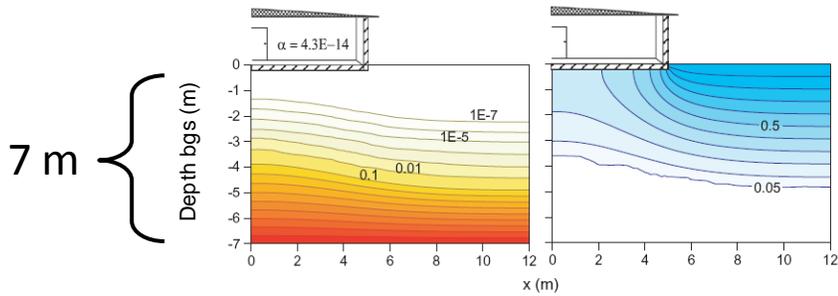


Figure 7. Effect of building type on soil-gas concentration distribution for high vapor source concentration (100,000 $\mu\text{g/L}$) and biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations are normalized by source and atmospheric concentrations, respectively.

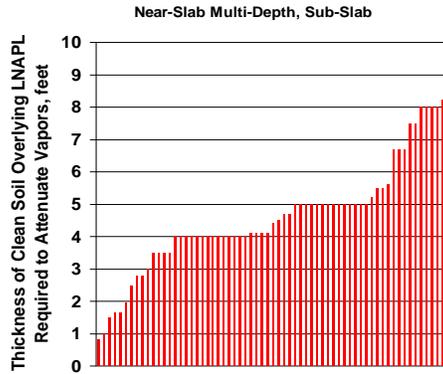
- For LNAPL and residual sources, field (soil-gas) data show full attenuation within 8 ft of the source (see figure, below, from R. Davis [2010] – also published in Hartman [2010]).

Figure from Davis (2010)

LNAPL & Soil Sources

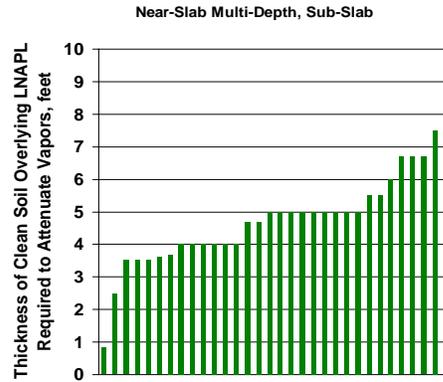
**Benzene: 48 exterior/near-slab +
22 sub-slab = 70 total**

■ Benzene SV Sample Event over LNAPL & Soil Sources



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

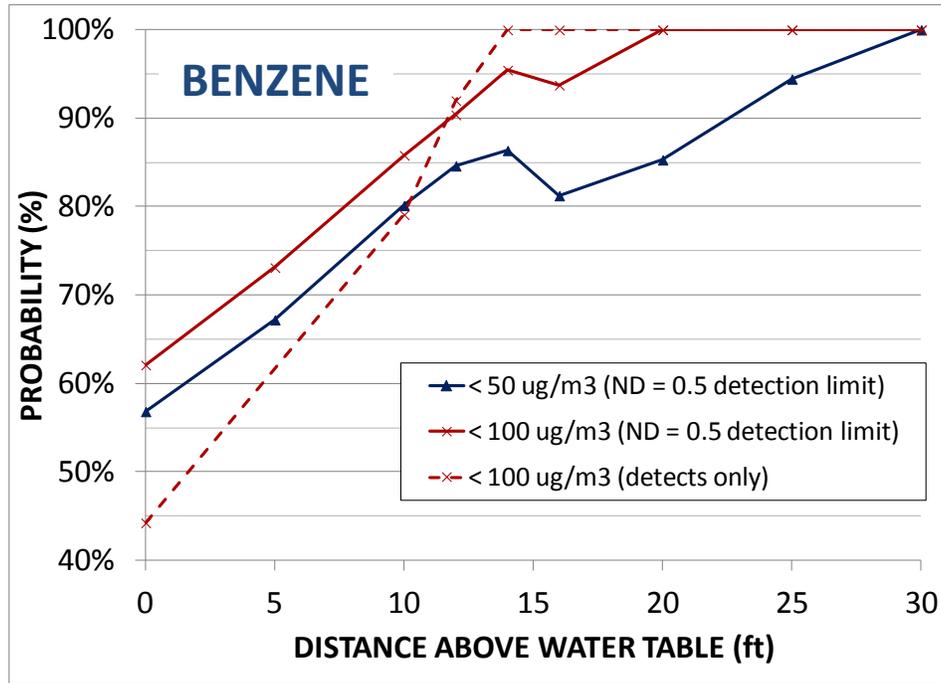
■ TPH SV Sample Event over LNAPL & Soil Sources



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

The following figure from Lahvis (2011) shows a greater than 95% probability that benzene concentrations in soil gas will attenuate below a conservative screening level for benzene in soil gas of 50 and 100 $\mu\text{g}/\text{m}^3$ (alternatively, a < 5 % probability of observing benzene concentrations > 100 $\mu\text{g}/\text{m}^3$) at distances of > ~25 ft and > ~13 ft from a LNAPL (residual or free-phase) source, respectively.

Figure from Lahvis (2011)



4.2 Scenario 2: Unweathered LNAPL in Soil

30 ft lateral and vertical source/building separation (exclusion) distance for an unweathered LNAPL (residual or free-phase) LNAPL source in soil and a building foundation

The same technical justification provided for Scenario 1 applies to Scenario 2. The proposed 30 feet lateral off-set distance is even more conservative for sources displaced laterally as indicated 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).

Figure 9 from Abreu and Johnson (2005)

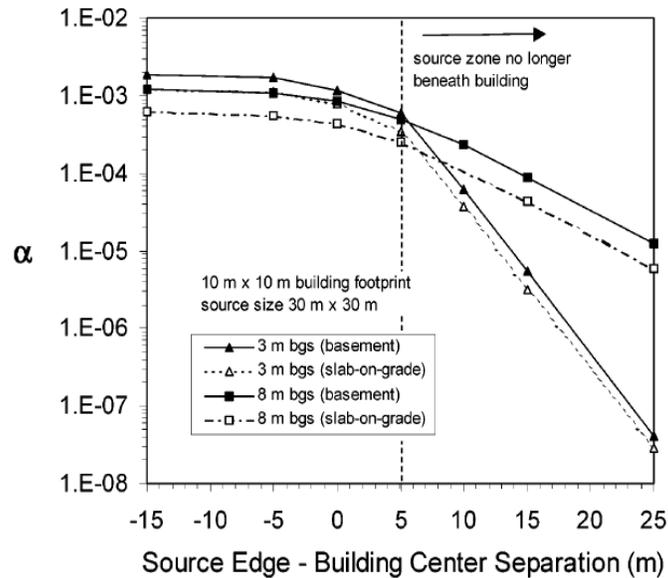


FIGURE 9. Changes in vapor attenuation coefficient (α) with vapor source–building separation and vapor source depth for basement and slab-on-grade foundation scenarios.

As discussed in the technical background section 3.2.2, 13 feet is more than adequate to fully attenuate vapors derived from LNAPL sources in soil and groundwater; therefore providing a 30' lateral distance screening criteria provides an additional safety factor.

4.3 Scenario 3: Dissolved Phase Benzene Concentrations in Groundwater

- 5 ft. vertical separation distance between a dissolved-phase source < 100 ug/L benzene and a building foundation (no oxygen (O₂) measurement)
- 10 ft. vertical exclusion distance for a dissolved-phase source < 1,000 ug/L benzene (no O₂ measurement)
- 5 ft. vertical separation distance between a dissolved-phase source < 1,000 ug/L and a building foundation (measured O₂ in soil gas ≥ 4%)

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

- Complete attenuation (~ 1E-07) is predicted within 2 m (6 ft.) of a soil gas source of benzene < 10 mg/L (assumes an approximate 40 mg/L dissolved phase benzene concentration, based on an approximation of benzene partitioning between soil gas and groundwater [dimensionless Henry's Law constant = 0.25]- see attached Figure 10 from Abreu et al. [2009]¹⁰). Even greater

¹⁰ Note figure from Abreu et al. (2009) was slightly modified to highlight the technical justification

hydrocarbon attenuation (lesser exclusion distances) is predicted for dissolved-phase sources in other less permeable (e.g., silty clay) unsaturated zone systems (Abreu et al, 2009). The attenuation is complete for the entire vapor (dissolved-phase) concentration range. The dissolved phase concentrations (especially) (i.e., 100 ug/L) and proposed exclusion distance specified in this scenario are therefore assumed to be very conservative. Note: in the figure below, “L” is the distance to the foundation from the source.

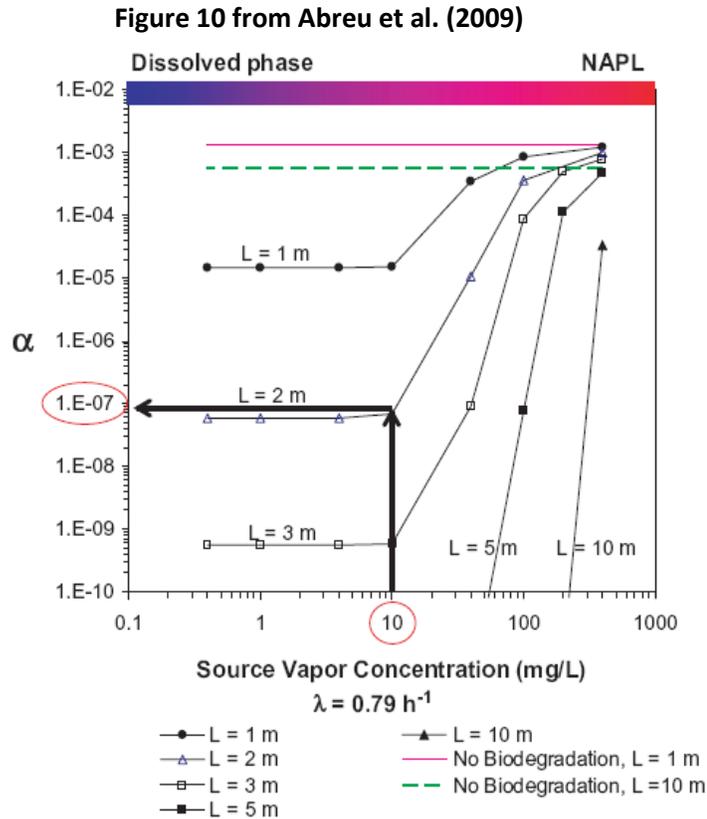


Figure 10. Use of the chart to select a semi-site-specific attenuation factor. For a source concentration of 10,000 $\mu\text{g/L}$ and a source-building separation of 2 m, the attenuation factor would be about $1\text{E}-7$.

- Model theory shows > 9 orders of magnitude (i.e. complete) attenuation (for reasonable approximations of the biodegradation rate $\lambda = 0.79 \text{ hr}^{-1}$) within a source/building separation distance of $L=3 \text{ m}$ (10 ft) in a sand unsaturated zone (Abreu et al. (2009)). This magnitude of attenuation is applicable for a benzene vapor source $< \sim 10 \text{ mg/L}$ (or $\sim 40 \text{ mg/L}$ dissolved phase source in groundwater assuming reasonable approximations for benzene partitioning between soil gas and groundwater (i.e., a dimensionless Henry’s Law constant = 0.25). Even greater hydrocarbon attenuation (lesser exclusion distances) is predicted for dissolved-phase sources in other less permeable (e.g., silty clay) unsaturated zone systems (Abreu et al, 2009). The attenuation is complete for the entire vapor (dissolved-phase) concentration range. The dissolved phase concentrations (especially) (1,000 $\mu\text{g/L}$) and proposed exclusion distance

specified in this scenario are therefore assumed to be very conservative. Note: in the figure below, “D” is the overall source depth and “L” is the distance to the foundation from the source.

Figure 6 from Abreu et al. (2009)

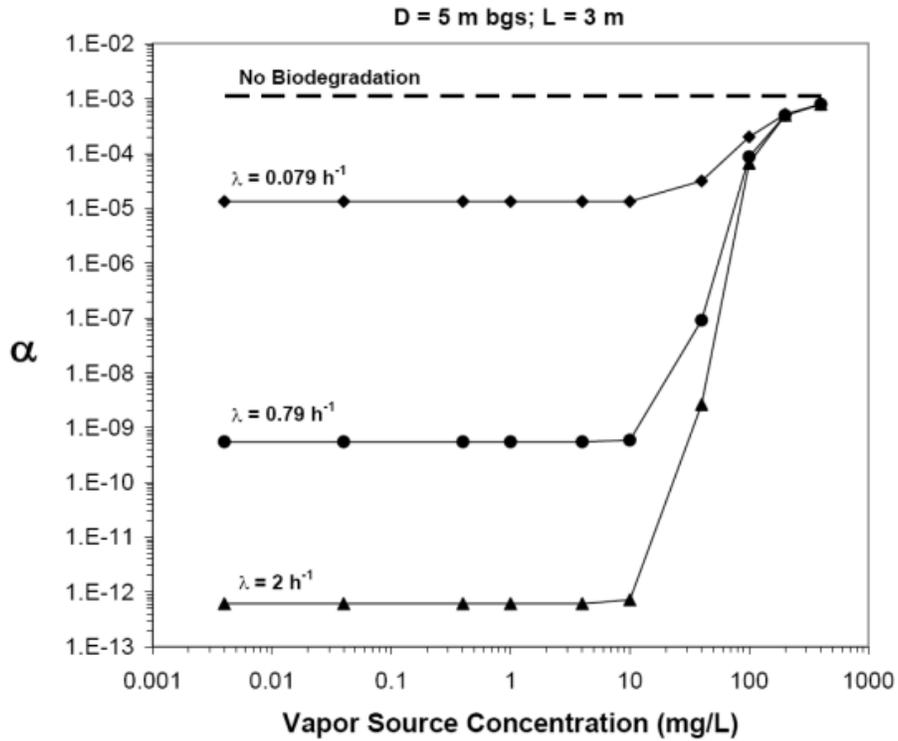
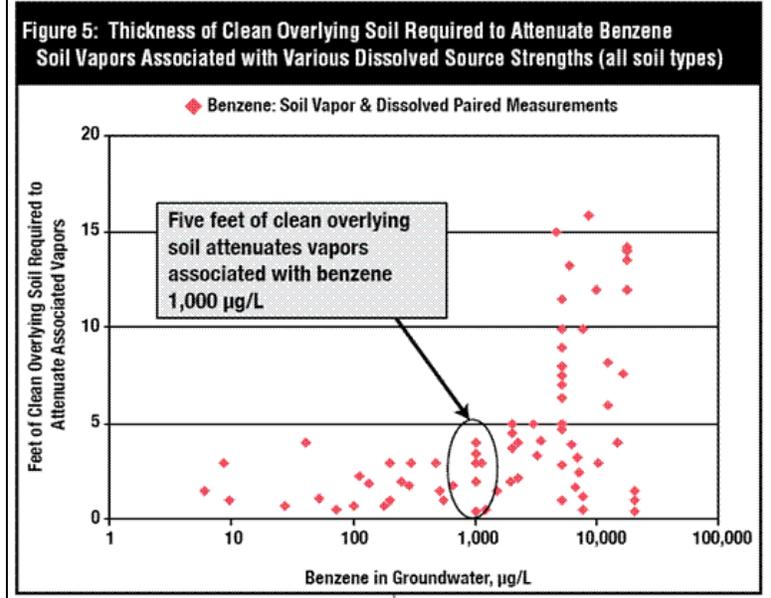


Figure 5—Influence of soil vapor source concentration and first-order biodegradation rates (λ) on vapor intrusion attenuation factors (α) for basement scenarios, homogeneous sand soil and source depth (D) of 5 m bgs (source-foundation separation L = 3 m).

- Field soil-gas data show complete soil-gas attenuation within 5 feet above benzene concentrations in groundwater of up to 6 mg/L (Davis, 2009).

Figure 5 from Davis (2009)



- Field (soil-gas) data from Davis (2009) and Wright (2011) show benzene concentrations in soil gas attenuate below $80 \mu\text{g/m}^3$ (see Figure 1) and $20 \mu\text{g/m}^3$ (see Figure 2) within 10 feet above the water table for dissolved-phase benzene concentrations up to $1,000 \mu\text{g/L}$ and $100 \mu\text{g/L}$, respectively at petroleum UST release sites.

Figure 1 - Lahvis (written communication)

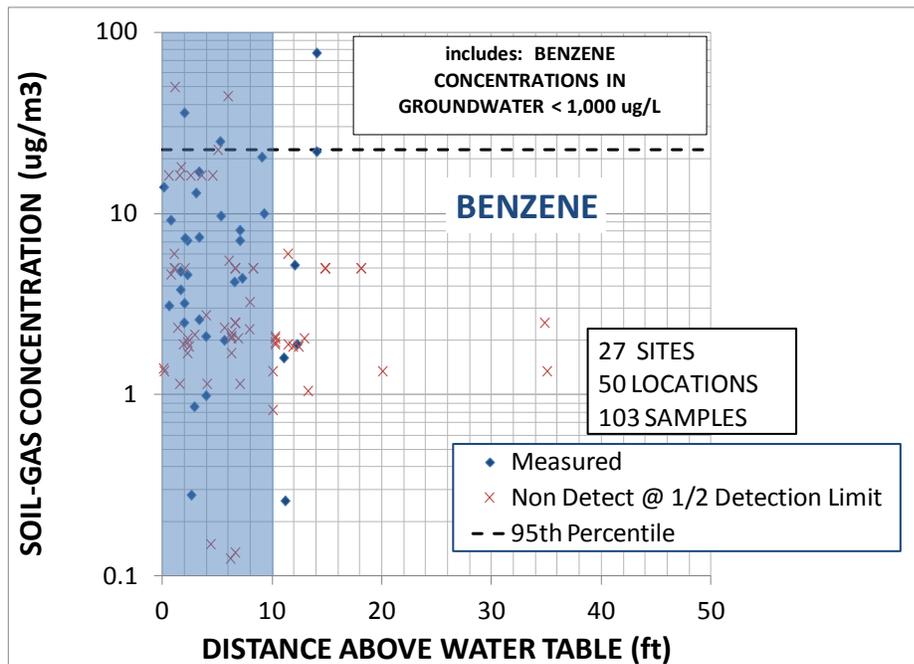


Figure 1. Benzene concentrations in soil gas as a function of distance above the water table for concentrations in groundwater $< 1,000 \mu\text{g/L}$. Analysis is based on soil gas data from Davis (2009) and Wright (2011).

Figure 2 - Lahvis (written communication)

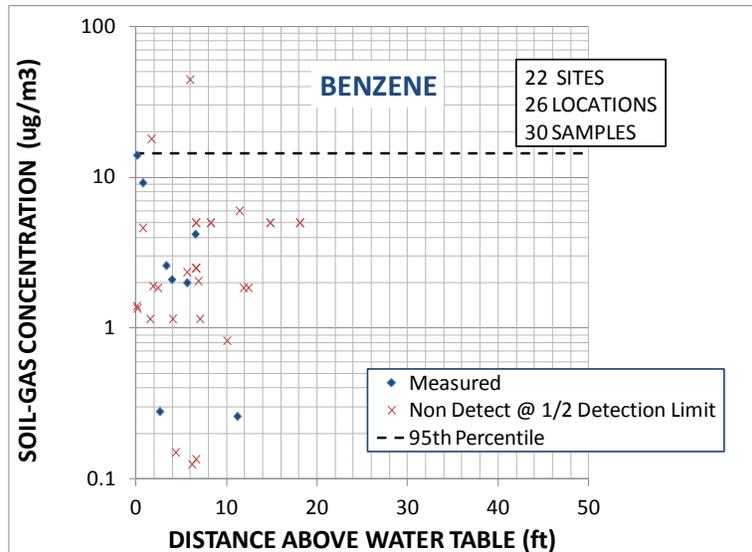


Figure 2. Benzene concentrations in soil gas as a function of distance above the water table for concentrations in groundwater < 100 ug/L. Analysis is based on soil gas data from Davis (2009) and Wright (2011).

- The probability of benzene vapor concentrations near the receptor exceeding a conservative screening level of 50 ug/m³ is less than 5 % at petroleum-UST release sites with benzene concentrations in groundwater < 1,000 ug/L. The probability is less than 5% regardless of the source-receptor separation distance (see Figure 3 – Lahvis [written communication]). The water table would have to be essentially in contact with a building foundation to create a potential concern for vapor intrusion at low concentration sites.

Figure 3 from Lahvis (written communication)

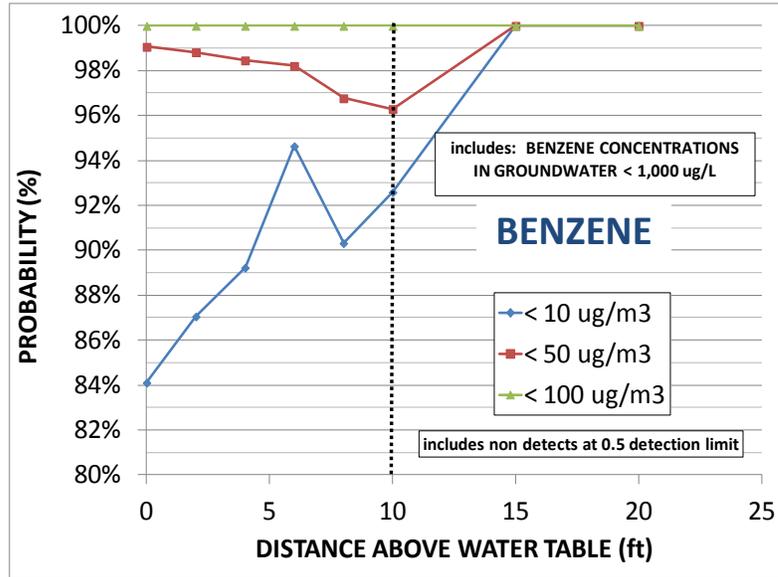


Figure 3. Probability of encountering benzene concentrations in soil gas above conservative screening-level concentrations of 10, 50, and 100 ug/m³ at various distances above the water table at retail-only locations. The data are associated benzene (source) concentrations in groundwater < 1,000 ug/L and are taken from the databases reported in Davis (2009) and Wright (2011).

- The probability of benzene vapor concentrations near the receptor exceeding a (very) conservative screening level (i.e., 10 ug/m³) at petroleum-UST release sites with benzene concentrations in groundwater < 100 ug/L is less than 5% regardless of the source-receptor separation distance (see Figure 4 from Lahvis [written communication]). The water table would have to essentially be in contact with a building foundation to create a potential concern for vapor intrusion at low concentration sites.

Figure 4 from Lahvis (written communication)

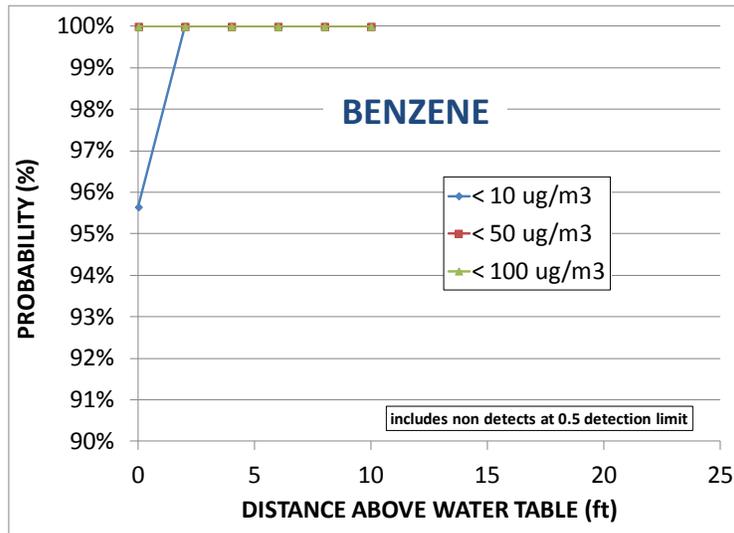


Figure 4. Probability of encountering benzene concentrations in soil gas above conservative screening-level concentrations of 10, 50, and 100 ug/m³ at various distances above the water table at retail-only locations. The data are associated benzene (source) concentrations in groundwater < 100 ug/L and are taken from the databases reported in Davis (2009) and Wright (2011).

- The model results from Abreu et al. (2009) (see Figure 3 below) show O₂ concentrations in excess of ~17% (0.8 * 21%) for a hydrocarbon (benzene) vapor source concentration of 1 mg/L (1,000 ug/L) (see plots in middle of the figure). This benzene (or BTEX) vapor source concentration is roughly equivalent to a dissolved phase source concentration of ~4,000 ug/L, which is > the maximum dissolved-phase benzene concentration “1,000 ug/L” defined for Scenario 3. This calculation assumes:
 - a) the dissolved-phase source is primarily BTEX (the most soluble hydrocarbon fraction)
 - b) vapor/aqueous partitioning occurs according to Henry’s law, and
 - c) a dimensionless Henry’s Law partition coefficient for benzene (or BTEX) of 0.25.
- Analyses of soil-gas data from Davis (2010) and Wright (2011) show that O₂ concentrations in soil gas are > 4% at sites with dissolved-phase sources of benzene in groundwater up to 15 mg/L (see Figure from Lahvis (2011)).

Figure 3 from Abreu et al (2009)

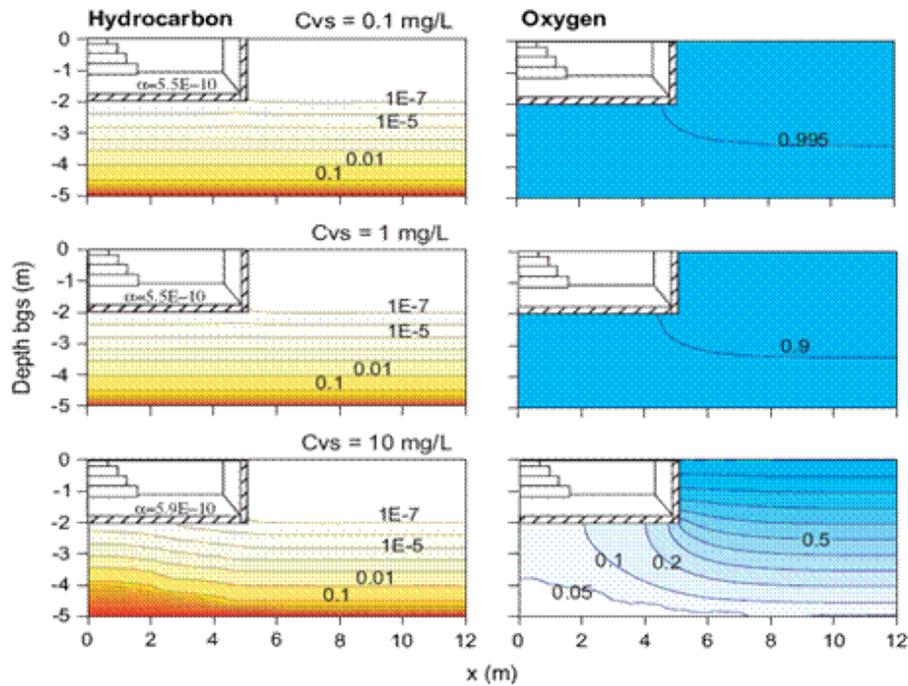


Figure 3. Effect of low vapor source concentration (C_{vs}) on soil-gas concentration distribution and vapor intrusion attenuation factors (α) for basement foundation scenarios and hydrocarbon biodegradation rate $\lambda = 0.79 \text{ h}^{-1}$. Hydrocarbon and oxygen concentrations are normalized by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

Figure from Lahvis (2011)

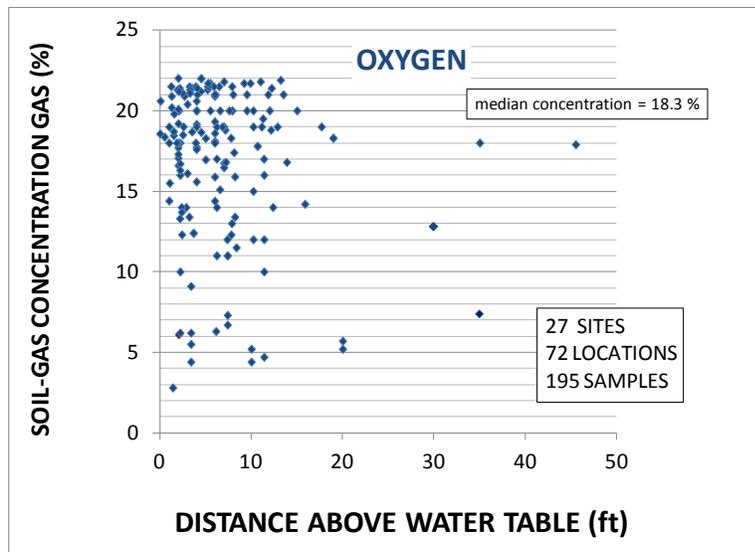


Figure. Oxygen concentrations measured in soil gas at various distances above dissolved-phase hydrocarbon (benzene) sources in groundwater with concentrations $< 15 \text{ mg/L}$. Analysis is based on soil gas data from Davis (2009) and Wright (2011).

Scenario 4: Direct Measurement of Soil Gas Concentrations

Application of a thousand-fold attenuation factor to risk-based soil-gas criteria (i.e. CHSSLs) for sources located more than 5 vertical feet from a building foundation.

- Model results (see Figure 10 from Abreu et al., 2009) show that biodegradation produces an approximate 10,000-fold attenuation of benzene concentrations in soil-gas up to ~10 mg/L or 10,000,000 ug/m³ within 2 m (5 ft) of a building foundation for reasonable approximations of the degradation rate in a sand unsaturated zone¹¹. The proposed one thousand-fold additional attenuation for benzene concentrations in soil gas up to 85,000 and 280,000 ug/m³ located more than vertical 5 feet from a building foundation is thus deemed conservative for residential and commercial settings, respectively.

Modified Figure 10 from Abreu et al. (2009)

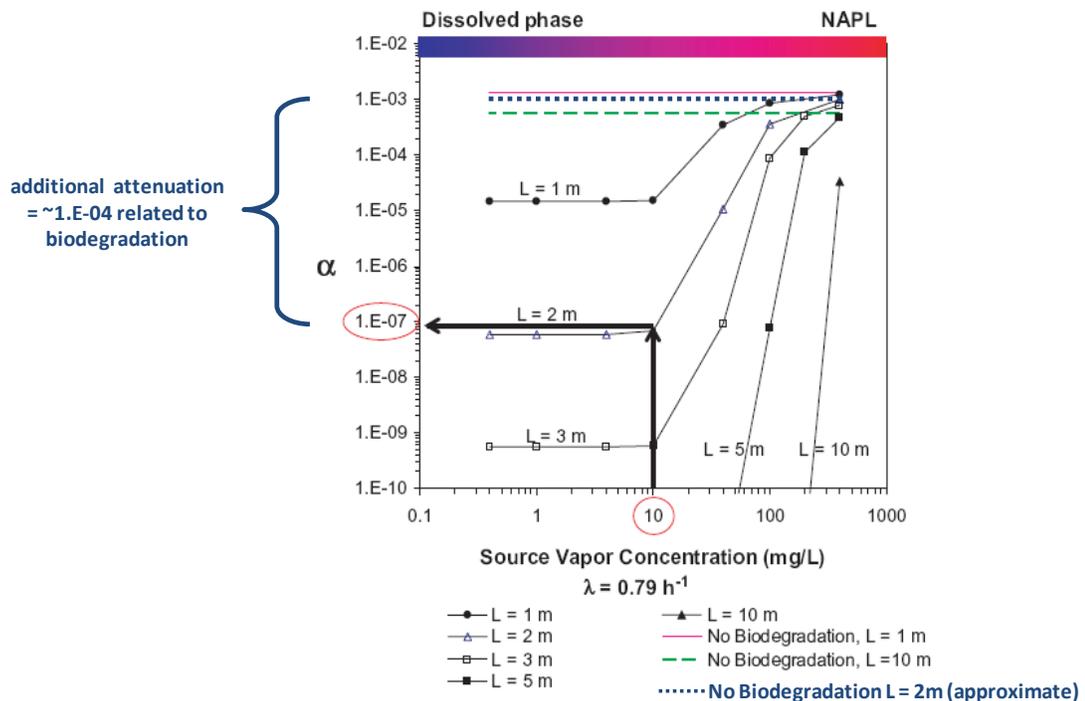


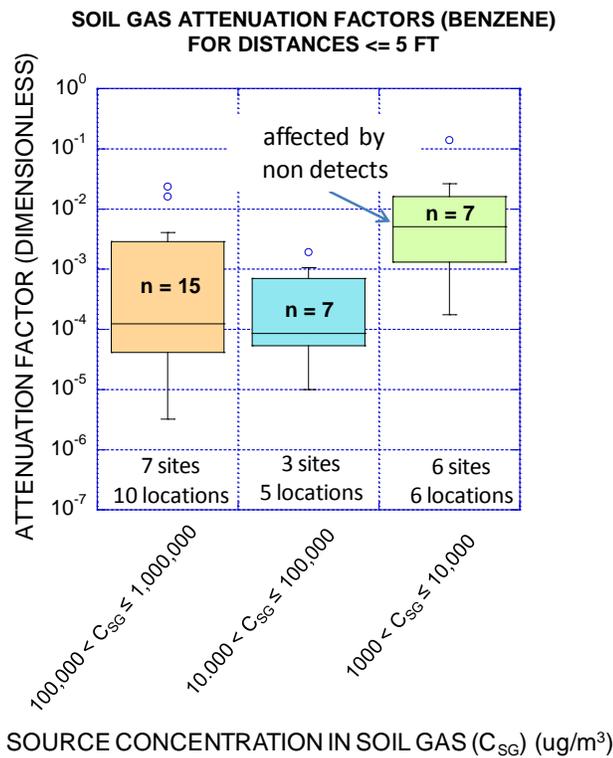
Figure 10. Use of the chart to select a semi-site-specific attenuation factor. For a source concentration of 10,000 µg/L and a source-building separation of 2 m, the attenuation factor would be about 1E-7.

- Measured field soil-gas (benzene) concentrations from Davis (2009) and Wright (2011) collected from vertically nested vapor probes support the model theory (see Figure below)

¹¹ Figure modified to show 'No Biodegradation L = 2 m (approximate)' and additional attenuation to highlight technical justification.

from Lahvis [written communication]). More specifically, these data show that benzene attenuation in the unsaturated zone generally exceeds 1000-fold within a 5 feet vertical distance of a benzene (source) soil-gas concentration range between 10,000 and 100,000 $\mu\text{g}/\text{m}^3$ (see Figure 5 – middle box). Similar attenuation is observed for benzene soil gas (source) concentrations ranging between 100,000 and 1,000,000 $\mu\text{g}/\text{m}^3$ (see Figure 5 – left hand box). Less attenuation is observed for benzene soil gas (source) concentrations ranging between 1,000 and 10,000 $\mu\text{g}/\text{m}^3$ (see Figure 5 – right hand box). The statistics are affected for this concentration range, however, by non-detect values reported at $\frac{1}{2}$ the detection limit. The soil-gas data are from the databases described by Davis (2009) and Wright (2011) for petroleum-UST release locations. This finding supports the model theory of Abreu et al. (2009) and the proposed use of a 1000-fold soil-gas bioattenuation factor..

Figure from Lahvis (written communication)



Each box encloses 50% of the data with the median value of the variable displayed as a line. The top and bottom of the box mark the limits of $\pm 25\%$ of the variable population. The lines extending from the top and bottom of each box mark the minimum and maximum values within the data set that fall within an acceptable range defined by the software. Any value outside of this range, called an outlier, is displayed as an individual point.

Figure 5. Box plots based on statistical analysis of benzene soil-gas data collected concurrently from vertically nested probe locations separated by distances ≤ 5 ft. The soil-gas data are taken from the databases reported in Davis (2009) and Wright (2011).

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Attachment 7

Technical Justification for Soil Screening Levels for Direct Contact and Outdoor Air Exposure Pathways

1 EXECUTIVE SUMMARY

Soil Screening Levels have been proposed to be used in conjunction with vapor intrusion criteria and groundwater criteria for identifying sites posing a low-threat to human health. That is, these Soil Screening Levels are just one of three sets of criteria that should be evaluated to determine if a site is low-threat.

The Soil Screening Levels discussed in this document have been developed for benzene, ethylbenzene, naphthalene, and polyaromatic hydrocarbon (PAH) to define sites that are low-threat with respect to “direct contact” with soil and inhalation of soil emissions. The exposure pathways considered in the site conceptual model are: ingestion of soil, dermal contact with soil and inhalation of dust and volatile emissions from soil. Note these exposure pathways are assumed to occur simultaneously, i.e., the screening levels are protective of the cumulative exposure from all four exposure pathways.

Standard USEPA risk assessment equations were used to derive the screening levels. The exposure parameter values, chemical toxicity values, and chemical fate and transport properties are based on standard values used in California.

Two sets of screening levels were developed for two soil horizons: one from 0 to 5 feet below ground surface (bgs), and one from 5 to 10 feet bgs. This document describes the technical background for the development of the soil screening levels. Three exposure scenarios (residential, commercial/industrial and utility trench scenario) were considered and the screening levels for each soil horizon were chosen to be the most conservative of the three scenarios.

The soil screening level for “PAH” is appropriate to be compared with site concentrations for the total concentration of the seven carcinogenic PAHs. The carcinogenic PAHs are: benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenz(a,h)anthracene, and indeno(1,2,3-cd)pyrene. The toxicity value used for the entire group of carcinogenic hydrocarbons is California’s Office of Environmental Health Hazard Assessment (OEHHA) cancer potency value for benzo(a)pyrene (OEHHA 2010). This is a conservative assumption because the few PAHs that are more carcinogenic than benzo(a)pyrene are not found in petroleum mixtures.

2 INTRODUCTION

The equations used to develop the Soil Screening Levels came from the USEPA Regional Screening Levels (RSLs; USEPA 2011). Exposure parameters values were assumed to equal the defaults values used in

California Department of Toxic Substances (DTSC) Office of Human and Ecological Risk (HERO) "Human Health Risk Assessment (HHRA) Note Number 1" (DTSC 2011). The Soil Screening Levels presented in this document are conservative because the assumptions used to calculate the values are based on conservative assumptions and exposure scenarios.

The volatilization factor used in the RSLs was replaced with a volatilization factor obtained from the American Society of Testing Material's (ASTM's) Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites (ASTM 1995). The ASTM volatilization factor used to calculate concentrations in outdoor air considers mass balance. The volatilization algorithm commonly used in USEPA screening level equations can overestimate the amount of contaminant volatilizing into outdoor air for volatile chemicals (Cal/EPA, 2005). In the ASTM volatilization algorithm, if the calculated volatilization rate depletes the source before the end of the exposure duration, then the volatilization rate is adjusted so that the total source mass is assumed to volatilize by the end of the exposure duration. By using this simple mass-balance check, it is ensured that the total amount volatilized does not exceed the total amount of contaminant in soil.

For dermal contact with soil, ingestion of soil, and inhalation of dust pathways, the exposure concentration in soil is assumed to be constant at the screening level for the entire exposure duration. This assumption is very conservative for volatile chemicals or chemicals expected to biodegrade in soil such as benzene, ethylbenzene and naphthalene.

2.1 Screening Levels vs. Risk

The Soil Screening Levels represent concentrations, below which, indicate the site is a low-threat risk for human health; they cannot be used to estimate site-specific risks. Multiple conservative assumptions were made when developing these Soil Screening Levels. Actual site risk is expected to be lower than the risk targets used to develop the screening levels. For example, for residential sites, the receptor is assumed to come into contact with soil with concentrations at the screening level almost every day (350 days/year) for a total of 30 years. While most residential exposures would not be at the default levels used in this analysis, the defaults used here are designed to be protective for this hypothetical "reasonable worst case" scenario.

Site concentrations that exceed the screening levels do not indicate unacceptable human health risks with regards to these pathways; rather, an exceedance may indicate that a site-specific evaluation of human health risk is warranted.

2.2 Chemicals Considered

The Soil Screening Levels were developed for benzene, ethylbenzene, naphthalene and PAHs. Total petroleum hydrocarbons (TPH) were not considered separately as chemicals of concern. The stakeholders chose not to include TPH in policy for the following reasons:

- TPH consists of a mixture of more than 2000 chemicals.

- Once in the soil, the TPH starts weathering immediately changing its composition through time and from one site to the next.
- Bulk TPH measurements, such as those obtained by analytical method 8015M, are not suitable for risk assessment because they do not provide information about the composition of the TPH with respect to chemical toxicity and fate and transport properties.
- None of the regulatory agencies in California that are responsible for requiring risk assessment have an approved analytical method for evaluating TPH for purposes of risk assessment (such as a fractionation method). In fact, most analytical labs in California are not familiar with TPH fractionation.
- Benzene, ethylbenzene and naphthalene more accurately capture the risk that TPH poses for human health concerns.

2.2 Requirements for Using Screening Levels

There is only one “model” used in calculation of the Screening Levels. This model assumes the following:

- The area of impacted soil is 25 m by 25 m (approximately 82 by 82 feet) or less. If the area of impacted soil is larger than this, then a site-specific analysis of direct contact risk may be warranted.
- The receptor is always located at the downgradient edge for purposes of inhalation calculations. For residential exposures, it is assumed that the receptor is located on site for 24 hours/day for the entire exposure duration. For industrial and utility workers, it is assumed that the worker is located onsite for 8 hours/day.
- The wind speed is assumed to equal 2.25 m/s on average. If the average wind speed is much lower, then a site-specific analysis of direct contact risk may be warranted.
- The default input parameters for all of the exposure scenarios were obtained from DTSC defaults for California hazardous waste sites. If the exposure scenario at the site varies from these assumptions (that is, it is more conservative), then a site-specific risk analysis may be warranted.

3 CONCEPTUAL SITE MODEL

This section describes the exposure scenarios and receptors considered in the development of the Soil Screening Levels. Screening levels were developed for two different soil horizons. A schematic of the conceptual site model for these two soil horizons is shown in Figure 1.

3.1 Exposure Pathways

The Screening Levels consider four exposure pathways simultaneously:

- ingestion of soil,
- dermal contact with soil,
- inhalation of volatile soil emissions, and

- inhalation of particulate emissions.

Ingestion of and dermal contact with soil are direct exposure pathways, i.e., the receptor is assumed to contact the soil directly and, therefore, the exposure point concentration is the actual concentration in soil. For the inhalation exposure pathways, the exposure medium is outdoor air; the outdoor air concentrations must be estimated using volatilization and particulate emission factors.

3.2 Receptors Considered

Soil Screening levels were calculated for three exposure scenarios, and then the most conservative screening level was chosen for the screening levels. The exposure scenarios considered were:

- residential,
- commercial/industrial, and
- workers in a utility trench or similar construction project.

It is assumed that all four of the exposure pathways (discussed in section 3.1) are potential exposure pathways for each of the three types of receptors. The input parameter values are different for each receptor, however.

For the residential exposure scenario, it is assumed that the receptor is a child for 6 years and then an adult for 24 years. When calculating carcinogenic risk, the total intake of a chemical over a lifetime is used; therefore, the carcinogenic residential screening levels are protective of the combined child plus adult scenario. Note, for benzo(a)pyrene (PAHs), the mutagenic exposure equations are used for calculating the screening level. In this case, the early life exposures (i.e., 0 to 2 years, 2 to 6 years and 6 to 16 years) are weighted more than they are in the non-mutagenic equations (see Table 1). For non-carcinogenic health effects, the intake is not added over the exposure period. In that case, the child is the more sensitive receptor, therefore the non-carcinogenic screening levels are developed for a child receptor and are protective for the adult resident as well.

The commercial/industrial exposure scenario assumes that the receptor is an adult and works in an office or outdoors at the site; however, the adult is not expected to be digging in the soil (i.e., coming into contact with soil below 5 feet below ground surface). In this scenario, it is assumed that the receptor works for a total of 25 years at 250 days/year at the same location. It is likely that the direct contact exposure assumptions are very conservative for this exposure scenario.

For the utility or construction worker, it is assumed that the worker may be working directly with the impacted soil. In this exposure scenario, the exposure duration is assumed to be much shorter than in the other two scenarios (1 year); however, the chemical intake per day is assumed to be higher due to increased incidental ingestion.

3.3 Depths to Which the Screening Levels Apply

Two sets of screening levels were developed, based on depth of impacted soil: one set applies to 0 to 5 feet bgs and the other set applies to 5 to 10 feet bgs. The screening levels applying to soil at 0 to 5 feet

bgs represent the lowest of the screening levels calculated for the resident, worker, and utility worker. Screening levels for soil from 5 to 10 feet bgs represent the lower value of either a utility trench/construction worker, or, the inhalation of outdoor air pathway for all of the receptors. That is, the full depth of 0 to 10 feet is assumed to contribute to outdoor air concentrations for all scenarios. Therefore, the screening levels for both soil horizons are protective of inhalation of volatile and particulate emissions.

For commercial/industrial receptors it is assumed that commercial workers could contact the soil at depths between ground surface and 5 feet. In the case of a utility trench or construction worker, it was assumed that direct contact (dermal and ingestion) with soils could occur at depths from 0 to 10 feet.

4 DERIVATION OF SCREENING LEVELS

This section describes how the Soil Screening Levels were calculated. Standard equations from the USEPA RSLs were used for everything except the volatilization term. A target risk level of 1×10^{-6} risk for carcinogens and a target hazard index of 1.0 for non-carcinogens were assumed in all cases.

4.1 Equations Used

4.1.1 Exposure Equations

The equations used to develop the Soil Screening Levels are shown in Tables 1 through 3, for each of the three receptors, and the variable definitions are shown in Table 4. Note, the USEPA considers the carcinogenic PAHs to be “mutagens” and as such has unique equations to calculate the screening levels. The mutagenic equations are for “early life exposures” and therefore only apply to the residential scenario.

4.1.2 Volatilization Factor

The volatilization factor (VF) used to predict outdoor air concentrations due to volatilization from the soil is based on the ASTM guidance (1995). The assumptions in the ASTM volatilization factor algorithm (ASTM 1995) are:

- Dispersion in air is modeled from a ground-level source. It is assumed that the air in the outdoor air “box” is well-mixed.
- The receptor is located onsite, directly over the impacted soil, 24 hours/day for the entire exposure duration.
- A long-term average exposure–point concentration is estimated for the entire exposure duration.

The conceptual model for volatile emissions and inhalation of outdoor air is shown in Figure 2. Note the assumed receptor location at the edge of the downwind side of the source (for 24 hours/day for the entire exposure duration for a resident) is the most conservative location that could be used. The dispersion of contaminant in the air, or mixing, is limited to the height of the breathing zone; that is, upward vertical dispersion (i.e., dilution), as the air blows towards the receptor, is not considered by the model. This is one exposure scenario where the situation assumed in the risk calculations would be

impossible to achieve in a real exposure scenario because the algorithm used to estimate the risk from the volatile emissions is very conservative.

The ASTM VF is actually composed of two equations as shown in Table 5: one equation assumes an infinite source, and the other one equation includes a mass balance check to limit the volatilization term so that the amount volatilized cannot exceed the total amount of mass in the soil initially. The VF is calculated using both equations and the lower of the two volatilization rates is used for the VF in the exposure equations. The default input values are shown in Table 6. It is assumed that the length and width of the source are 25 m each (approximately 82 feet by 82 feet). The thickness of impacted soil is assumed to equal 3.05 m (10 feet).

4.1.3 Particulate Emission Factor

A particulate emission factor (PEF) is used to estimate the outdoor air concentrations due to chemicals airborne on particulates (dust). The default value used for the PEF for the residential and commercial/industrial scenarios is 1.3×10^9 [(mg/kg)/(mg/m³)] (DTSC 2011). For the utility trench (construction) worker, a PEF value of 1×10^6 [(mg/kg)/(mg/m³)] was used (DTSC 2011).

4.2 Exposure Parameter Values Used

All of the default exposure parameters for the receptors were obtained from DTSC's "Human Health Risk Assessment (HHRA) Note Number 1" (DTSC 2011). Table 4 shows the default values used for each parameter and provides the reference document where each parameter value was obtained.

4.2.1 Ingestion of Soil

Receptors working or playing outdoors may ingest soil through incidental contact of the mouth with hands and clothing. For the residential and commercial exposure scenarios, one of the very conservative assumptions made is that the chemical concentrations remain constant over time in the soil. In reality, this would not be the case, especially for volatile chemicals in the top few feet of soil, where most of the direct contact would occur. Benzene, ethylbenzene and naphthalene are highly fugitive in surface soil, quickly depleting the upper soil depths.

4.2.2 Dermal Contact with Soil

Some soil contaminants may be absorbed across the skin into the bloodstream. Absorption will depend upon the amount of soil in contact with the skin, the concentration of chemicals in soil, the skin surface area exposed, and the potential for the chemical to be absorbed across the skin. Note, USEPA assumes that benzene, ethylbenzene, and naphthalene will not be on the skin long enough (due to volatilization) to absorb through the skin, therefore dermal uptake for these chemicals is not calculated.

4.2.3 Inhalation of Volatile and Particulate Emissions in Outdoor Air

The inhalation exposure route includes the inhalation of both volatile and particulate emissions. The inhalation slope factors and non-carcinogenic inhalation reference doses are shown in Table 7.

4.3 Chemical Parameter and Toxicity Values Used

The default chemical parameter values came from the RWQCB 2 Environmental Screening Levels (2007). The toxicity values for non-carcinogenic toxicity came from USEPA's On-line Risk Information System (IRIS, 2011). The carcinogenic toxicity values for benzene, ethylbenzene, and naphthalene came from OEHHA's list of cancer potency factors (OEHHA 2009). The carcinogenic oral slope factor for benzo(a)pyrene came from OEHHA's Public Health Goals for Chemicals in Drinking Water for Benzo(a)pyrene (OEHHA 2010).

5 RESULTS: SOIL SCREENING LEVELS

Table 8 (which is included here for convenience) shows the Soil Screening Levels.

Table 8: Soil Screening Levels

Depth (feet)	Benzene (mg/kg)	Ethylbenzene (mg/kg)	Naphthalene (mg/kg)	PAH* (mg/kg)
0 to 5	1.9	21	9.7	0.063
5 to 10	2.8	32	9.7	4.6

*Notes: Based on the seven carcinogenic PAHs as benzo(a)pyrene toxicity equivalent [BaPe]. The PAH screening level is only applicable where soil was affected by either waste oil and/or Bunker C fuel.

Note, the screening levels for naphthalene are the same for the top 5 feet as the 5 to 10 foot depth. This is because naphthalene has carcinogenic toxicity for the inhalation pathway and not for the oral (and dermal pathways). The carcinogenic mode of action was the driver (i.e., the carcinogenic screening levels were less than the non-carcinogenic screening levels) and the inhalation pathway was the limiting pathway for both soil horizons.

Table 9 shows the soil screening levels calculated for each exposure scenario. Note that the lowest screening level was chosen for the two different soil depths to obtain the screening levels in Table 8.

Table 9: Summary of Soil Screening Levels for Each Receptor

Chemical	Residential		Commercial/ Industrial		Utility Worker
	0 to 5 feet bgs mg/kg	Volatilization to outdoor air (5 to 10 feet bgs) mg/kg	0 to 5 feet bgs mg/kg	Volatilization to outdoor air (5 to 10 feet bgs) mg/kg	0 to 10 feet bgs mg/kg
Benzene	1.9	2.8	28	810	180
Ethylbenzene	21	32	250	9,400	1,800
Naphthalene	9.7	9.7	3,100	3,100	2,200
PAH	0.063	190	0.68	160,000	4.6

As can be seen by comparing tables 8 and 9, the volatilization to outdoor air for the residential scenario was the limiting pathway for all of the chemicals except PAH. For PAH, the utility worker screening level (4.6 mg/kg) was the limiting screening level for the 5 to 10 feet below ground surface.

6 DISCUSSION OF RESULTS

This document has presented Soil Screening Levels to be used to identify sites that are low threat to human health risk for the direct contact pathways from impacted soil. These Soil Screening Levels are designed to be used in conjunction with the Vapor Intrusion Criteria and Groundwater Criteria to determine if the site is a low-threat from all exposure pathways.

Three exposure scenarios were considered: residential, commercial/industrial, and a utility trench/construction worker. The final Soil Screening Levels were chosen as the lowest values for each receptor. The equations used were based on the equations used by USEPA in the development of the RSLs, with the exception of the volatilization rate. A volatilization rate term from ASTM was substituted for the RSL volatilization term so that mass balance could be considered in the volatilization term (only).

OEHHA has indicated that the residential exposure scenario is protective for other sensitive uses of a site. This means that these screening levels are also appropriate for other sensitive uses of the property (e.g., day-care centers, hospitals, etc.) (OEHHA 2005).

7 REFERENCES

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TABLES

Table 1: Equations Used to Develop Soil Screening Levels for the Direct Contact Pathways for a Residential Exposure Scenario

(page 1 of 3)

Carcinogenic – Residential
<p>Incidental ingestion of soil,</p> $SL_{\text{res-sol-ca-ing}} = \frac{TR \times AT_{\text{Carc}} \times 365 \text{ d/yr}}{SF_o \times EF_r \times IFS_{\text{adj}} \times 1\text{E}-6 \text{ kg/mg}}$ <p>where</p> $IFS_{\text{adj}} = \left[\frac{ED_c \times IRS_c}{BW_c} + \frac{ED_a \times IRS_a}{BW_a} \right]$ <p>Inhalation of particulates and volatiles,</p> $SL_{\text{res-sol-ca-inh}} = \frac{TR \times AT_{\text{Carc}} \times 365 \text{ d/yr}}{IUR \times \left(\frac{1000 \text{ ug}}{\text{mg}} \right) \times EF_r \times \left(VF_r + \frac{1}{PEF_r} \right) \times (ED_c + ED_a) \times ET_r \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right)}$ <p>Dermal Contact with soil,</p> $SL_{\text{res-sol-ca-der}} = \frac{TR \times AT_{\text{Carc}} \times 365 \text{ d/yr}}{\frac{SF_o}{GIABS} \times EF_r \times DFS_{\text{adj}} \times ABS_d \times 1\text{E}-6 \text{ kg/mg}}$ <p>where</p> $DFS_{\text{adj}} = \left[\frac{ED_c \times SAS_c \times AF_c}{BW_c} + \frac{ED_a \times SAS_a \times AF_a}{BW_a} \right]$ <p>Total</p> $C_{\text{res-sol-ca-tot}} = \frac{1}{\frac{1}{SL_{\text{res-sol-ca-ing}}} + \frac{1}{SL_{\text{res-sol-ca-inh}}} + \frac{1}{SL_{\text{res-sol-ca-der}}}}$

Table 1: Equations Used to Develop Soil Screening Levels for the Direct Contact Pathways for a Residential Exposure Scenario

(page 2 of 3)

Noncarcinogenic (Hazard) – Residential	
Incidental ingestion of soil	$C_{res-sol-nc-ing} = \frac{THQ \times BW_c \times ED_c \times 365 \text{ d/yr}}{EF_r \times ED_c \times \frac{1}{RfD_o} \times IRS_c \times \frac{1E-6 \text{ kg}}{\text{mg}}}$
Inhalation of particulates and volatiles,	$C_{res-sol-nc-inh} = \frac{THQ \times ED_c \times 365 \text{ d/yr}}{EF_r \times ED_c \times ET_r \times \frac{1 \text{ day}}{24 \text{ hours}} \times \frac{1}{RfC} \left(VF_r + \frac{1}{PEF_r} \right)}$
Dermal contact with soil,	$C_{res-sol-nc-der} = \frac{THQ \times BW_c \times ED_c \times 365 \text{ d/yr}}{EF_r \times ED_c \times \left(\frac{1}{RfD_o \times GIABS} \right) \times SAS_c \times AF_c \times ABS_d \times \frac{1E-6 \text{ kg}}{\text{mg}}}$
Total	$C_{res-sol-nc-tot} = \frac{1}{\frac{1}{SL_{res-sol-nc-ing}} + \frac{1}{SL_{res-sol-nc-inh}} + \frac{1}{SL_{res-sol-nc-der}}}$

Table 1: Equations Used to Develop Soil Screening Levels for the Direct Contact Pathways for a Residential Exposure Scenario

(page 3 of 3)

Carcinogenic – Mutagenic	
Incidental ingestion of soil,	
$SL_{res-sol-mu-ing} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{SF_o \times EF_r \times IFSM_{adj} \times 1E-6 \text{ kg/mg}}$	
where	
$IFSM_{adj} = \frac{ED_{0-2} \text{ (years)} \times IRS_c \times 10}{BW_c} + \frac{ED_{2-6} \text{ (years)} \times IRS_c \times 3}{BW_c} + \frac{ED_{6-16} \text{ (years)} \times IRS_a \times 3}{BW_a} + \frac{ED_{16-30} \text{ (years)} \times IRS_a \times 1}{BW_a}$	
Inhalation of particulates and volatiles,	
$SL_{res-sol-mu-inh} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{IUR \times \left(\frac{1000 \text{ ug}}{\text{mg}} \right) \times EF_r \times \left(VF_{s-r} + \frac{1}{PEF_r} \right) \times ET_r \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right) \times \left(\frac{ED_{0-2} \text{ (years)} \times 10 + ED_{2-6} \text{ (years)} \times 3}{ED_{6-16} \text{ (years)} \times 3 + ED_{16-30} \text{ (years)} \times 1} \right)}$	
Dermal Contact with soil,	
$SL_{res-sol-mu-der} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{\frac{SF_o}{GIABS} \times EF_r \times DFSM_{adj} \times ABS_d \times 1E-6 \text{ kg/mg}}$	
where	
$DFSM_{adj} = \left[\frac{ED_{0-2} \text{ (years)} \times SAS_c \times AF_c \times 10}{BW_c} + \frac{ED_{2-6} \text{ (years)} \times SAS_c \times AF_c \times 3}{BW_c} + \frac{ED_{6-16} \text{ (years)} \times SAS_a \times AF_a \times 3}{BW_a} + \frac{ED_{16-30} \text{ (years)} \times SAS_a \times AF_a \times 1}{BW_a} \right]$	
Total	
$C_{res-sol-mu-tot} = \frac{1}{\frac{1}{SL_{res-sol-mu-ing}} + \frac{1}{SL_{res-sol-mu-inh}} + \frac{1}{SL_{res-sol-mu-der}}}$	

Table 2: Equations Used to Develop Soil Screening Levels for the Direct Contact Pathways for a Commercial/Industrial Exposure Scenario

Carcinogenic – Commercial/Industrial (c/i)	
Incidental ingestion of soil,	
$SL_{c/i-sol-ca-ing} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{SF_o \times EF_{c/i} \times ED_{c/i} \times IRS_{c/i} \times 1E-6 \text{ kg/mg}}$	
Inhalation of particulates and volatiles,	
$SL_{c/i-sol-ca-inh} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{IUR \times \left(\frac{1000 \text{ ug}}{\text{mg}} \right) \times EF_{c/i} \times \left(VF_{c/i} + \frac{1}{PEF_{c/i}} \right) \times ED_{c/i} \times ET_{c/i} \times \left(\frac{1 \text{ day}}{24 \text{ hours}} \right)}$	
Dermal Contact with soil,	
$SL_{c/i-sol-ca-der} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{\frac{SF_o}{GIABS} \times EF_{c/i} \times ED_{c/i} \times SAS_{c/i} \times AF_{c/i} \times ABS_d \times 1E-6 \text{ kg/mg}}$	
Total	
$C_{c/i-sol-ca-tot} = \frac{1}{\frac{1}{SL_{c/i-sol-ca-ing}} + \frac{1}{SL_{c/i-sol-ca-inh}} + \frac{1}{SL_{c/i-sol-ca-der}}}$	
Noncarcinogenic – Commercial/Industrial	
Incidental ingestion of soil	
$C_{c/i-sol-nc-ing} = \frac{THQ \times BW_{c/i} \times ED_{c/i} \times 365 \text{ d/yr}}{EF_{c/i} \times ED_{c/i} \times \frac{1}{RfD_o} \times IRS_{c/i} \times \frac{1E-6 \text{ kg}}{\text{mg}}}$	
Inhalation of particulates and volatiles,	
$C_{c/i-sol-nc-inh} = \frac{THQ \times ED_{c/i} \times 365 \text{ d/yr}}{EF_{c/i} \times ED_{c/i} \times ET_{c/i} \times \frac{1 \text{ day}}{24 \text{ hours}} \times \frac{1}{RfC} \times \left(VF_{c/i} + \frac{1}{PEF_{c/i}} \right)}$	
Dermal contact with soil,	
$C_{c/i-sol-nc-der} = \frac{THQ \times BW_{c/i} \times ED_{c/i} \times 365 \text{ d/yr}}{EF_{c/i} \times ED_{c/i} \times \frac{1}{RfD_o \times GIABS} \times SAS_{c/i} \times AF_{c/i} \times ABS_d \times \frac{1E-6 \text{ kg}}{\text{mg}}}$	
Total	
$C_{c/i-sol-nc-tot} = \frac{1}{\frac{1}{SL_{c/i-sol-nc-ing}} + \frac{1}{SL_{c/i-sol-nc-inh}} + \frac{1}{SL_{c/i-sol-nc-der}}}$	

Table 3: Equations Used to Develop Soil Screening Levels for the Direct Contact Pathways for a Utility Trench Worker or Construction Exposure Scenario

Carcinogenic – Utility Trench Worker (ut)	
Incidental ingestion of soil,	
$SL_{ut-sol-ca-ing} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{SF_o \times EF_{ut} \times ED_{ut} \times IRS_{ut} \times 1E-6 \text{ kg/mg}}$	
Inhalation of particulates and volatiles,	
$SL_{ut-sol-ca-inh} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{IUR \times \left(\frac{1000 \text{ ug}}{\text{mg}}\right) \times EF_{ut} \times \left(VF_{ut} + \frac{1}{PEF_{ut}}\right) \times ED_{ut} \times ET_{ut} \times \left(\frac{1 \text{ day}}{24 \text{ hours}}\right)}$	
Dermal Contact with soil,	
$SL_{ut-sol-ca-der} = \frac{TR \times AT_{Carc} \times 365 \text{ d/yr}}{\frac{SF_o}{GIABS} \times EF_{ut} \times ED_{ut} \times SAS_{ut} \times AF_{ut} \times ABS_d \times 1E-6 \text{ kg/mg}}$	
Total	
$C_{ut-sol-ca-tot} = \frac{1}{\frac{1}{SL_{ut-sol-ca-ing}} + \frac{1}{SL_{ut-sol-ca-inh}} + \frac{1}{SL_{ut-sol-ca-der}}}$	
Noncarcinogenic – Utility Trench Worker	
Incidental ingestion of soil	
$C_{ut-sol-nc-ing} = \frac{THQ \times BW_{ut} \times ED_{ut} \times 365 \text{ d/yr}}{EF_{ut} \times ED_{ut} \times \frac{1}{RfD_o} \times IRS_{ut} \times \frac{1E-6 \text{ kg}}{\text{mg}}}$	
Inhalation of particulates and volatiles,	
$C_{ut-sol-nc-inh} = \frac{THQ \times ED_{ut} \times 365 \text{ d/yr}}{EF_{ut} \times ED_{ut} \times ET_{ut} \times \frac{1 \text{ day}}{24 \text{ hours}} \times \frac{1}{RfC} \left(VF_{ut} + \frac{1}{PEF_{ut}}\right)}$	
Dermal contact with soil,	
$C_{ut-sol-nc-der} = \frac{THQ \times BW_{ut} \times ED_{ut} \times 365 \text{ d/yr}}{EF_{ut} \times ED_{ut} \times \left(\frac{1}{RfD_o} \times GIABS\right) \times SAS_{ut} \times AF_{ut} \times ABS_d \times \frac{1E-6 \text{ kg}}{\text{mg}}}$	
Total	
$C_{ut-sol-nc-tot} = \frac{1}{\frac{1}{SL_{ut-sol-nc-ing}} + \frac{1}{SL_{ut-sol-nc-inh}} + \frac{1}{SL_{ut-sol-nc-der}}}$	

Table 4: Default Exposure Parameters (continued)

Parameter	Variable Name	Units	Value	Reference
Averaging time for carcinogens	AT_{carc}	years	70	70 years by definition (USEPA 1989)
Body weight, residential child	BW_c	kg	15	DTSC HERO (2011)
Body weight, residential adult	BW_a	kg	70	DTSC HERO (2011)
Body weight, commercial/industrial	$BW_{c/i}$	kg	70	DTSC HERO (2011)
Body weight, utility worker	BW_{ut}	kg	70	DTSC HERO (2011)
Exposure duration, residential child	ED_c	years	6	DTSC HERO (2011)
Exposure duration, residential adult	ED_a	years	24	DTSC HERO (2011)
Exposure duration, commercial/industrial	$ED_{c/i}$	years	25	DTSC HERO (2011)
Exposure duration, utility worker	ED_{ut}	years	1	DTSC HERO (2011)
Exposure frequency, residential	EF_r	d/year	350	DTSC HERO (2011)
Exposure frequency, commercial/industrial	$EF_{c/i}$	d/year	250	DTSC HERO (2011)
Exposure frequency, utility worker	EF_{ut}	d/year	250	DTSC HERO (2011)
Exposure time for outdoor air, residential	ET_r	hours/day	24	DTSC HERO (2011)
Exposure time for outdoor air, commercial/industrial	$ET_{c/i}$	hours/day	8	DTSC HERO (2011)
Exposure time for outdoor air, utility worker	ET_{ut}	hours/day	8	DTSC HERO (2011)
Soil ingestion rate, residential child	IRS_c	mg/d	200	DTSC HERO (2011)
Soil ingestion rate, residential adult	IRS_a	mg/d	100	DTSC HERO (2011)
Soil ingestion rate, commercial/industrial	$IRS_{c/i}$	mg/d	100	DTSC HERO (2011)
Soil ingestion rate, utility worker	IRS_{ut}	mg/d	330	DTSC HERO (2011)
Soil to skin adherence factor, residential child	AF_c	mg/cm ²	0.2	DTSC HERO (2011)
Soil to skin adherence factor, residential adult	AF_a	mg/cm ²	0.07	DTSC HERO (2011)
Soil to skin adherence factor, commercial/industrial	$AF_{c/i}$	mg/cm ²	0.2	DTSC HERO (2011)
Soil to skin adherence factor, utility worker	AF_{ut}	mg/cm ²	0.8	DTSC HERO (2011)
Skin surface area exposed to soil, residential child	SAS_c	cm ²	2900	DTSC HERO (2011)
Skin surface area exposed to soil, residential adult	SAS_a	cm ²	5700	DTSC HERO (2011)
Skin surface area exposed to soil, commercial/industrial	$SAS_{c/i}$	cm ²	5700	DTSC HERO (2011)
Skin surface area exposed to soil, utility worker	SAS_{ut}	cm ²	5700	DTSC HERO (2011)

Table 4: Default Exposure Parameters (concluded)

Parameter	Variable Name	Units	Value	Reference
Particulate emission factor, residential	PEF_r	m ³ /kg	1.3 x 10 ⁹	DTSC HERO (2011)
Particulate emission factor, commercial/industrial	$PEF_{c/i}$	m ³ /kg	1.3 x 10 ⁹	DTSC HERO (2011)
Particulate emission factor, utility worker	PEF_{ut}	m ³ /kg	1.0 x 10 ⁶	DTSC HERO (2011)
Dermal absorption factor from soils	ABS_d	unitless	See Table 7	
Gastrointestinal absorption factor	$GIABS$	unitless	See Table 7	
Oral cancer slope factor	SF_o	1/(mg/kg-d)	See Table 7	
Inhalation Unit Risk	IUR	1/(ug/m ³)	See Table 7	
Oral reference dose	RfD_o	mg/kg-d	See Table 7	
Inhalation reference dose	RfC	mg/m ³	See Table 7	
Target hazard quotient	THQ	unitless	1	OEHHA (2005)
Target individual excess lifetime cancer risk	TR	unitless	1 x 10 ⁻⁶	OEHHA (2005)

References:

ASTM (1996). American Society for Testing and Materials, Standard Guide to Risk-Based Corrective Action Applied at Petroleum Release Sites, ASTM E1739-95, Philadelphia, PA.

DTSC HERO (2010). Department of Toxic Substances Control, Office of Human and Ecological Risk (HERO). Human Health Risk Assessment (HHRA) Note Number 1. Recommended DTSC Default Exposure Factors for Use in Risk Assessment at California Hazardous Waste Sites and Permitted Facilities. May 20, 2011

OEHHA (2005). Human-Exposure-Based Screening Numbers Developed to Aid Estimation of Cleanup Costs for Contaminated Soil, Integrated Risk Assessment Branch, Office of Environmental Health Hazard Assessment. (Cal/EPA).

USEPA. 1989. Risk Assessment Guide for Superfund (RAGS) Volume I Human Health Evaluation Manual (Part A) EPA/540/1-89/002, Office of Emergency and Remedial Response. December 1989.

Table 5: Equations Used to Estimate Volatilization and Particulate Emission Factors

Volatilization and Particulate Emission Factors

Effective Diffusion Coefficient (D_{eff})

$$D_{eff} = D_{air} \left(\frac{\theta_a^{10/3}}{\theta_T^2} \right) + D_{water} \frac{1}{H} \left(\frac{\theta_w^{10/3}}{\theta_T^2} \right)$$

Volatilization Factor (VF)

Infinite source:

$$VF \left[\frac{\text{ng/m}^3 - \text{air}}{\text{ng/kg} - \text{soil}} \right] = \frac{2 \cdot W \cdot \rho_b}{U_{air} \cdot \delta_{air}} \sqrt{\frac{D_{eff} \cdot H}{\pi(\theta_w + FOC \cdot K_{oc} \cdot \rho_b + H \cdot \theta_a) \tau}} \times 10^3 \frac{\text{cm}^3 \text{kg}}{\text{m}^3 \text{g}}$$

Mass-balance considered:

$$VF \left[\frac{\text{ng/m}^3 - \text{air}}{\text{ng/kg} - \text{soil}} \right] = \frac{W \cdot \rho_b \cdot d}{U_{air} \cdot \delta_{air} \cdot \tau} \times 10^3 \frac{\text{cm}^3 \text{kg}}{\text{m}^3 \text{g}}$$

Calculate VF using both equations, then use the lower of the two values.

VF_r : Use $\tau = \tau_c + \tau_r$

$VF_{c/i}$: Use $\tau = \tau_{c/i}$

VF_{ut} : Use $\tau = \tau_{ut}$

Table 6: Default Volatilization and Soil-Specific Parameters

Parameter	Variable Name	Units	Value	Reference
Fraction organic carbon in soil	FOC	G OC/g soil	0.01	ASTM (1996)
Thickness of impacted soil	d	cm	305	ASTM (1996) (10 feet)
Wind speed in outdoor air mixing zone	U_{air}	cm/s	225	ASTM (1996)
Width of source area parallel to wind, or groundwater flow direction	W	cm	2500	ASTM (1996)
Outdoor air mixing zone height	δ_{air}	cm	200	ASTM (1996)
Volumetric air content in vadose-zone soils	θ_A	(cm ³ air)/(cm ³ soil)	0.26	ASTM (1996)
Total soil porosity	θ_T	(cm ³ voids)/(cm ³ soil)	0.38	ASTM (1996)
Volumetric water content in vadose-zone soils	θ_W	(cm ³ water)/(cm ³ soil)	0.12	ASTM (1996)
Soil bulk density	ρ_b	g/cm ³	1.7	ASTM (1996)
Averaging time for vapor flux, residential adult	τ_r	s	7.57E8	ASTM (1996) = ED _r in sec
Averaging time for vapor flux, residential child	τ_c	s	1.89E8	ASTM (1996) = ED _c in sec
Averaging time for vapor flux, commercial/industrial	$\tau_{c/i}$	s	7.88E8	ASTM (1996) = ED _{c/i} in sec
Averaging time for vapor flux, utility worker	τ_{ut}	s	3.15E7	ASTM (1996) = ED _{ut} in sec
Effective diffusion coefficient in soil	D_{eff}	cm ² /s	Chem. specific	calculated
Diffusion coefficient in air	D_{air}	cm ² /s	Chem. specific	See Table 7.
Diffusion coefficient in water	D_{water}	cm ² /s	Chem. specific	See Table 7.
Organic carbon-water sorption coefficient	K_{oc}	mL/g	Chem. specific	See Table 7.
Henry's Law coefficient	H	(cm ³ water)/(cm ³ air)	Chem. specific	See Table 7.

References:

ASTM. 1996. Standard Guide to Risk-Based Corrective Action Applied at Petroleum Release Sites, ASTM E1739-95, Philadelphia, PA.

Table 7: Chemical Parameter Values

Chemical Parameters	Units	Benzene	Ethylbenzene	Naphthalene	PAH ¹	Reference
Henry's Law constant	-	0.23	0.32	0.02	2.0E-5	SF RWQCB ESLs
Organic carbon partition coefficient	ml/g	58.9	360	1200	5.5E+6	SF RWQCB ESLs
Diffusion coefficient in air	cm ² /s	0.088	0.075	0.059	ND	SF RWQCB ESLs
Diffusion coefficient in water	cm ² /s	9.8E-6	7.8E-6	7.5E-6	ND	SF RWQCB ESLs
Toxicity Parameters						
Oral slope factor (SF _o)	1/(mg/kg-d)	0.1	0.011	ND	1.7	OEHHA (2009, 2010 – BaP PHG)
Inhalation unit risk (IUR)	1/(ug/m ³)	2.9E-5	2.5E-6	3.4E-5	1.1E-3	OEHHA (2009)
Oral reference dose (RfD _o)	mg/kg-d	0.004	0.1	0.020	ND	USEPA IRIS
Reference concentration (RfC)	mg/m ³	30	1000	3	ND	USEPA IRIS
Dermal absorption factor from soil	-	ND	ND	0.13	0.13	SF RWQCB ESLs
Gastrointestinal absorption factor	-	1	1	1	1	SF RWQCB ESLs

ND = No Data

SF RWQCB ESLs. Regional Water Quality Control Board (RWQCB) Region 2 – San Francisco. 2008. Screening for Environmental Concerns at Sites with Contaminated Soil and Groundwater. Interim Final. May

OEHHA (2009). OEHHA Cancer Potency Values as of July 21, 2009.

USEPA IRIS. USEPA Integrated Risk Information System on-line database.

¹ The chemical properties for benzo(a)pyrene were used as a surrogate for the “PAH” group.

Table 8: Soil Screening Levels

Depth (feet)	Benzene (mg/kg)	Ethylbenzene (mg/kg)	Naphthalene (mg/kg)	PAH* (mg/kg)
0 to 5	1.9	21	9.7	0.063
5 to 10	2.8	32	9.7	4.6

*Based on the seven carcinogenic PAHs as benzo(a)pyrene toxicity equivalent [BaPe].

The PAH screening level is only applicable where soil is affected by either waste oil and/or Bunker C fuel.

Table 9: Summary of Soil Screening Levels for Each Receptor

Chemical	Residential		Commercial/ Industrial		Utility Worker
	0 to 5 feet bgs mg/kg	Volatilization to outdoor air (5 to 10 feet bgs) mg/kg	0 to 5 feet bgs mg/kg	Volatilization to outdoor air (5 to 10 feet bgs) mg/kg	0 to 10 feet bgs mg/kg
Benzene	1.9	2.8	28	810	180
Ethylbenzene	21	32	250	9,400	1,800
Naphthalene	9.7	9.7	3,100	3,100	2,200
PAH	0.063	190	0.68	160,000	4.6

FIGURES

Figure 1. Conceptual Site Model for the Soil Screening Levels.

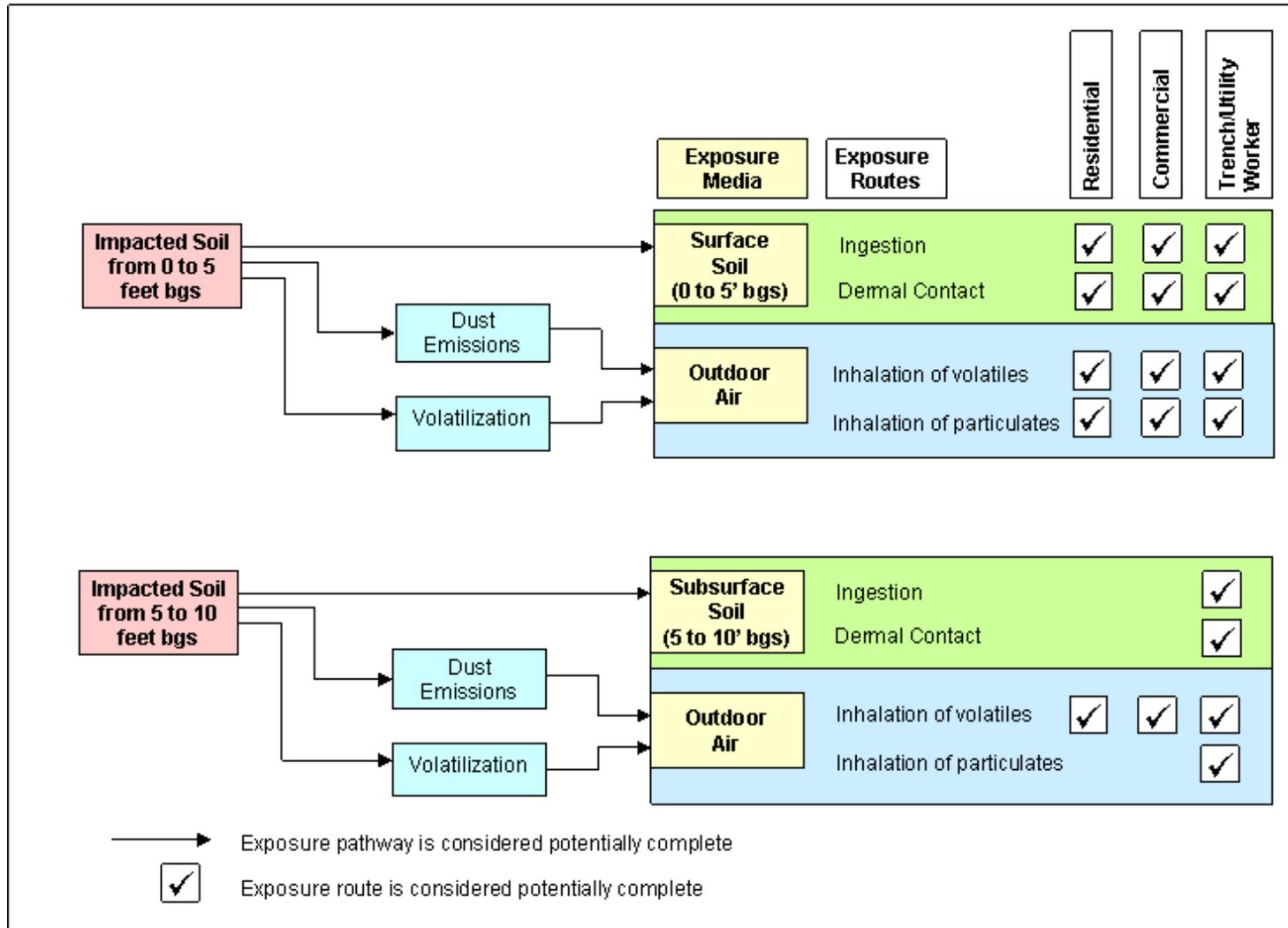


Figure 2. Schematic for the ASTM Volatilization Factor.

