Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds (DRAFT)
External Peer Review Record
May 4-June 15, 2012

CONTENTS:

Peer Review Charge Questions

Draft Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds; April 18, 2012

Peer Review Matrix

James B. Cowart, David J. Folkes, and Dr. Jeffrey P. Kurtz (EnviroGroup Limited)

Review
- Vapor Intrusion at a Diesel LNAPL Site (2005 Poster by James B. Cowart, PE, and Lindsay Breyer, CIH)
- Attenuation Factors for Hydrocarbons Associated With a Diesel Spill (2004 paper by Lindsay Breyer, CIH, and James B. Cowart, PE)

Mr. Cowart:
Curriculum Vitae
Conflict of Interest Form

Mr. Folkes:
Curriculum Vitae
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Dr. Kurtz:
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Todd A. McAlary (Geosyntec Consultants)
Review
• A Case Study on the Influence of Aerobic Biodegradation on Vapor Intrusion at a Former Refinery Property (2010 paper by Todd McAlary, Paul Nicholson, David Bertrand, Hester Groenevelt, and Robert Ettinger)
• Effects of Alternate Petroleum Hydrocarbon Sources in the Vadose Zone on the Vapor Intrusion Pathway beneath a Residential Community (paper by Paul Michalski, Shannon Thompson, Charlie DeWolf, Paul Nicholson, Todd McAlary)
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Dr. Mark A. Widdowson (Virginia Tech)
Review
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Peer Review Charge for:
U.S. Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response (OSWER).

Subject Report and Study:

Background:
EPA’s Office of Underground Storage Tanks (OUST) is developing guidance for addressing vapor intrusion at sites where petroleum has been released from underground storage tank (UST) systems. Vapor intrusion from UST sources is referred to as petroleum vapor intrusion (PVI). OUST’s guidance will assist EPA, states, and tribes address petroleum-contaminated sites where PVI may occur. The guidance will identify criteria that distinguish whether or not potential receptors are at significant risk from PVI. This will eliminate the need for unnecessary indoor air sampling or other sampling and monitoring.

To support its guidance development efforts, OUST contracted with Golder/RTI to prepare the attached report, which describes and analyzes a database of environmental data collected at petroleum release sites. The database includes field data from 70 sites across the United States, Canada, and Australia, which were compiled and provided by other investigators, most notably Robin Davis of the Utah Department of Environmental Quality and Peter Eremita of the Maine Department of Environmental Protection.

To develop and support the separation distances the stated objectives of the RTI/Golder study are to:

- Assemble an empirical database from petroleum release sites where the PVI pathway has been evaluated via primarily soil gas and groundwater measurements,
- Consolidate and independently check database efforts to date and enter and check newly available data,
- Analyze the database and available case studies to determine when and under what conditions there is the potential for a complete PVI pathway at a site,
- Review published modeling studies on PHC vapor transport and intrusion as a supporting line-of-evidence, and
- Identify methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.

Peer Review Charge Questions:
As a peer reviewer, you are being asked to review the Golder/RTI Report and provide opinion and perspective regarding:

- the scientific appropriateness of the database for OUST’s purposes;
- whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST’s purposes; and
- whether the reported conclusions are adequately supported by the data and analyses.
Specific questions to which answers are requested are:

1. Is the report written in a manner that is clear, robust, and transparent for its intended purpose?
2. Does the report meet its stated objectives (listed above) for which it was conducted? If not, please indicate any identified gaps.
3. Are there any additional scientific issues relating to the stated objectives that are not addressed in the report?
4. Are the criteria for data acquisition during the underlying studies (i.e., Davis, Eremita, Peargin and Kolhatkar) and into the assembled database adequately described? Do these criteria ensure that the estimated attenuation in vapor concentrations in the vadose zone at each site:
   - can be reasonably attributed to aerobic biodegradation (versus other explanations); and
   - is an appropriate value for predicting potential indoor air concentrations in nearby buildings?
5. Is the assembled database adequately large and sufficiently representative of subsurface conditions and indoor air concentrations for purposes of reliably determining presumptive criteria for each of the following scenarios:
   - petroleum releases from USTs; and
   - petroleum releases from other sites (e.g., refineries, terminals, transmission pipelines)?
6. Are the statistical methods applied to the data appropriate for the data set and for the comparison being made?
7. Are the findings of the report of adequate scientific integrity to support establishment of a vertical distance between a source of petroleum vapor contamination and an overlying receptor in determining whether an UST site could pose a significant health risk to building occupants? Have all the factors that influence, or potentially influence, biodegradation (e.g., soil moisture, seasonal and climatological effects, preferential transport pathways, type of petroleum fuel, surface cover) been adequately considered?
8. Does the Golder/RTI Report provide a sound basis for applying the proposed vertical separation distances for aromatic and aliphatic petroleum hydrocarbons (e.g., benzene) to other common fuel constituents (e.g., naphthalene) and fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide)?
9. Are you aware of additional references or other resources that could be added to the report, or would be useful in meeting the stated objectives of the report? Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?
10. Do you have any additional comments on the report itself or its intended use that have not been explicitly solicited? Please cite line number(s) in the report pertaining to specific comments.

Additional Information:
If during the course of your review, you require a copy of any of the cited references, please contact Catherine Sims, Environmental Management Support, Inc., either by phone (301-589-5318) or email (Catherine.sims@emsus.com).
Draft Report

Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds

Prepared by
Golder Associates and RTI International

for

U.S. Environmental Protection Agency
Office of Underground Storage Tanks
Washington, DC 20460

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1. Introduction

This study is an evaluation of empirical data and select modeling studies of the behavior of petroleum hydrocarbon (PHC) vapors in subsurface soils and how they can affect subsurface-to-indoor air vapor intrusion (VI), henceforth referred to as petroleum vapor intrusion or “PVI” for short. The purpose of this study is to support the development of a soil vapor screening methodology for PHC compounds for the U.S. Environmental Protection Agency’s Office of Underground Storage Tanks (U.S. EPA OUST); consequently, the focus is primarily on characterizing PVI at Subtitle I underground storage tank (UST) sites with petroleum fuel releases. However, PVI data from other types of sites (fuel terminals, petroleum refineries) are also presented and discussed.

1.1 Background

In support of its general guidance development effort for the VI exposure pathway, U.S. EPA has compiled an empirical database of paired measurements of subsurface media (groundwater, soil gas) and indoor air concentrations, which consists primarily of data for chlorinated solvent chemicals, with very limited data for PHC compounds (approximately 3 percent of the database) (U.S. EPA, 2012a). The study discussed in this document is exclusively directed at PHCs and only analyzes subsurface media (soil gas, soil, and groundwater) concentrations and other supporting data for PHCs. The rationale for this focus on subsurface PHC measurements is that PHC vapors can rapidly biodegrade in the presence of oxygen and attenuate to much lower concentrations in soil gas (U.S. EPA, 2011).

Because the bioattenuation process is well documented and widespread (U.S. EPA, 2011), the analysis of subsurface soil gas data from sites provides an opportunity for developing improved and more realistic screening evaluation methods for PHC compounds based on the observed attenuation. These data can be used to identify “an exclusion distance,” defined in this report as the contamination source-separation distance at which the potential for PVI is deemed negligible. This exclusion distance, and much of the underlying data on which it is based, primarily stems from the work of Robin Davis, a regulator with the Utah Department of Environment’s UST program (see Davis, 2009, 2010, 2011a, and 2011b).

As part of a group of interested parties organized by U.S. EPA OUST to develop guidance and methods specific to PVI, Ms. Davis began to gather soil gas and groundwater data from UST sites across the United States where PVI investigations had been conducted. Through collaboration with the work group and other PVI practitioners, Ms. Davis’ effort led to the “exclusion criteria” concept and an expanded PVI database (Davis, 2009); the May 2011 version of her database was used as the basis for the effort described in this report, although data from other sources were also incorporated into the database used in this report.

In addition, several similar parallel efforts are in progress in this country (Lahvis et al., In prep.; Peargin and Kolhatkar, 2011), and Australia (Wright, 2011, 2012) using somewhat different data sets than the one used in this document. Regarding these complementary database evaluations, the benzene data from sites in the United States and Canada are identical for this
database study and the Lahvis et al. (In prep.) effort. The main differences between Lahvis et al. (In prep.) and this U.S. EPA study are that:

1. The Lahvis et al. (In prep.) study includes data from sites in Wright’s (2011) Australian database, whereas the U.S. EPA database does not\(^1\).

2. The U.S. EPA database includes a more extensive evaluation of a range of chemicals, including aromatic and aliphatic hydrocarbon fractions, whereas the focus of Lahvis et al. (In prep.) is benzene vapor attenuation.

Section 9 of this report compares and contrasts these parallel studies and their results with the results of this study.

1.2 Goals and Objectives

The goal of this study was to provide information on the behavior of PHCs with respect to vapor intrusion that would support establishing an assessment framework and set of criteria for evaluating potential petroleum vapor migration from subsurface to indoor air. The study included three general scenarios:

1. Sites with a relatively high potential for a complete PVI pathway\(^2\) and possible unacceptable risks.

2. Sites with a relatively high potential for an incomplete PVI pathway.

3. Sites with an unknown potential for a complete PVI pathway and risk, thus requiring further assessment.

The main intent of the evaluation was to determine if the vapor migration pathway is complete (or incomplete) to indoor air. Risk in this context is the potential to exceed human health-based concentration criteria in indoor air due to VI.

This report addresses a key part of this framework: the identification and justification of exclusion distances between contamination and receptors that can be used to quickly assess whether the PVI pathway is complete. However, the scope of this study did not include development of the framework and criteria that will be needed to apply these exclusion distances as part of the developing PVI guidance.

To develop and support the exclusion distances, the objectives of this study were to:

- Assemble an empirical database from petroleum release sites where the PVI pathway has been evaluated via primarily soil gas and groundwater measurements;

- Consolidate and independently check existing databases and enter and check newly available data;

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\(^1\) The U.S. EPA database does include one site in Perth, Australia, from Patterson and Davis (2009).

\(^2\) For the purposes of this report, a complete PVI pathway is defined as measureable indoor petroleum hydrocarbon vapor concentrations that come from a subsurface contamination source.
• Analyze the database and available case studies to determine when and under what conditions there is the potential for a complete PVI pathway at a site;
• Review published modeling studies on PHC vapor transport and intrusion as a supporting line-of-evidence; and
• Identify methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.

1.3 Document Organization

This report is organized as follows:
• Section 2 describes the conceptual site model (CSM) for aerobic biodegradation of PHC vapors and select case studies where PVI has been documented.
• Section 3 provides a review of select modeling studies of the biodegradation of PHCs in the subsurface.
• Section 4 provides a review of empirical database studies of PHC vapor attenuation.
• Section 5 provides a review of exclusion distances for PVI in existing state VI guidance.
• Section 6 describes the PVI database development, structure, and content.
• Section 7 describes the PVI database analysis approach and methods.
• Section 8 describes the PVI database analysis results.
• Section 9 provides a discussion of the results and comparisons with other studies.
• Section 10 provides conclusions drawn based on this study.

2. Conceptual Site Model and Select Case Studies

The CSM for PVI described below builds on the CSM described in U.S. EPA (2011), with additional emphasis on the difference in PHC vapor concentrations for light nonaqueous phase liquid (LNAPL) and dissolved groundwater contamination sources. In addition, select case studies indicating a confirmed or likely complete transport pathway for PVI are described.

2.1 Aerobic Biodegradation Processes

Petroleum liquids (e.g., gasoline, diesel) are moderately soluble in water and often form separate phase liquids commonly referred to as LNAPLs when released into the environment. When LNAPL reaches the water table, it tends to accumulate and spread laterally and vertically (as the water table rises and falls) to form a smear zone where residual LNAPL occupies soil pore spaces across the water table. A dissolved hydrocarbon groundwater plume that extends beyond the LNAPL source zone is formed as PHC compounds dissolve from the LNAPL into groundwater.

Volatilization of PHCs will occur from both LNAPL and dissolved (groundwater) hydrocarbon sources. Methane and carbon dioxide gas may be generated through microbial
breakdown of PHC compounds in anaerobic source zones. Fuel oxygenates, such as ethanol and methyl tert-butyl ether (MTBE), can also be present in the vapor phase in the unsaturated zone proximate to LNAPL source zones.

The biodegradation of PHC vapors is relatively rapid when oxygen is present; therefore, aerobic biodegradation can typically limit the concentration and subsurface migration of PHC vapors in unsaturated soils and in groundwater. Modeling studies (Abreu and Johnson, 2006; DeVaull, 2007a; Abreu et al., 2009) and field studies (Ririe et al., 2002; Hers et al., 2000; Roggemans et al., 2001; Fitzpatrick and Fitzgerald, 2002) indicate that the potential for PVI is greatly reduced when aerobic biodegradation processes occur in soils between the hydrocarbon source and receptor (building foundation).

The aerobic biodegradation process between the hydrocarbon source and receptor may be conceptualized with respect to fluxes where the oxygen availability must exceed microbial metabolically driven oxygen demand associated with the hydrocarbon source (Lahvis et al., In prep.). Hydrocarbon biodegradation rates are rapid (e.g., half-lives on the order of hours to days; DeVaull, 2007b, 2011) and typically are much faster than the rate of hydrocarbon transport by diffusion and advection within the unsaturated zone. For this reason, there are typically sharp reaction fronts where the PHC vapor concentrations attenuate by orders of magnitude over short distances (e.g., 1 to 5 ft [0.3 to 1.5 m]) and where there is a corresponding decrease in the oxygen concentrations, as observed in several field studies (Lahvis and Baehr, 1999; Hers et al., 2000; Sanders and Hers, 2006; Davis et al., 2009; Luo et al., 2009). The lower threshold oxygen concentrations required to support aerobic biodegradation of PHC vapors are reported to be in the range of 1 to 4 percent (DeVaull, 2007b).

2.2 Factors Influencing Aerobic Biodegradation

Biodegradation of petroleum hydrocarbons has been reported in more than 70 years of publications (ZoBell, 1946; Atlas, 1981; Leahy and Colwell, 1990), including PHC liquids and gases; straight, branched, and ring-structure PHC compounds with single and multiple carbon bonds; by many microbial species, including 30+ genera of bacteria, 25+ genera of fungi, and several algae (although not every chemical is degraded by every microbial species); in marine, freshwater, sediment, and soils environments; and in direct metabolism and co-metabolism (co-oxidation). Microbial degradation of petroleum produces biomass, intermediate products (alcohols, aldehydes, organic acids), and the ultimate mineralization products carbon dioxide (CO₂) and water (H₂O). In general, relatively fast acclimation times are observed, absent other limits, by population enrichment (fast biomass growth) and/or plasmid transfer. Acclimation times tend to be shorter with prior chemical exposure. Environmental conditions under which petroleum biodegradation has been observed range from 0° to 70°C, salinity up to 25 parts per thousand sodium chloride (NaCl), and pH from 6 to 10, although optimum conditions can be narrower. Aerobic biodegradation is the primary mechanism in the unsaturated zone, but anaerobic biodegradation near source zones may also occur through other electron acceptors present (nitrate, sulfate, etc.) (strict or facilitative), or under fermentative or methanogenic conditions (DeVaull et al., 1997; Madigan et al., 2010). There have been extensive compilations of rates of aerobic degradation specific to vadose zone aerobic soils (e.g., DeVaull et al., 1997; Hers et al., 2000; Ririe et al., 2002; Davis et al., 2009; DeVaull, 2011).
The U.S. Air Force Bioventing Initiative study of 125 sites indicated that environmental factors, such as soil moisture, nutrients, and pH, did not significantly influence biodegradation activity and respiration rates, except for one site located in the Mohave Desert with very dry soils (moisture content of 2 percent), although some biological activity did still occur at this moisture content (Leeson and Hinchee, 1996). Biological activity is limited when the moisture content is at or below the permanent wilting point (Zwick et al., 1995; Holden et al., 1997), which is expected to be rare in most geological and climatic environments (note that the empirical database for this project includes sites in dry areas).

Aerobic biodegradation of PHCs is a robust process that has been demonstrated under a wide range of environmental conditions. Important factors influencing aerobic biodegradation of PHC vapors include the:

- Vapor source hydrocarbon concentration, flux, and composition (including methane);
- Oxygen demand (i.e., the oxygen required to biodegrade the available hydrocarbons and any other organic matter that is present);
- Distance between the vapor source and the building;
- Soil type and properties; and
- Size and characteristics of the building and adjacent land surface.

2.3 Dissolved versus LNAPL Vapor Sources

The PHC vapor source concentration is highly dependent on whether partitioning occurs from compounds present as a dissolved phase in groundwater or directly from LNAPLs present above the capillary fringe. The vapor mass flux from LNAPLs present in the unsaturated zone will be higher than for a dissolved source because for a dissolved source, chemicals must diffuse through water in the capillary zone before reaching continuous gas-filled soil pores, and hydrocarbons may also be attenuated through biodegradation and sorption within the capillary zone. The vapor mass flux for LNAPL source zones will also tend to be sustained for longer periods of time given the larger contaminant mass and lower biodegradation rates compared with dissolved sources. In addition, the vapor composition will be different depending on whether the vapor source is LNAPL or the dissolved phase. For LNAPL sources, there will tend to be a higher proportion of relatively insoluble PHC compounds, including aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), such as naphthalene. For dissolved sources, there will tend to be higher concentrations of the more soluble chemicals, including single-ring aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (Lahvis et al., In prep.).

The differences in the PHC vapor concentrations and fluxes for LNAPL and dissolved vapor sources are an important distinction for defining exclusion distances (Figure 1). Conceptually, the source type (dissolved or LNAPL) will affect the position of the aerobic reaction front in the unsaturated zone relative to the oxygen source. For dissolved sources, the reaction front will be located close to the hydrocarbon source (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009), while for LNAPL sources, the reaction front position is more variable, but typically is located at greater distances from the source compared with dissolved sources (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009).
dissolved vapor sources, case study meta analyses and database evaluations reported in the literature indicate no confirmed cases of PVI for a wide range of site conditions (Davis, 2009; McHugh et al., 2010).

2.4 Conditions for Increased Potential for Petroleum Vapor Intrusion

As described in U.S. EPA (2011), certain site conditions, such as the following, may result in increased potential for PVI:

- **Direct contact between contamination (either dissolved or LNAPL) and a building foundation.** Most documented cases of PVI are for this condition (McHugh et al., 2010).

- **Insufficient separation distance.** For biodegradation to limit the potential for PVI, a sufficiently thick layer of “clean,” oxygenated soil is needed between the building foundation and the contamination (the required thickness will depend on source type). Clean soil is defined as un-impacted by residual LNAPL.

- **Preferential transport pathways.** If a preferential pathway connects a contamination source to a building, the chemical transport can be faster and extend farther than transport through the surrounding soils.

- **Anaerobic (low oxygen) conditions.** Building foundations and adjacent land surfaces with low effective diffusivity and soil-air permeability can reduce oxygen transfer to the subsurface by serving as a surface cap. Natural conditions can also limit oxygen availability, as evidenced by low oxygen concentrations found in the presence of some highly organic soils (e.g., peat) or areas where methane is naturally high. The relative importance of a potential capping effect is not well understood, although significant diffusive oxygen transport through intact concrete can occur, as indicated by measured rates reported in the literature (Branco and de Brito, 2004; Kobayashi and Shuttoh, 1991; Tittarelli, 2009). Advective transport of atmospheric air to the subsurface also can occur through openings (e.g., cracks, drains, sumps) in the building foundation during time periods when the building is positively pressurized. These mechanisms can limit the potential for low oxygen conditions beneath a building.

- **Production of methane gas.** Methane may be produced through microbial breakdown of PHC compounds in anaerobic source zones, and the presence of ethanol in a source zone may increase the generation rate of methane compared with a gasoline LNAPL-only source zone (Nelson et al., 2010; Spalding et al., 2011; Jourabchi et al., 2012). Note that releases of fuel containing 10% ethanol (E10) are most likely included in the reviewed database (this document, see Section 6.3) and in Lahvis et al. (In prep.). Evaluation of methane generation from ethanol fuel blends is an area of active research (Jewell and Wilson, 2011). Methane production can result in soil gas pressures and flow toward receptors and may deplete oxygen that otherwise could be used for biodegradation of the PHC vapors. Elevated methane therefore could increase the potential for PVI at a PHC release site. However, to our knowledge, there are no published data from UST sites where significant source zone advection has
been an issue. Concentrations of methane above the lower explosive limit can present a flammability and explosion risk.

2.5 Case Studies Indicating Confirmed or Likely Complete Transport Pathway for Petroleum Vapor Intrusion

Confirmed occurrences of subsurface vapor intrusion to indoor air or elevated subslab hydrocarbon vapor concentrations at petroleum sites are rare in the literature, but are important to understand for defining the inclusion criteria—that is, sites where PVI is likely to be found and evaluation of PVI is warranted.

Eight case study sites were identified in the literature where PVI was confirmed or likely (Table 1). Five sites were refinery or petrochemical sites, and three were UST sites. Common site conditions involved the following: large fuel releases, extensive LNAPL contamination at the water table, and shallow depth to LNAPL contamination, although at two sites the separation distances between the building and LNAPL source were approximately 25 to 30 ft (7.6 to 9.1 m). Factors that appeared to contribute to PVI at sites with somewhat deeper contamination were a possible capping effect at a former refinery site (unknown location) and heavy rain and/or a sharp water table rise at a site with a very large petroleum fuel release (Hartford, Illinois).

2.5.1 Refinery Site, Perth, Australia (Patterson and Davis, 2009)

Monitoring at a former refinery site near Perth, Australia, with a kerosene LNAPL source below the interior of a building, but much lower hydrocarbon and near-atmospheric oxygen concentrations near the edge and beside the building. The slab-on-grade building footprint area is 2,700 ft² (251 m²) with a 30-ft (9.1-m) wide concrete apron on three sides of the building, and uncovered open ground on one side of the building. The building is underlain by sand with a LNAPL zone across the water table at approximately 10 ft (3.0 m) below ground surface (bgs). The effective diffusion coefficient for chemical transport through concrete was measured at the site and was found to be relatively low compared with published data, indicating the concrete slab was not overly porous. The relatively low diffusivity of the concrete may have reduced oxygen transport to the subsurface under the building. In addition, because of the wide concrete aprons, the effective area of the building with respect to oxygen transport restrictions may be larger than its footprint.

2.5.2 Chatterton Petrochemical Site, Vancouver, B.C., Site (Hers et al., 2000; Hers et al., 2002)

At the former Chatterton petrochemical site near Vancouver, B.C., a building (greenhouse) was constructed above a residual LNAPL source comprising benzene, toluene, and xylene. Monitoring indicated depletion of oxygen (<1 percent) and a complete PVI pathway when the building was continually depressurized (to approximately 10 Pa), but only partial oxygen depletion and no complete pathway under natural (near-neutral) pressure conditions. The slab-on-grade building footprint area was 610 ft² (57 m²), the building was underlain by sand, and the depth to the LNAPL smear zone was 5 ft (1.5 m) below the building foundation slab.
2.5.3 Refinery Site, Casper, Wyoming (Luo et al., 2009)

Monitoring at a site in Casper, Wyoming, indicated a complete PVI pathway at a refinery site with a light distillate (gasoline-range) LNAPL source. LNAPL contamination was present in the unsaturated zone at depths between about 1 and 5 ft (0.3 and 1.5 m) below a small warehouse-type building with a slab-on-grade foundation. Monitoring of subslab soil gas indicated oxygen was depleted (<1 percent) below the interior regions of the building, but not below the edges of the building.

2.5.4 Former Refinery Site (Unknown location) (Luo et al., 2010)

Monitoring at a former refinery site (unknown location) with a building overlying a light distillate (gasoline-range) LNAPL source indicated relatively uniform and elevated (60 to 160 mg/L) PHC vapor concentrations and depleted oxygen beneath and around the building foundation. The building footprint area is 2,100 ft² (195 m²) with a basement depth of 5 ft (1.5 m) bgs. The ground surface is predominantly grass covered, except on one side of the building where there is an asphalt/concrete parking lot. Soils with LNAPLs were first encountered at about 30 to 35 ft (9.1 to 10.7 m) bgs; therefore, the separation distance between the building foundation and contamination (LNAPL) is approximately 25 to 30 ft (7.6 to 9.1 m). Detailed soil respiration and soil-air permeability test results suggest two possible reasons for the observed behavior: 1) significant background oxygen uptake in surface soils and/or 2) physically limited oxygen transport from the atmosphere. Soil oxygen uptake rates in shallow soil ranged from 2 to 25 mg-oxygen/kg-soil/day. There were silt and clay layers between 2 to 5 ft (0.7 to 1.5 m) and 7 to 8 ft (2.1 to 2.4 m) bgs, both with soil-air permeabilities of less than 1 × 10⁻¹⁴ m². The results from Luo et al. (2010) suggest both of these reasons are plausible.

2.5.5 Refinery Site, Hartford, Illinois (Illinois Department of Public Health, 2010)

Monitoring at a refinery site in Hartford, Illinois, with a very large petroleum fuel spill (several million gallons) indicated episodic PVI occurred when there were heavy rain events or a sharp rise in the water table. The vadose zone soils consisted of coarse sand overlain by fine sediments, and the depth to groundwater ranged from 7 to 10 m (23 to 33 ft) bgs.

2.5.6 UST Site, Stafford, New Jersey (Sanders and Hers, 2006)

Monitoring of a house above a residual gasoline LNAPL source at a site with sandy soils indicated PVI of MTBE, 2,2,4-trimethylpentane (TMP), and cyclohexane, but not benzene, toluene, and xylene compounds. The depth to the LNAPL source was 10.75 ft (3.27 m), which was 5.25 ft (1.60 m) below the basement foundation. The source soil vapor concentrations of benzene, 2,2,4-TMP, and MTBE were 0.66 mg/L, 2.1 mg/L, and 5.9 mg/L, respectively. It was inferred that MTBE and 2,2,4-TMP were attenuated to a lesser degree than benzene because of their greater solubility. No PVI was detected at several nearby buildings that were either above the residual LNAPL or dissolved hydrocarbon source.
2.5.7 UST Site, Ogden, Utah, Mini-Mart Release (McHugh et al., 2010)

A large release at a UST site in Ogden, Utah, resulted in free product gasoline floating on shallow groundwater less than 1 m (3.3 ft) below the bottom of the slab. Petroleum odors were reported in a building, which were mitigated by installing a positive pressure HVAC system.

2.5.8 UST Site, Gunnison, Utah, Top Stop Release (McHugh et al., 2010)

A large, sudden gasoline release (20,000 gallons [75,708 L]) occurred at a UST site in Gunnison, Utah. The vadose zone soils consisted of silty sand and gravel overlain by sandy silt, and the depth to groundwater was 4 to 5 m (13 to 16 ft) bgs. The soil headspace photoionization detector (PID) readings in the LNAPL source zone were in the range of 100’s to 1,000’s ppmv. In the first several months after the release occurred, people complained of gasoline odors, and elevated PID readings were reported in several buildings up to 500 m (1,640 ft) from the release site in the direction of groundwater flow.

3. Review of Modeling Studies

Numerous modeling studies of aerobic biodegradation have been conducted to evaluate biodegradation processes, identify factors influencing biodegradation, compare modeled to predicted hydrocarbon vapor attenuation, and estimate first-order biodegradation rates (e.g., Jury et al., 1983; Lahvis and Baehr, 1999; Hers et al., 2000; Ririe et al., 2002; Grathwohl and Maier, 2002; Robinson and Tursczynowisz, 2005; Abreu and Johnson, 2005; Abreu and Johnson, 2006; DeVaull, 2007b; Abreu et al., 2009; Davis et al., 2009; DeVaull, 2011; Hers et al., 2012; U.S. EPA, 2012b).

Modeling studies using representative first-order decay rates indicate that aerobic biodegradation is a rapid, and in some cases, essentially instantaneous process and that attenuation of benzene, toluene, and xylene vapor concentrations occurs over relatively short distances of a few feet, which is consistent with the observed field data (e.g., Hers et al., 2000; Davis et al., 2009). The biodegradation of aliphatic hydrocarbon compounds is less well studied, but available data suggest bioattenuation distances may be greater for aliphatic hydrocarbons compared with aromatic hydrocarbon compounds (Hers et al., 2012). An important input to modeling studies is the first-order decay rate; a comprehensive compilation of such rates is provided in DeVaull (2011).

The modeling studies reviewed below were selected to provide insight on the vertical and lateral attenuation of PHC vapors and, where possible, the influence of factors such as vapor concentration source strength and layered soil deposits on PHC vapor migration and attenuation. This review represents a line of evidence that can help inform the development process for exclusion distances.

3.1 Abreu Three-Dimensional Model Simulations

Abreu and Johnson (2005) present the theoretical basis for a three-dimensional model for predicting soil vapor-to-indoor air attenuation factors incorporating subsurface processes of diffusion, gas-phase advection through building depressurization, oxygen-limited first-order
biodecay, and uniform mixing of vapors entering a building. Subsequent three-dimensional
modeling studies of interest are summarized below.

### 3.1.1 Three-Dimensional Model Simulations—Below-Building Contamination Source and Homogeneous Soil Conditions

Abreu et al. (2009) presents model simulation results for oxygen-limited aerobic
biodegradation for a scenario where building parameters representative of a residential house and an unsaturated zone comprising a homogenous sand unit were assumed. The “hydrocarbon” modeled in this study was assumed to have the same fate and transport properties as benzene. Oxygen-limited decay was simulated in the aerobic portion of the unsaturated zone (i.e., when oxygen concentrations exceeded 1 percent). A first-order decay rate of 0.79 h⁻¹ was assumed for the hydrocarbon (benzene), which is consistent with published rates (e.g., DeVaul, 2011).

Potentially conservative attributes of the Abreu et al. (2009) model simulations include the following: 1) oxygen transport occurs only through cracks in the foundation and not through intact concrete; 2) the building is continuously depressurized; thus, no atmospheric air moves downward into the soil at times when the building is pressurized, for cases where pressure cycling is a relevant condition, and 3) there is no oxygen recharge through pressure effects caused by wind and/or atmospheric pressure changes. Potentially non-conservative attributes of the modeling are primarily that spatially variable soil properties (e.g., moisture, porosity, permeability) were not considered. Conceptually, there are scenarios where layered systems consisting of a fine-grained, wet surface soil layer underlain by a coarser-grained, drier soil layer could increase the potential for oxygen limitations below buildings.

The Abreu et al. (2009) model results are summarized in Figure 2. For context, the database compiled for this study indicates representative total hydrocarbon vapor concentrations between 100 and 200 mg/L above gasoline LNAPL distributed above the capillary fringe, and the approximate lower end of this range likely indicates weathered gasoline sources. For a dissolved vapor source, the database indicates that the maximum total petroleum hydrocarbon (TPH) vapor concentration measured in vapor was 10 mg/L, with >99 percent of the data indicating TPH vapor concentrations less than 1 mg/L.

The model-predicted vapor attenuation factors presented in Figure 2 are highly sensitive to source hydrocarbon concentrations above 10 mg/L. Below 10 mg/L, the attenuation factors are relatively constant for a given separation distance. For a source vapor hydrocarbon concentration representative of weathered gasoline (100 mg/L), the model predictions shown in Figure 3 indicate that a vertical separation distance of 23 ft (7.0 m) or more is required for aerobic reaction front development within the unsaturated zone; however, the model predictions may be conservative, as previously discussed.

Abreu et al. (2009) also present a chart that provides representative attenuation factors that apply to all source hydrocarbon vapor concentrations below 10 mg/L and for a range of biodegradation rates (Figure 4). There are significant reductions in attenuation factors when aerobic biodegradation is included, relative to the non-biodegradation case; for example, for a separation distance of 5 ft (1.5 m), there is an approximate three orders-of-magnitude reduction in the attenuation factor with biodegradation at a first-order decay rate of 0.79 h⁻¹.
3.1.2 Three-Dimensional Model Simulations—Lateral Migration Scenario and Homogeneous Soil Conditions

U.S. EPA (2012b) presents a modeling study of conceptual model scenarios for the VI pathway where the Abreu and Johnson (2005) model was used for a range of simulation scenarios, including oxygen-limited aerobic biodegradation of PHC compound vapors (using benzene as a surrogate for TPH). The building assumptions in U.S. EPA (2012b) are similar to those described in Abreu et al. (2009). One of the scenarios evaluated was the influence of PHC source and building lateral separation distance on the predicted vapor attenuation factor. The simulations were conducted for a TPH vapor concentration of 200 mg/L, a 2-m (6.6 ft) deep basement, two contamination source depths (3 m and 8 m [9.8 ft and 26 ft] bgs), and a range of first-order decay rates (0.018, 0.18, and 1.8 h⁻¹). The predicted vapor attenuation factors decrease rapidly as the lateral distance increases. For example, the vapor attenuation factor for a shallow LNAPL source that is offset approximately 15 ft (4.6 m) from the edge of the building is $1 \times 10^{-6}$ for a decay rate of 0.018 h⁻¹ and less than $1 \times 10^{-10}$ for a decay rate of 0.18 h⁻¹. The vapor attenuation factor for a shallow below-building LNAPL source and same biodecay rate is approximately $1 \times 10^{-3}$. A key point is that there is greater attenuation, and hence lower vapor attenuation factors, for the lateral compared with vertical building-contamination source separation scenarios.

3.1.3 Three-Dimensional Model Simulations—Surface Capping Scenario

U.S. EPA (2012b) also presents aerobic biodegradation modeling simulations of the influence of variable soil moisture and layered soil deposits, including a two-layer capping scenario with a 1-m (3.3-ft) thick surface soil layer with higher moisture content (60 percent saturation) underlain by a soil layer with a lower moisture content (20 percent saturation). The hydrocarbon source for these simulations was located at 8-m (26-ft) depth, below a house with a 2-m (6.6-ft) deep basement. For a high source hydrocarbon vapor concentration (200 mg/L), the attenuation factor predicted for the two-layer scenario was one order of magnitude greater than the single-layer scenario (Table 2). For a lower source vapor concentration (2 mg/L), the vapor attenuation factor for the two-layer scenario was $7.1 \times 10^{-15}$. Although a single-layer simulation was not performed for the lower source strength, the two-layer scenario attenuation factor is very low and indicates essentially complete biodegradation, and the cap had no effect on the hydrocarbon vapor attenuation below the building.

3.1.4 Comparison of Modeled to Measured Soil Vapor Concentration Data

The three-dimensional model predictions of vertical profiles of hydrocarbon vapor and oxygen concentrations showed good agreement between measured and modeled data for three sites evaluated by Abreu and Johnson (2006). The estimated first-order biodegradation rate for these studies ranged between 0.18 and 0.4 h⁻¹. The three-dimensional model was also applied to compare measured and modeled hydrocarbon vapor concentrations for the former refinery site (unknown location), described in Section 2 of this report (Luo et al., 2010). A good comparison was obtained when the model incorporated site-specific conditions (a surface soil layer of low diffusivity and low soil-air permeability), but when generic (homogeneous) soil conditions were assumed, the model was not conservative and under-predicted the measured concentrations by a
factor of approximately 100. The first-order rate incorporated in the Luo et al. (2010) model
simulations was 0.18 h\(^{-1}\).

3.2 DeVaull (2007b) Study (BioVapor Model Development)

DeVaull (2007b) presents the theory and model simulation results for a subsurface soil
vapor-to-indoor air chemical PVI model that includes oxygen-limited biodegradation (the model
described is the basis for the BioVapor model [American Petroleum Institute (API), 2012]). The
processes simulated by the algebraic model are one-dimensional upward diffusion and aerobic
biodegradation of chemicals in a homogeneous subsurface soil layer and mixing of vapors within
a building enclosure. The soil is divided into a shallow aerobic layer where first-order decay is
assumed to occur and a deeper anaerobic layer in which biodegradation does not occur because
of oxygen limitations. The boundary between the aerobic and anaerobic zones is determined
iteratively to match oxygen demand to oxygen supply.

The model results indicate that vapor intrusion of PHCs can be significantly less than
indicated by estimates that neglect biodegradation. A model sensitivity analysis using specified
ranges of scenario parameters showed a high degree of sensitivity to oxygen availability, soil
properties, and biodegradation rates. The attenuation factor varied by more than nine orders of
magnitude about a specified attenuation factor of \(1 \times 10^{-8}\); however, the corresponding variation
in contamination source to foundation separation distance was within only a factor of
approximately three. A conclusion drawn by Devaull (2007b) is that identifying a distance where
PVI is unlikely to occur is a more robust screening tool than an attenuation factor for PHC
compounds.

Favorable comparison of the one-dimensional model to the three-dimensional results of
Abreu and Johnson (2005) is shown in DeVaull (2007b). With matched model parameters, both
models show similar estimates of indoor-to-subsurface source vapor concentrations and similar
sensitivities of both attenuation factor and exclusion distance to changes in model parameters.

3.3 DeVaull (2010) Study of BioVapor Application

DeVaull (2010) presents BioVapor model simulations where the sensitivity of the model
predictions was evaluated for a residential house scenario, dissolved gasoline source
concentrations, and a hydrocarbon vapor source–building separation distance of 5 ft (1.5 m). The
model simulations, in part, were designed to provide insight on the applicability of the dissolved-
source exclusion distance of 5 ft (1.5 m) proposed by Davis et al. (2009). The source
groundwater concentrations were 1 mg/L benzene and 3 mg/L each for toluene, ethylbenzene,
and xylenes, for a total benzene, toluene, and xylene source concentration of 10 mg/L. The
source vapor concentrations were estimated from the Henry’s Law constant and a groundwater-
to-source vapor attenuation factor of 0.1, resulting in source benzene and total benzene, toluene,
and xylene vapor concentrations of 12 mg/m\(^3\) and 120 mg/m\(^3\), respectively. The oxygen mass
transfer to below the building, a key model input parameter for the BioVapor model, was
estimated from 13 studies where the soil gas advection rate and/or diffusive oxygen mass transfer
rate were measured for small buildings.
Devaull (2010) presents model-predicted indoor air concentrations as a function of the effective foundation airflow rate, which is conceptually easier to understand than the oxygen mass transfer rate (Figure 5). For modeling purposes, the foundation airflow rate is converted to an oxygen mass transfer rate. The model predicts low indoor air benzene concentrations (less than 1 μg/m³) for the range of effective foundation airflow rates considered. It is also instructive to note that the model results for recalcitrant non-degrading chemicals show an opposite trend in that the indoor air benzene concentration increases as the effective foundation airflow rate increases.

3.4 Summary of Modeling Studies

The results of the modeling studies cannot be directly correlated to distances (or exclusion distances) where PVI is unlikely to occur, but for dissolved vapor sources they indicate very low attenuation factors and negligible potential for a complete PVI pathway, including a modeling scenario where a surface capping effect was simulated.

For LNAPL vapor sources, the Abreu et al. (2009) three-dimensional model simulations for a residential house scenario and homogeneous soil conditions predict that a vertical separation distance of 23 ft (7.0 m) or more is required for aerobic reaction front development within the unsaturated zone. The modeling results for smaller separation distances and an LNAPL source indicated the attenuation factor calculated by the model is sensitive to a surface capping effect.

The modeling results indicate further evaluation of factors potentially influencing oxygen supply and demand, such as source vapor concentration strength, building size, surface foundation and soil layer properties, and natural soil oxygen demand, is warranted for the LNAPL source scenario.


Three published studies that analyze empirical data on PHC vapor attenuation are summarized below.

Davis (2009) obtained soil gas data from 53 geographical locations in the United States and Canada and from an analysis of 259 benzene and 210 TPH samples and then estimated that 5 ft and 30 ft (1.5 m and 9.1 m) of vertical thicknesses of clean soil are required to significantly attenuate benzene and TPH vapors emanating from the dissolved-phase and LNAPL sources, respectively. Dissolved-phase sites were defined on the basis of benzene concentrations in groundwater < 1,000 μg/L. The data obtained by Davis (2009) are incorporated in this study.

Peargin and Kolhatkar (2011) evaluated 218 pairs of benzene soil vapor and groundwater concentration data from 25 sites. Data were categorized in bins based on 10^{-2} to 10^{-6} excess cancer risk and assuming a soil vapor-to-indoor air attenuation factor of 0.01 (U.S. EPA, 2002). No benzene soil gas concentrations exceeding 300 μg/m³ (risk-based air concentration for 10^{-5} cancer risk multiplied by 0.01) were observed at vertical separation distances greater than 15 ft (4.6 m). Benzene soil vapor concentrations exceeding 300 μg/m³ were only observed above
groundwater sources where benzene concentrations exceeded 1,000 μg/L. The authors concluded that the data support a CSM where benzene vapor transport at concentrations exceeding target screening values can only occur where groundwater source concentrations are high, defined for this study as a dissolved benzene concentration greater than 1,000 μg/L. Some of the data analyzed by Peargin and Kolhatkar (2011) that were provided to Davis (2009) are incorporated in this study. The remaining Peargin and Kolhatkar (2011) data were not readily accessible during the time frame of this study.

Wright (2011) presents data from 124 sites in Australia. There are 1,080 pairs of benzene soil vapor and groundwater concentration data; 41 percent of the data were obtained at sites with fractured rock aquifer systems and 12 percent represent data obtained below building foundations (i.e., subslab). The analysis resulted in vertical exclusion distances of 5 to 10 ft (1.5 to 3.0 m) for relatively “low-strength” dissolved-phase sources (benzene < 1 mg/L and TPH < 10 mg/L), and ~30 ft (~10 m) for LNAPL and poorly characterized dissolved-phase sources (including sites with large building slabs). The lower threshold benzene and TPH soil vapor concentration for estimating the exclusion distances was based on 5 percent of the lowest Australian Health Screening Levels (Friebel and Nadebaum, 2011). None of the Australian data analyzed by Peargin and Kolhatkar (2011) that were provided to Davis (2009) are incorporated in this study but are analyzed by Lahvis et al. (In prep). A preliminary analysis of the Australian data suggested that the conclusions of the empirical analysis would not change if the Australian data were included; therefore, the data were not incorporated into this study.

5. Review of Exclusion Distances in Existing Vapor Intrusion Guidance

Most regulatory approaches identify distances for determining when a PVI assessment is not warranted—defined as “exclusion distances” in this report, although guidance on vertical and lateral exclusion distances for PHCs based on detailed evaluations of empirical data and/or modeling studies is a recent development.

Most states exclude sites from the need for VI assessments if they are more than a specified distance from the source of vapor contamination, which generally is the 100-ft (30-m) lateral distance, although guidance for New Hampshire, New Jersey, Connecticut, and Massachusetts includes a 15- to 30-ft (4.6- to 9.1-m) exclusion distance for aerobically biodegradable chemicals.3 The technical justification for the exclusion distance criteria is relatively limited or not provided in guidance by these jurisdictions.

Several states are in the process of developing or have recently developed guidance for PHCs based on a pathway exclusion distance approach; guidance from New Jersey, California, and Wisconsin is summarized below. Specifically:

- The New Jersey Department of Environmental Protection (NJ DEP, 2012) recommends a PVI investigation based on a 30-ft (9.1-m) critical distance criterion for PHC-related groundwater contamination and a 100-ft (30-m) criterion for PHC-

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3 The U.S. EPA’s 2002 Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils specified vertical and lateral exclusion distances of 100 ft (30 m), based on empirical observations of the approximate distance from the interpolated edge of chlorinated solvent plumes where indoor vapor detections were observed; this guidance did not address vapor intrusion from petroleum releases.
related free product contamination. As an alternative approach, NJ DEP (2012) allows for an exclusion distance approach based on benzene concentrations for gasoline contamination. A PVI investigation is not necessary if the vertical separation distance between the water table (all references to water table are for seasonal high conditions) and building slab is:

- At least 10 ft (3.0 m), for a benzene groundwater concentration $\leq 1,000 \, \mu g/L$;
- At least 5 ft (1.5 m), for a benzene groundwater concentration $\leq 100 \, \mu g/L$; or
- At least 5 ft (1.5 m), for oxygen $\geq 2$ percent (v/v) in the unsaturated zone, and a benzene groundwater concentration $\leq 1,000 \, \mu g/L$.

The gasoline exclusion criteria apply only when all of the following four conditions exist: 1) the building is relatively small, 2) the area around the building is not extensively paved, 3) clean soil exists between the water table and the building, and 4) NAPL is not present within 30 ft (9.1 m) of the building (vertically and horizontally) (see NJ DEP [2012] for additional details).

- The California EPA (2011) presents an exclusion distance approach to managing retail petroleum sites, characterized as a “low-threat” closure scenario. The exclusion distances were based on a review of empirical data (primarily Lahvis [2011] and Davis [2009]) and modeling studies (primarily Abreu et al. [2009]). Four scenarios are defined each with benzene exclusion distance criteria as follows:

  - **Scenario 1—Unweathered LNAPL on groundwater:**
    - A 30-ft (9.1-m) vertical bioattenuation zone between an unweathered LNAPL (residual or free-phase) source and a building foundation.

  - **Scenario 2—Unweathered LNAPL in soil:**
    - A 30-ft (9.1 m) lateral and vertical separation distance between an unweathered LNAPL (residual or free-phase) source in soil and a building foundation.

  - **Scenario 3—Dissolved phase benzene concentrations in groundwater:**
    - With no oxygen measurements:
– A 5-ft (1.5 m) vertical separation distance between a dissolved-phase benzene source < 100 μg/L and a building foundation.

– A 10-ft (3.0 m) vertical exclusion distance for a dissolved-phase benzene source < 1,000 μg/L and a building foundation.

  • With oxygen > 4 percent:

– A 5-ft (1.5 m) vertical separation distance between a dissolved-phase benzene source < 1,000 μg/L and a building foundation.

– Scenario 4—Direct measurement of soil gas concentrations:

  • Application of a bioattenuation (additional attenuation) factor of 1,000 times to risk-based soil gas criteria (i.e., vapor sources) located within 5 ft (1.5 m) of a building foundation.

Wisconsin’s Department of Natural Resources (2010) in their guidance states that where no petroleum odors are detected, PVI can be ruled out at most petroleum release sites with low source concentrations where there is 5 ft (1.5 m) in the horizontal and vertical direction of clean, unsaturated soil with an oxygen content greater than or equal to 5 percent between the residual petroleum and the building. Larger exclusion distances are specified when free product is present (30 ft [9.1 m]) or benzene concentrations in groundwater exceed 1 mg/L (20 ft [6.1 m]). When the above distance thresholds and other criteria (e.g., no preferential pathways, no fractured bedrock) are met, a PVI assessment is not required.

6. Database Development, Structure, and Content

6.1 Database Development and Checking

The starting point for the PVI database developed for this study is a database compiled by Ms. Robin Davis of the State of Utah (the “Davis” database). Ms. Davis compiled data on PHC vapor behavior from over 50 sites starting in 2003; the May 2011 version of the Davis database
was imported and used for this analysis. The Davis database includes information on primarily groundwater and soil vapor chemistry, soil properties, and other site data.

The Davis database was imported into Microsoft Access and then exported into a working Microsoft Excel spreadsheet to enable data checking, addition, and analysis. The original Davis database was expanded by adding new data fields to describe the data types needed to meet the objectives of this study. The data were checked against the original data (e.g., reports, journal articles) when available, and all available references are included as electronic files linked to the database. Additional data were also added to the database, such as the comprehensive data on 11 Maine sites made available from Peter Eremita of the Maine Department of Environmental Protection (Maine DEP).

Once the checks and additions were complete, the Excel spreadsheets were re-imported into the Access database and checked and cleaned for consistency and accuracy of import using queries and manual checks. The final Access database is available as an attachment to this report, along with spreadsheet outputs of the basic data used in the data analysis.

### 6.2 Database Structure

The tables and fields in the PVI database and a comprehensive data dictionary and entity relations diagrams are provided in Appendices A and B, respectively. An Excel spreadsheet was designed to facilitate evaluation, analysis, and presentation of data relations in the PVI database and was used to perform the analyses described in this report. Filters were added for most data fields, enabling screening of data based on site conditions and other applicable attributes.

The different data types are summarized as follows:

- **Background data**: Site location, geologic setting, contamination type, and generic soil description.
- **Facility type**: UST, fuel terminal, petroleum refinery, and petrochemical plant.
- **Site conditions**: Soil type, water-filled and total porosity, and surface cover at soil vapor probe (bare ground, asphaltic pavement, building).
- **Sampling data**: For each probe, vertical depth from ground surface to water table, to top of contamination, and to media sampling locations. Lateral distance between soil gas probe and groundwater monitoring well and between soil gas probe and UST facility infrastructure (e.g., tanks, fuel dispensers) and buildings.
- **Analytical data**: Sampling date, analytical method, quality control data, and chemistry data for soil, groundwater, and soil vapor. Analytes in the database are fixed gases (oxygen, carbon dioxide, methane); benzene, toluene, and xylene; TPH; naphthalene; MTBE; 1,3-butadiene; hexane; heptane; and aromatic and hydrocarbon fractions according to methods prescribed by the State of Massachusetts.
- **Building data**: Building use (e.g., residential, commercial, institutional), foundation type, and building size, for example.
As part of the data verification process, certain data quality indicators were reviewed to ensure data of known and acceptable quality. The database was processed to remove data of unacceptably quality or type, as follows: 1) analytical data obtained by unacceptable methods, or no reported methodology or evidence of quality assurance/quality control processes, to remove suspect quality data; 2) soil gas data from fractured rock systems due to the potential for preferential soil gas flow; 3) benzene concentrations in groundwater below detection level because it is not meaningful to conduct an analysis when no contamination source exists, and 4) lateral spacing between groundwater monitoring well and soil gas probe (for paired data) greater than about 30 ft (9.1 m) because of variability in sources (this information was not available for all data).

The following analytical methods for hydrocarbon compounds were considered acceptable: EPA Method TO-15, EPA Method TO-3, Modified EPA 8260, and Massachusetts Air Phase Hydrocarbons. The following analytical methods for fixed gases were considered acceptable: ASTM D1946 and EPA Method 3C. Note that because Ms. Davis performed these checks for the data imported from the Davis database, these checks were not repeated for this analysis, but some spot-checks were made.

As part of the database development process, it was considered whether data should be screened out based on the presence/absence of probe leak tracer test results. Given that a significant proportion of the data are older data for which no leak tracer was conducted, or leak tracer testing was not reported, this criterion was not adopted for data screening; however, it should be noted that much of the recent data include leak tracer test data.

6.3 Database Content

The number of sites and site locations in the PVI database are listed in Table 3. The contents of the database for key fields are summarized in Tables 4 and 5. The majority of the sites are UST release sites, although the database also includes data from fuel terminals and petroleum refineries. Most sites were affected by gasoline releases, although a small number of sites have other types of PHC contamination (e.g., diesel, kerosene). The gasoline composition was unknown and assumed to be variable with respect to fuel oxygenate composition, given the relatively broad time span for data collection (1995 to 2011). Gasoline containing ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large increase in use in 2006 (U.S. EPA, 2009), so some sites in the database where recent releases occurred likely have gasoline containing ethanol.

Subslab vapor samples were obtained at 38 sites with buildings. Almost all buildings in the database were residential houses or smaller commercial buildings (Table 3 includes the building footprint area when available). At a few sites, soil vapor samples were obtained from below and beside a building.

The database is populated to varying degrees depending on the data type. It contains data for most sites and records on facility type, vertical distances, surface cover, soil type, and benzene and TPH vapor concentrations. Groundwater benzene and TPH concentration data are also available for many sites, and the database also includes data on fixed gases for a majority of the sites. For the other analytes listed above (e.g., toluene, ethylbenzene, xylenes, naphthalene),
the database includes data for fewer sites, although the data set for aromatic and aliphatic hydrocarbons is substantial because recent data from 11 Maine sites are included. Although indoor air data are included for a limited number of sites, indoor air data were not used in the analysis because of the limited number of data points and the known effect of background in introducing bias in soil vapor-to-indoor air attenuation factors for PHC compounds.

Key statistics on the quantity of records in the database are:

- Number of benzene soil vapor records = 879
- Number of oxygen soil vapor records = 645
- Number of records with paired benzene soil vapor and groundwater data = 823

Additional information on each site in the database is provided in Tables 4 and 5 and in the database itself. Many of the original sources of the data in the database (e.g., reports, journal articles, figures, data tables) are referenced and linked in the database to a full set of electronic document files organized by site.

7. Database Analysis Approach and Methods

The data analysis began with an evaluation of whether the soil gas data at the site were obtained in an area of LNAPL or dissolved-phase groundwater contamination. Given the importance of the contamination source type on soil vapor concentrations, the analyses were conducted separately for the LNAPL and dissolved sources. The data analysis consisted of three main parts:

1. Exploratory data plots, discussed in Section 7.1.1;
2. Estimation of vapor concentration attenuation distance using the “vertical distance method,” discussed in Section 7.1.2 developed for this analysis; and
3. Estimation of non-contaminated vertical soil thickness needed for concentration attenuation using the “clean soil method,” discussed in Section 7.1.3, developed by Davis for her database.

The source zone identification and three data analysis methods are described below.

7.1 Source Zone Identification Methods (LNAPL versus Dissolved Indicators)

Several indicators were adopted for identifying whether the soil gas probe was located in an area of LNAPL or dissolved-phase contamination (Table 6).

The primary indicator is direct evidence of LNAPL, such as a sheen or product in a nearby monitoring well, borehole logs indicating a sheen or significant hydrocarbon staining in soil, or when the author of the site investigation report indicated the soil gas probe was installed in an LNAPL source zone. This was the determining factor for approximately 80 percent of the sites identified as having LNAPL contamination.
Indirect or secondary indicators are as follows:

- **Groundwater Concentration Data:** Benzene and/or TPH groundwater concentration data from which the presence of LNAPL near the soil gas probe was inferred. This was the determining indicator for approximately 13 percent of the sites.

- **Soil Concentration Data:** Benzene and/or TPH soil concentration data from which the presence of LNAPL near the soil gas probe was inferred. This was the determining indicator for approximately 2 percent of the sites (one site).

- **Proximity to Fuel Storage/Dispensing Facilities:** Soil gas probes installed within 20 ft (6.1 m) of the tank field or dispenser. This was the determining indicator for approximately 5 percent of the sites.

For sites with limited site investigation data, the secondary indicators were important to enable appropriate classification of the sites with respect to LNAPL versus dissolved sources. However, a sensitivity analysis showed that the exclusion distances were not sensitive to the benzene and TPH groundwater concentration thresholds because direct indicators were the determining factor for a large percentage (80 percent) of the site data (see Section 8.2).

### 7.1.1 Groundwater Concentration Data

Concentrations of chemicals that approach their effective solubility are indirect evidence for LNAPL. For example, Bruce et al. (1991) suggest groundwater concentrations greater than the effective solubility multiplied by 0.2 as possible evidence for LNAPL. For gasoline when a benzene mole fraction of 0.01 was assumed, the threshold was 3 mg/L, assuming a ratio of 0.2. Given the uncertainty in these estimates, a slightly higher threshold for the benzene groundwater concentration equal to 5 mg/L was adopted for identification of LNAPL sites. A TPH threshold groundwater concentration of 30 mg/L was adopted based on the calculated approximate average ratio of benzene to TPH groundwater concentrations in the database. An LNAPL source site was identified on the basis of either the benzene or TPH groundwater concentration exceeding the threshold.

The concentration indicators adopted for evaluating the database are considered reasonable for identifying dissolved versus LNAPL sites for the purposes of this study. For guidance development or other purposes, it may be appropriate to establish slightly different (likely lower) thresholds depending on the objectives of the data evaluation.

### 7.1.2 Soil Concentration Data

Concentrations of chemicals in soil that approach an estimated LNAPL saturation concentration are indirect evidence for LNAPL. The soil saturation concentration is highly dependent on chemical and soil properties. Concentrations representative of possible LNAPLs suggested in the literature include a TPH gasoline range concentration (gasoline range organics or GRO) greater than 100 to 200 mg/kg and a TPH diesel range organics (DRO) concentration greater than 10 to 50 mg/kg (e.g., ASTM, 2006; Alaska Department of Environmental Conservation, 2011).
The thresholds adopted for identifying LNAPL sites are a benzene soil concentration of 10 mg/kg and a TPH (gasoline) soil concentration of 250 mg/kg. The benzene concentration (10.7 mg/kg rounded down to 10 mg/kg) was estimated from the equation for soil saturation ("C_sat") and the default input parameters in Exhibit 9 of the U.S. EPA Soil Screening Guidance (U.S. EPA, 1996). A TPH soil concentration of 250 mg/kg was adopted to provide for a slightly more conservative screening basis (i.e., more sites are included as dissolved sites with higher thresholds) than the ranges reported in the literature cited above. An LNAPL source site was identified on the basis of either the benzene or TPH soil concentration exceeding the threshold.

7.1.3 Proximity to Fuel Storage/Dispensing Facilities

Soil gas probes located near or within former UST fields or fuel dispenser areas are considered to have a higher probability of being within LNAPL zones, and, therefore, were categorized as within LNAPL source zones. A threshold distance of 20 ft (6.1 m) was selected to approximately correspond to the exclusion criteria distance that was estimated for LNAPL sites, as described in Section 8 of this report (i.e., a screening distance greater than the exclusion distance would not be appropriate).

For soil gas probes located near USTs or dispensers there is also greater potential for soil contamination within the vadose zone, which confounds the estimation of clean soil thicknesses for exclusion distances. When available, borehole logs and other information were reviewed to determine the depth to contamination to improve the accuracy of the estimation process. Fifteen sites included data for soil gas probes that were within 20 ft (6.1 m) of USTs or dispensers. A data flag identifying such probes was included so these data could be filtered, if desired.

7.2 Data Analysis Methods

The data analysis consisted of three main parts:

1. Exploratory data analyses to evaluate data trends and relations between different media (e.g., groundwater versus soil gas) and analytes (e.g., hydrocarbon versus oxygen),

2. Plots of benzene and other hydrocarbon soil vapor concentrations versus the vertical separation distance of the vapor probe above the contamination source ("vertical distance method"), and

3. Estimated thickness of un-impacted soil for benzene vapors to attenuate to below a threshold ("clean soil method"). This technique required establishing rules for data interpolation.

The analysis focused on benzene given its importance for risk evaluations; however, it was also performed for select other compounds, including those analyzed at the Maine sites where full-spectrum hydrocarbon analyses are available (e.g., hexane, aliphatic and aromatic fractions).
Given that the database was set up to allow for filtering, the influence of site type (UST, fuel terminal, petroleum refinery), soil properties, presence or absence of buildings, and other factors was evaluated.

### 7.2.1 Exploratory Data Analysis

The exploratory data analysis involved evaluating the relations between groundwater and soil vapor concentrations, and oxygen and hydrocarbon concentrations to assess whether there were thresholds for minimum concentrations where aerobic biodegradation readily occurs (Davis et al., 2009; Sweeney, 2012). The rationale for this analysis is described in Section 8.1.

### 7.2.2 Vertical Distance Method

The vertical distance method involved plotting soil vapor concentration versus distance above a source and estimating either statistically the soil vapor concentrations or the probability for the soil vapor concentration to be less than a concentration threshold for variable distances above the contamination source. The conditional probabilities were estimated as follows:

\[
P (C_v \leq C_{\text{threshold}} / z > d, \text{Contamination (z = 0)} = \text{LNAPL or dissolved})
\]

where \( C_v \) is the soil vapor concentration, \( C_{\text{threshold}} \) is the soil vapor concentration threshold, \( z \) is the vertical direction, \( d \) is the vertical distance from the top of the contamination to the soil gas probe, and source contamination is characterized as either an LNAPL or dissolved source.

The data were sorted in a cumulative distribution of specified vertical separation distances from the source (e.g., \( \geq 0, \geq 2, \ldots, \geq n \) ft). The conditional probabilities were calculated for two different benzene vapor concentration thresholds (50 or 100 \( \mu \)g/m\(^3\) for benzene) using two different methods:

1. Probability \( P = N [C_v < C_{\text{threshold}}]/N [\text{total}] \) where \( N [C_v < C_{\text{threshold}}] \) is the number of benzene vapor concentrations less than the threshold and \( N [\text{total}] \) is the total number of concentration measurements; for this analysis, concentrations below the reporting limits were replaced with half the reporting limit, a common first approximation for non-detect measurements.

2. Probability was estimated from the concentration distribution calculated by the non-parametric Kaplan-Meier method (Kaplan and Meier, 1958).

Approximately 31 percent and 57 percent of benzene soil vapor concentrations associated with LNAPL and dissolved-phase sources, respectively, were non-detects, i.e., below specified reporting limits. The Kaplan-Meier method is a robust, non-parametric method for considering data below reporting limits, particularly when there are multiple reporting limits (Helsel, 2005; 2006).

The next step was to estimate the depth to contamination, which is important for an accurate estimation of the thickness of un-impacted soil needed for attenuation of soil vapor concentrations. For LNAPL sites, this depth was estimated from boring logs and indications of LNAPL zones (e.g., observations of product, high headspace organic vapor concentrations above
500 to 1,000 parts per million [ppm], and soil chemistry data); in the absence of data, the depth to contamination was assumed to be the seasonal high water table. For dissolved sites, the depth to contamination was the depth to the water table closest to the time the soil gas data were obtained.

7.2.3 Clean Soil (Davis) Method

The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of unimpacted clean soil required for soil vapor benzene concentrations to attenuate to below a defined threshold, which for this analysis is 100 μg/m³. The purpose of conducting this analysis was to enable comparison to published exclusion distances based on this method previously reported by Davis (2009; 2010). A clean soil thickness was calculated except when the vertical distance between soil gas probes was greater than 10 ft (3.0 m), because there is insufficient resolution (i.e., spacing between probes) for meaningful estimation of the thickness when the vertical distance between probes is greater than about 10 ft (3.0 m). Two methods were used to estimate the clean soil thickness:

- Method A: Distance to first soil gas probe with benzene $C_{\text{vapor}} < 100 \mu g/m^3$ where:
  - Lower depth = $D_l = $ Depth to top of contamination
  - Upper depth = $D_u = $ Depth to first probe with benzene $C_{\text{vapor}} \leq 100 \mu g/m^3$
  - Distance = $D_l - D_u$

- Method B: Interpolated distance to between a soil gas probe with benzene $C_{\text{vapor}} > 100 \mu g/m^3$ and a soil gas probe with $C_{\text{vapor}} < 100 \mu g/m^3$ where:
  - Lower depth = $D_l = $ Depth to top of contamination
  - Upper depth = $D_u = $ Interpolated as halfway between the depths to a probe with benzene $C_{\text{vapor}} \leq 40 \mu g/m^3$ and $C_{\text{vapor}} > 100 \mu g/m^3$; however, if the lower concentration is greater than 40 $\mu g/m^3$, then $D_u = $ depth to first probe with benzene $C_{\text{vapor}} \leq 100 \mu g/m^3$
  - Distance = $D_l - D_u$, subject to minimum thickness of 0.5 ft (0.2 m).

For both Methods A and B, benzene concentrations below reporting limits were replaced with half the reporting limit.

A lower concentration threshold was considered warranted for Method B because of the potential for the halfway distance interpolation to be non-conservative when the lower concentration is much greater than 100 $\mu g/m^3$ (which is often the case) and the upper concentration is just less than 100 $\mu g/m^3$. The 40 $\mu g/m^3$ threshold is subjective, but when the upper benzene vapor concentration is less than this threshold, the halfway interpolation method is more accurate. Although more complicated and possibly more accurate interpolation rules could have been developed, Method B was intended as a simple, approximate method.

For locations where the measured soil vapor benzene concentration does not attenuate to less than $< 100 \mu g/m^3$, a clean soil thickness cannot be calculated, but a minimum clean soil...
thickness (i.e., greater than) is reported as the distance between the shallowest soil gas probe and
the top of contamination.

An example calculation of clean soil thicknesses and exclusion distances is presented in
Figure 6. For the Area 1A soil gas probe profile, the Method A and B distances are 11 ft (3.4 m)
and 9 ft (2.7 m), respectively. For Site D, the benzene concentration in the shallowest probe is
greater than 100 μg/m³ in the shallowest probe; therefore, the clean soil thickness is identified as
greater than 11 ft (3.4 m) in the database.

### 7.3 Soil Vapor Concentration Thresholds

An important part of the analysis was defining a soil vapor concentration threshold when
soil PVI would typically not be of potential concern. The concentration threshold was based on
the expected attenuation in vapor concentrations between shallow soil vapor and indoor air, and
the toxicity of the chemical under consideration.

The processes that affect the vapor concentration in indoor air for a shallow soil vapor
source are primarily soil gas advection and ventilation and mixing of the chemical within the
enclosed space (Hers et al., 2003; Johnson, 2005), although some additional biodegradation and
sorption could also occur between a shallow vapor source and an indoor environment. Several
modeling studies provide insight on the attenuation factor for a typical residential house. Yao et
al. (2011) reported attenuation factors between $2 \times 10^{-4}$ and $7 \times 10^{-3}$ for a numerical modeling
calculated attenuation factors between $4.4 \times 10^{-3}$ and $7.3 \times 10^{-3}$ for a shallow soil vapor source
and representative input parameters for a residential house. A similar study by Hers et al. (2003)
included a sensitivity analysis where the maximum attenuation factor for a range of conditions
was $9 \times 10^{-3}$ and a relatively good comparison (within an order of magnitude) was obtained
between Johnson and Ettinger model predictions and measured attenuation factors for
chlorinated solvent chemicals. Although this comparison is for chlorinated solvent chemicals, it
is relevant here because it identifies typical attenuation factors between shallow or subslab vapor
and indoor air, irrespective of possible biodegradation processes.

The U.S. EPA database of empirical vapor attenuation factors (U.S. EPA, 2012a) is
another information source, although selection of a representative attenuation factor was
challenging. This is because the empirical attenuation factors vary over several orders of
magnitude, due to the variability in both indoor air and subslab vapor concentrations, and
background sources of chemicals in indoor air.

The U.S. EPA database 50th and 95th percentiles of the subslab attenuation factor are
$5.0 \times 10^{-3}$ and $1.8 \times 10^{-1}$, respectively, for the data set limited to indoor air concentrations above
the 90th percentile literature background concentration. For the data set filtered based on subslab
vapor concentrations greater than 100 times the literature background, the 50th and 90th
percentiles of the subslab attenuation factor are $2.5 \times 10^{-3}$ and $2.0 \times 10^{-2}$, respectively. Based on
the above review, a shallow soil vapor-to-indoor air attenuation factor of 0.01 was considered a
reasonably conservative factor for the analysis.
Risk-based indoor air concentrations for a residential scenario are provided in Table 7 for the chemicals of potential concern considered in this analysis. The risk-based indoor air concentrations assume a residential scenario, continuous life-time exposure to vapors, and no exposure amortization. For chemicals other than benzene, a risk-based soil vapor concentration (RBCv) was calculated as 100 times the risk-based air concentration. The thresholds adopted for benzene, 50 and 100 μg/m$^3$, were based primarily on practical considerations relating to the detection limit (i.e., the frequency of non-detects increases as the benzene concentration decreases). For comparison, assuming an attenuation factor of 0.01, the calculated benzene threshold is 29 μg/m$^3$ for an incremental lifetime cancer risk (ILCR) of $1 \times 10^{-6}$, and 290 μg/m$^3$ for an ILCR of $1 \times 10^{-5}$.

8. Database Analysis Results

8.1 Exploratory Data Analysis

The cumulative distributions of benzene concentrations in groundwater are plotted in Figure 7 for hydrocarbon sources classified as dissolved phase and LNAPL. The groundwater benzene concentrations for LNAPL sites are higher than for dissolved sites, but for a proportion of the LNAPL site data, there are relatively low benzene groundwater concentrations. This may be due to spatial variability in groundwater concentrations, highly weathered residual-phase LNAPL that is relatively depleted of benzene, variable well screen intervals relative to the water table, and vadose zone LNAPL sources.

The relations between benzene concentrations in groundwater and deep soil vapor probes (within 3 ft [0.9 m] of the contamination source) for dissolved and LNAPL sources are shown in Figure 8. There is no apparent correlation for dissolved-source data, but a weak proportional relation exists between groundwater and soil vapor concentrations for LNAPL source data.

For dissolved-source data, the measured deep benzene vapor concentrations are, in almost all cases, at least an order of magnitude (10 times) and, in many cases 2 orders of magnitude (100 times), less than the predicted soil vapor concentration based on Henry’s Law partitioning. A dimensionless Henry’s Law constant of 0.14 was used for benzene, which is based on a groundwater temperature of 15°C, considered a representative value based on the groundwater temperature map in U.S. EPA (2004).

For the LNAPL source data, the measured benzene vapor concentrations are significantly less than predicted for benzene groundwater concentrations less than approximately 1 mg/L. For concentrations greater than 1 mg/L, the benzene vapor concentrations for some data points are close to the predicted concentrations by Henry’s Law, which is consistent with an LNAPL source and limited attenuation between the source and deep soil vapor sample.

The poor correlation between groundwater and soil vapor concentrations is likely due to 1) variable well screen intervals relative to the water table, 2) variable biodegradation between the groundwater and lowermost soil gas sampling location, and 3) spatial variability and differences in dissolved-phase concentrations at groundwater and soil gas sampling locations.
The relation between co-located oxygen and PHC vapor concentrations has been hypothesized as potentially providing insight on biodegradation processes and a possible lower oxygen limit for occurrence of aerobic biodegradation. The expectation is low oxygen at high hydrocarbon vapor concentrations and high oxygen (near atmospheric) at low hydrocarbon vapor concentrations, excluding sites where there is high natural oxygen demand. The oxygen versus TPH vapor concentration data indicate general trends consistent with expected behavior and notably no data indicating depleted oxygen for dissolved sources, but considerable scatter in the data (Figure 9). For LNAPL sources, the low oxygen concentrations (less than 2 percent) occur when TPH vapor concentrations exceed approximately 1 mg/L. Some data points where oxygen and TPH vapor concentrations are both elevated may be due to the introduction of oxygen during sampling or analysis. Although the data suggest that aerobic biodegradation can occur at low oxygen concentrations (on the order of 1 to 2 percent), of greater relevance for the aerobic depth is the oxygen flux into the soil from the atmosphere and not the lowest oxygen concentration measured in soil.

The database includes methane data for 23 sites. Methane concentrations exceeded 5 percent (lower explosive limit in air) at four sites (three UST sites and one petroleum refinery site), but were less than 1 percent at the remaining 19 sites. There was no apparent correlation between methane and benzene vapor concentrations in this limited data set. Three of the four sites with elevated methane concentrations were investigated prior to 2000, so the methane at these sites was not associated with ethanol in the gasoline leaked into the subsurface.

The relations between benzene and ethylbenzene and benzene and xylenes soil vapor concentrations are shown in Figure 10. As shown, qualitatively there is a relatively good correlation between these two analyte pairs, although for the benzene-xylenes comparison, the xylenes’ vapor concentrations for low concentrations are generally (up to two orders of magnitude) higher than the benzene concentrations.

### 8.2 Vertical Distance Method

For the vertical distance method, soil vapor concentrations (of the PHC compounds listed below) are compared with risk-based vapor concentrations, RBC, (risk-based indoor air concentrations multiplied by 100), and for benzene, the probability that the soil vapor concentration is less than a defined threshold (50 and 100 μg/m³) for varying source-separation distances was estimated. For definition of exclusion distances, a probability greater than 95 percent was considered a reasonable threshold.

#### 8.2.1 All Data

The data analysis was conducted for 1) dissolved sources; 2) LNAPL sources, incorporating data for just UST sites; and 3) LNAPL sources, incorporating data for all facility types (UST, fuel terminal, petroleum refinery, and petro-chemical) (Figures 11 through 15). There are only PHC fraction and hexane data for UST sites; hence, we do not include a figure for the all-LNAPL sites category for these compounds. The following compounds were evaluated: benzene, xylenes, hexane, 2,2,4-TMP, and Massachusetts Department of Environmental...
Protection (MADEP) hydrocarbon fractions (C9-10 aromatics, C5-8 aliphatics, and C9-12 aliphatics).  

For the benzene analysis, nondetects were addressed both by the common practice of substituting half the detection limit for non-detects and by using the more statistically robust Kaplan-Meier non-parametric method. The Kaplan-Meier method resulted in similar or slightly higher (0 to 7 percent) probabilities than the substitution method. The probabilities the soil vapor concentration being less than a threshold was estimated for 5 and 30 mg/L groundwater concentration thresholds for benzene and TPH, respectively, which are part of the LNAPL hydrocarbon indicators (Table 6). A sensitivity analysis was conducted where the threshold for the benzene groundwater concentration was varied between 1 and 10 mg/L, and the TPH groundwater concentration was varied between 10 and 50 mg/L. The resulting variation in probability (estimated using the substitution method) for this range was less than 0.5 percent, indicating the results are not sensitive to the concentration thresholds (possibly because groundwater is a poor predictor of soil vapor concentrations).

The analysis results show distinct differences between the three scenarios considered (Table 8).

For dissolved sources, greater than 97 percent and 94 percent of the benzene soil vapor concentrations are less than the specified thresholds of 50 and 100 μg/m³, respectively, for source-separation distances as small as 0 ft (Table 8 and Figures 11 and 12). Comparisons for other compounds evaluated indicate that soil vapor concentrations above risk-based soil vapor concentrations occurred only for separation distances smaller than 3 ft (0.9 m). The analysis indicates there is a low probability of exceeded risk-based thresholds for small separation distances for dissolved sources.

For LNAPL sources, the PHC vapor concentrations were plotted against the separation distance between the soil gas probe and hydrocarbon source (Figures 13 through 15). The maximum concentrations of benzene and other hydrocarbon vapor concentrations were several orders of magnitude greater than for dissolved sources, but concentrations of benzene soil vapor concentrations decreased rapidly between 10 and 15 ft (3.0 and 4.6 m) separation distance and for other compounds at smaller separation distances, although it should be noted that the data sets for other compounds are relatively small. For LNAPL sources that are limited to UST sites, approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds (50 and 100 μg/m³) at a source-separation distance of approximately 15 ft (4.6 m), which increases to approximately 30 ft (9.1 m) when all LNAPL facility types are included.

Soil vapor data for 2,2,4-TMP for LNAPL sources (all facility types) were limited (Figure 16). There were elevated 2,2,4-TMP vapor concentrations (0.01 to 10 mg/L) representing data from two sites; at one site, concentrations remained elevated for separation distance.

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4 Naphthalene was not analyzed because soil vapor concentrations are low and below levels of concern based on maximum soil vapor concentrations and expected attenuation between soil vapor and indoor air. The maximum detected naphthalene soil vapor concentrations at any separation distance are 100 μg/m³ for dissolved sources and 180 μg/m³ for LNAPL sources. Conducting an analysis was not meaningful because of the high proportion of non-detects (81 percent for dissolved sources, 86 percent for NAPL sources) and raised detection limits.

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The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
distances as great as 50 ft (15 m). The U.S. EPA IRIS database does not contain toxicity reference factors for 2,2,4-TMP.

The analysis results indicate benzene is the risk driver, with greater occurrences of exceedances of risk-based vapor concentrations for larger separation distances, when compared with the other compounds evaluated.

8.2.2 Influence of Surface Cover

The potential influence of a surface cover was evaluated through comparison of the probabilities of benzene soil vapor concentrations that are less than 100 μg/m³ for varying soil-separation distances and through analysis of oxygen concentrations for three different surface covers: building concrete foundations, pavement, and bare-ground cover (Figures 17 and 18). The data sets evaluated were limited to LNAPL sources because oxygen is not limiting for dissolved-source sites.

When all the facility types were considered (which yields the largest data set), the analysis of probabilities for varying soil-separation distances indicated different results depending on surface cover. The probabilities of benzene soil vapor concentrations less than 100 μg/m³ were between 5 and 20 percent greater for the ground cover scenario, compared with the pavement and building scenarios, which yielded similar results (Figure 17). The oxygen concentration results were generally consistent with the above probabilities, with no oxygen concentrations below 2 percent for the ground cover scenario (excluding results for zero separation distance); however, several data points indicated oxygen concentrations less than 2 percent for separation distances up to 11 ft (3.4 m).

The above analysis was repeated for just LNAPL sources and UST sites. The results were different in that the probabilities for benzene concentrations less than 100 μg/m³ were similar for the ground cover and building scenarios, but were between 5 and 20 percent lower for the pavement scenario (Figure 18). The reason for this difference is not known, although it is noted that LNAPL sources and buildings will tend to be smaller at UST sites, compared with petroleum refinery or fuel terminal sites. There was a lower frequency of data points with low oxygen concentrations for UST sites, compared with the analysis where all facility types were considered.

These analyses suggest surface cover type can affect oxygen availability and PHC vapor transport. However, because the vertical distance method evaluation includes soil vapor concentration data from below buildings at 33 UST sites (Table 4), the results are considered sufficiently robust with respect to including the potential influence of surface cover.

8.2.3 Influence of Soil Type

The potential influence of soil type is evaluated through comparison of the probabilities of benzene soil vapor concentrations less than 100 μg/m³ for varying soil-separation distances and for two general soil types: fine grained and coarse grained (Figure 19). The probabilities of benzene soil vapor concentrations less than 100 μg/m³ were similar for dissolved-source sites for the two soil types. For LNAPL source sites, the probabilities are between 6 and 16 percent...
greater for coarse-grained soils than those for fine-grained soils for small separation distances, but at larger separation distances, there is a reversal in the trend. Based on the analysis, it is not possible to identify if soil type has an influence on benzene soil vapor concentrations and probabilities of exceedances.

8.3 Clean Soil (Davis) Method

The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-impacted clean soil required for soil vapor benzene concentrations to attenuate to below a defined threshold, which for this analysis is 100 μg/m³. As described in Section 7, two interpolation methods were used as part of the estimation process. The results of the analyses are shown in Figures 20 through 22 and can be summarized, as follows:

- For dissolved-source sites, there is no trend relative to dissolved benzene groundwater concentrations, and the 95th percentile clean soil thicknesses (calculated using Excel) for Methods 1 and 2 are 10 ft (3.0 m) and 5.4 ft (1.6 m), respectively.
- For LNAPL (UST-only) source sites, there is an increase in the clean soil thicknesses for benzene groundwater concentrations greater than approximately 5 mg/L. The 95th percentile clean soil thicknesses (incorporating all the data) for Methods 1 and 2 are 13.9 ft (4.2 m) and 13.5 ft (4.1 m), respectively. A small percentage of the data points represent vertical profile data where the shallowest benzene soil vapor concentration is greater than 100 μg/m³; therefore, an attenuation distance could not be calculated (green symbols on Figures 20 through 22).
- For LNAPL (all sites) source sites, there is a similar trend to UST-only sites with respect to clean soil thickness versus benzene groundwater concentrations. The 95th percentile clean soil thicknesses for Methods 1 and 2 are 20.0 ft (6.1 m) and 16.2 ft (4.9 m), respectively. A small percentage of the data points represent vertical profile data where the shallowest benzene soil vapor concentration was greater than 100 μg/m³.

9. Discussion

9.1 Conceptual Site Model and Mathematical Models

The CSM for PHC vapor behavior is the basis for the framework developed for identifying exclusion distances and inclusion criteria. At sites with dissolved PHC contamination in groundwater, aerobic biodegradation is expected to result in the attenuation of PHC vapors, such that there is limited potential for a complete PVI pathway, except for sites with very shallow contamination. For sites with shallow LNAPL contamination, there is greater potential for oxygen limitations below buildings and a complete PVI pathway, depending on site conditions. Case studies reviewed suggest that the potential for a complete PVI pathway may exist at non-UST (i.e., petroleum refinery) sites with large-volume LNAPL releases, particularly where there are large buildings or a capping effect based on geologic conditions.

The mathematical modeling studies reviewed, in general, support the empirical analysis in that model simulations for dissolved PHC sources predict very low vapor attenuation factors,
except for small source-separation distances (i.e., less than about 5 ft [1.5 m]). For LNAPL sources, the modeling simulations suggest hydrocarbon vapor attenuation behavior consistent with the case studies and empirical data. Although the modeling studies are instructive, there has been limited evaluation of the range of possible mechanisms for oxygen migration to below buildings, including diffusive oxygen transport through concrete foundations and processes for advective soil gas transport, which could be important at LNAPL source sites.

9.2 Methods and Characteristics of the Database

The results of the analysis may be used to derive exclusion distances based on the probability of benzene vapor concentrations being less than defined thresholds for varying contamination source-building separation distances and qualitative comparisons of soil vapor concentrations to risk-based soil vapor concentrations for other compounds. The clean soil method is an alternative method for defining exclusion distances, but requires interpolation to avoid overly conservative results. This site-by-site interpolation process introduces uncertainty particularly for sites where there is poor resolution with respect to vertical concentration gradients (i.e., from soil gas probes that are too far apart).

The database is representative of a broad range of environmental site conditions, climatic conditions (including dry areas), soil types, and land-surface covers that may be found at UST sites. Although the data analysis indicates that the type of surface cover (e.g., building foundation, pavement, open ground) can have an effect on the attenuation of benzene vapor and oxygen concentrations, the database includes subslab or vapor data from deeper distances below buildings for 38 sites with small- to medium-sized buildings. This is considered a sufficiently large data set, such that exclusion distances derived from the analysis will include the potential influence of surface cover.

The sites in the database were investigated between 1995 and 2011. Gasoline containing ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large increase in use in 2006 (U.S. EPA, 2009). Information on whether gasoline containing ethanol is present at specific sites is not available in the current database, but some sites in the database with recent releases likely have gasoline containing ethanol.

The sources of uncertainty associated with the analysis, and for which additional validation studies should be considered, include the influence of ethanol content in gasoline on methane generation rates and aerobic biodegradation of PHC vapors (particularly high ethanol content fuels), sites with extensive high organic matter content soils (e.g., peat) with potentially high natural oxygen demand, and large buildings where there may be increased potential for oxygen limitations for certain foundation conditions. Although this analysis included an evaluation of data for non-UST (e.g., petroleum refinery, fuel terminal) sites, uncertainty about aerobic biodegradation of PHC vapors remains for larger volume NAPL releases than typically encountered at UST sites.

Subsurface utilities are commonplace in urban areas, but their presence does not necessarily equate to a preferential pathway of significance for PVI. However, a utility corridor that directly connects an LNAPL source and the interior of a building may represent a significant preferential pathway and is considered an inclusionary factor for PVI assessment. This analysis
also does not include results for fractured rock unsaturated zone systems between the PHC source and building receptor.

9.3 Data Analysis Results

For dissolved sources, the vertical distance method indicates that the probability of benzene vapor concentrations being less than the defined concentration thresholds (50 and 100 μg/m³) is 94 to 97 percent (Kaplan-Meier statistics) for small source-separation distances (as little as 0 ft), meaning that PVI is unlikely to occur unless a dissolved source is very close to a building foundation. For development of exclusion distances for dissolved sites, allowance should be made for uncertainty in water table elevations due to seasonal variability. For LNAPL sources, the vertical distance method indicates that there is a very low probability of benzene vapor concentrations being less than the defined thresholds at distances less than about 15 ft (4.6 m) when just UST facilities are considered and about 30 ft (9.1 m) when all facility types evaluated are considered.

The data indicate a weak correlation between benzene concentrations in groundwater and deep soil vapor, but for the clean soil method, a trend was observed when the clean soil thicknesses needed for benzene vapor attenuation increased when dissolved benzene concentrations were above approximately 5 mg/L (i.e., indicative of LNAPL source zones).

9.4 Exclusion Distance Assessment Framework

The assessment framework for vertical exclusion distances requires identification of the PHC source type (dissolved phase or LNAPL) based on a multiple lines of evidence approach similar to that described earlier in this report (see Table 6). This framework could include groundwater concentration thresholds for benzene (and potentially other chemical parameters), but given the uncertainty in the relation between groundwater and soil vapor concentrations, this should not be the primary factor for screening sites. Thresholds for soil vapor concentrations (e.g., minimum oxygen thresholds) could also be considered; however, this is not considered mandatory as long as there is sufficient rigor in the site characterization approach to delineate PHC sources and define clean soil zones along with robust methods for identifying LNAPL versus dissolved sites. For sites with dissolved-phase contamination, it will also be important to characterize water table fluctuations in relation to building structures.

An exclusion distance approach for LNAPL sources should also include inclusionary criteria designed to capture sites that fall outside of the findings of the above analysis, including non-UST facilities (related to size of petroleum release), high organic-rich soils (e.g., peat), large building foundations (e.g., associated with apartment complexes or commercial/industrial buildings), and significant subsurface preferential pathways. Future research may indicate certain ethanol contents in gasoline may also warrant inclusion and PVI assessments because of their tendency to generate methane that can interfere with the biodegradation of PHCs.

9.5 Lateral Exclusion Distances

Greater attenuation of PHC vapors is expected when hydrocarbon sources are offset laterally from buildings compared with sources that are directly below buildings. Although the
modeling studies reviewed for this effort suggest that conceptually similar lateral exclusion distances could be applied as the vertical distances addressed in this document, from a practical standpoint, the uncertainty associated with delineating a PHC source near existing or future buildings warrants larger lateral distances than those suggested based on the analysis for the dissolved and LNAPL UST-only cases.

9.6 Comparison with Other Studies

Five different PHC data analysis efforts conducted in roughly the same time frame (this one, Davis [2009], Lahvis et al. [in prep.], Wright [2011], and Peargin and Kolhatkar [2011]) support essentially the same exclusion distances for PHC UST sites, in spite of differences in the base data analyzed and each study’s approach to the analysis. This suggests an underlying consistency in mechanisms for PHC biodegradation in the subsurface and supports the protectiveness of the use of these distances as exclusion criteria for UST petroleum release sites.

10. Conclusions

Approaches for assessing PVI that do not account for aerobic biodegradation processes are typically highly conservative. The statistical analysis of soil gas data from 70 sites presented in this study, along with four other similar but distinct efforts, provided an opportunity for developing improved and more efficient screening evaluation methods for PHC compounds based on the observed attenuation and an exclusion distance approach, defined as the contamination source-separation distance at which there is limited potential for a complete PVI pathway. The focus of this analysis was primarily on characterizing PVI at UST sites with petroleum fuel releases, although data from other types of sites (fuel terminals, petroleum refineries) were also considered. Important findings of this study include the following.

1. Knowledge of the PHC source type (dissolved versus LNAPL) and the vertical separation distance between the source and receptor (building foundation) is a critical factor affecting PVI and is an important metric for site screening.

2. For dissolved sources:
   a. For the vertical distance method, greater than 97 percent and 94 percent of the benzene soil vapor concentrations (based on Kaplan-Meier statistics) are less than the specified concentration thresholds (50 and 100 μg/m³, respectively) for contamination source-building separation distances as small as 0 ft. For other compounds evaluated, soil vapor concentrations above risk-based soil vapor concentrations only occurred for separation distances smaller than 3 ft (0.9 m).
   b. For the clean soil method (Method B), the 95th percentile vertical clean soil thickness for benzene vapor attenuation is approximately 5.4 ft (1.6 m).
   c. The analysis indicates for dissolved sources there is a low probability of exceeding risk-based concentrations for small separation distances.

3. For LNAPL sources and UST sites:
a. For the vertical distance method, approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds for a source-building separation distance of approximately 15 ft (4.6 m). For other compounds evaluated, soil vapor concentrations above risk-based soil vapor concentrations occurred at smaller separation distances.

b. For the clean soil method, the 95th percentile vertical clean soil thickness for benzene vapor attenuation is approximately 13.5 ft (4.1 m).

4. For LNAPL sources and all facility types considered (UST, petroleum refinery, fuel terminal, and petro-chemical sites), the findings are:

a. For the vertical distance method, over 95 percent of the benzene soil vapor concentrations are less than the thresholds for a source-building separation distance of approximately 30 ft (9.1 m). For other compounds evaluated, soil vapor concentrations above risk-based soil vapor concentrations occurred at smaller separation distances.

b. For the clean soil method, the 95th percentile vertical clean soil thickness for benzene vapor attenuation is approximately 16.4 ft (5.0 m).

5. The data indicate benzene is the risk driver, with greater occurrences of exceedances of risk-based vapor concentrations for larger contamination source-building separation distances compared with other compounds evaluated.

6. The data indicate a weak correlation between benzene concentrations in groundwater and soil vapor from deeper distances, but for the clean soil method, a trend was observed where clean soil thicknesses for benzene vapor attenuation increased when the dissolved benzene concentrations were above approximately 5 mg/L.

7. Surface cover type appears to have a weak effect on oxygen availability and PHC vapor transport, and depending on the data set used, either sites with pavement or building surface covers had lower probabilities of benzene concentrations less than 100 μg/m² for a given source-separation building separation, although these findings are uncertain given the size of the data set and variable results.

8. Because the vertical distance method evaluation includes soil vapor concentration data from below buildings at 33 UST sites, the results are considered sufficiently robust with respect to including the potential influence of surface cover.

The findings of this study have important implications for improved and more efficient screening methods for PHC compounds based on the observed attenuation in PHC vapor concentrations and an exclusion distance approach. Inclusionary criteria or conditions not analyzed in this database, and where more detailed PVI assessment is considered warranted, include non-UST facilities, high organic-rich soils (e.g., peat), large building foundations (e.g., associated with apartment complexes or commercial/industrial buildings), and significant subsurface preferential pathways. Future research may indicate that certain ethanol contents in
gasoline may also warrant inclusion and PVI assessments because of their tendency to generate methane that can interfere with the biodegradation of PHCs.

11. References


Branco, F.A., and J. de Brito. 2004. *Handbook of Concrete Bridge Management.* American Society of Civil Engineers (ASCE), ASCE Press, Reston, VA.


The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.


Wisconsin Department of Natural Resources. 2010. Addressing Vapor Intrusion at Remediation & Redevelopment Sites in Wisconsin. Madison, WI: Department of Natural Resources. PUB-RR-800. December.


### Table 1. Summary of Case Study Sites with Confirmed or Likely Occurrences of Petroleum Vapor Intrusion

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance L Nayl-Building</th>
<th>Building Size</th>
<th>Source Vapor Concentrations</th>
<th>Facility</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casper, Wyoming (Luo et al., 2009)</td>
<td>1–5 ft (0.3–1.5 m)</td>
<td>2,300 ft²</td>
<td>TPH = 100 mg/L</td>
<td>Refinery</td>
<td>Shallow LNAPL source</td>
</tr>
<tr>
<td>Chatterton (Hers et al., 2000)</td>
<td>5 ft (1.5 m)</td>
<td>610 ft²</td>
<td>TPH = 40 mg/L</td>
<td>Petro-chemical</td>
<td>VI only when DP ~ 10 Pa</td>
</tr>
<tr>
<td>Perth (Patterson and Davis, 2009)</td>
<td>10 ft (3.0 m)</td>
<td>2,700 ft²</td>
<td>TPH = 20 mg/L</td>
<td>Refinery</td>
<td>30-ft (9.1 m) building apron on 3 sides of building</td>
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<tr>
<td>Unknown (Luo et al., 2010)</td>
<td>25–30 ft (7.6–9.1 m)</td>
<td>2,100 ft²</td>
<td>TPH ~ 60-160 mg/L</td>
<td>Refinery</td>
<td>Capping effect from geology observed</td>
</tr>
<tr>
<td>Hartford, Illinois (Illinois DPH, 2010)</td>
<td>Depth to groundwater ~ 23–33 ft (~7–10 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>Refinery</td>
<td>Very large spill, episodic PVI events when heavy rain or sharp rise in water table</td>
</tr>
<tr>
<td>Stafford, New Jersey (Sanders and Hers, 2006)</td>
<td>5.25 ft (1.6 m)</td>
<td>700 ft²</td>
<td>Benzene = 0.66 mg/L, 2,2,4-TMP = 2.1 mg/L, MTBE = 5.9 mg/L</td>
<td>UST</td>
<td>VI observed for MTBE, 2,2,4-TMP and cyclohexane but not for BTEX</td>
</tr>
<tr>
<td>Ogden, Utah Mini-Mart (McHugh et al., 2010)</td>
<td>3.3 ft (1.0 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>UST</td>
<td>Large release, odors detected in building</td>
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<tr>
<td>Gunnison, Utah Top-Stop (McHugh et al., 2010)</td>
<td>Depth to groundwater ~ 13–16 ft (~4–5 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>UST</td>
<td>Sudden 20,000-gallon (75,708 L) release, odors detected in buildings up to 500 ft (152 m) downgradient of source</td>
</tr>
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</table>
Table 2. Select Three-Dimensional Abreu and Johnson (2005) Model Simulation Results from U.S. EPA (2012b)

<table>
<thead>
<tr>
<th>Source Hydrocarbon Vapor Concentration (mg/L)</th>
<th>Vapor Intrusion Attenuation Factor</th>
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<tr>
<td>200</td>
<td>$6.7 \times 10^{-5}$</td>
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<td>2</td>
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</tr>
</tbody>
</table>

Notes: Depressurized building (~5 Pa), residential house with 2-m (6.6-ft) deep basement, depth to hydrocarbon vapor source = 8 m (25.3 ft), first-order decay constant equal to 0.18 h\(^{-1}\).

Table 3. Number of Sites by Country and States in PVI Database (February 2012)

<table>
<thead>
<tr>
<th>Location</th>
<th>Sites</th>
<th>Location</th>
<th>Sites</th>
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<td>New Jersey</td>
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<td>Other Countries</td>
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<tr>
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<td>Australia</td>
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Total Sites = 70
<table>
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<tr>
<th>Site Name</th>
<th>City</th>
<th>State or Province</th>
<th>Contamination Source</th>
<th>Vapor Source Type</th>
<th>Soil Type</th>
<th>Site Type</th>
<th>Building Use</th>
<th>Foundation Type</th>
<th>Media Sampled</th>
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<td>UST</td>
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<td>State or Province</td>
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<td>Soil Type</td>
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(continued)
Table 4. Summary of Information in PVI Database (continued)

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(continued)
Table 4. Summary of Information in PVI Database (continued)

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<th>State or Province</th>
<th>Contamination Source</th>
<th>Vapor Source Type</th>
<th>Soil Type</th>
<th>Site Type</th>
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1 For contamination type: G = gasoline, D = diesel, J = jetfuel, E = ethanol, K = kerosene; G* for MN sites inferred to be gasoline-impacted sites, but no confirmatory data provided.
2 Dis = dissolved. An arbitrary threshold for smaller versus larger building was set as 2,500 ft².
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<th>Heptane</th>
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<th>1,3-Butadiene</th>
<th>TPH</th>
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<th>MDPE PTH Fractions</th>
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<td>Teasdale</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>N/A</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Tesoro #40</td>
<td>Salt Lake</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>TO-15 (C5-11)</td>
<td>0</td>
<td>2</td>
<td>2</td>
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</tbody>
</table>

(continued)
Table 5. Soil Vapor Analyses in PVI Database (continued)

<table>
<thead>
<tr>
<th>Site Name</th>
<th>City</th>
<th>Benzene</th>
<th>Toluene</th>
<th>Ethylbenzene</th>
<th>Xylenes</th>
<th>Naphthalene</th>
<th>2,2,4-Trimethylpentane</th>
<th>Hexane</th>
<th>Heptane</th>
<th>MTBE</th>
<th>1,3-Butadiene</th>
<th>TPH</th>
<th>TPH Method</th>
<th>MADEP TPH Fractions</th>
<th>Oxygen</th>
<th>Carbon</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Eleven #23387</td>
<td>Murray</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>Modified TO-3 GC/FID</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Refinery Site</td>
<td>Unknown</td>
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<td>53</td>
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<td>31</td>
<td>31</td>
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<td>Chatterton Research Site</td>
<td>Delta</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>7</td>
<td>Gastector</td>
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<td>North Battleford</td>
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<td>5</td>
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<td>0</td>
<td>9</td>
<td>TO-15 C6-10</td>
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<td>9</td>
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<tr>
<td>Perth</td>
<td>Perth</td>
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<td>0</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Number Sites with Data</td>
<td></td>
<td>65</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>18</td>
<td>21</td>
<td>20</td>
<td>13</td>
<td>11</td>
<td>59</td>
<td>N/A</td>
<td>11</td>
<td>41</td>
<td>39</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Total Number Analyses</td>
<td></td>
<td>879</td>
<td>362</td>
<td>362</td>
<td>377</td>
<td>236</td>
<td>147</td>
<td>143</td>
<td>121</td>
<td>87</td>
<td>772</td>
<td>0</td>
<td>87</td>
<td>645</td>
<td>594</td>
<td>357</td>
<td></td>
</tr>
</tbody>
</table>

1 For contamination type: G=gasoline, D=diesel, J=jetfuel, E=ethanol, G* for MN sites inferred to be gasoline-impacted sites, but no confirmatory data provided.
2 Dis = dissolved
Table 6. Potential LNAPL Hydrocarbon Indicators

<table>
<thead>
<tr>
<th>Type</th>
<th>Indicator</th>
<th>Measures and Screening Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adopted for this study</td>
<td>Current or historic presence of LNAPL in groundwater or soil</td>
<td>Laboratory and/or field observations, sheens, results of paint filter, dye and shake tests</td>
</tr>
</tbody>
</table>
| Indirect                                  | Individual PHC compound and/or TPH concentrations approaching (>0.2) effective solubilities or effective soil saturation concentrations ("Csat" concentration) | Groundwater  
- benzene > 5 mg/L  
- TPH > 30 mg/L (gasoline)  
Soil  
- benzene > 10 mg/kg  
- TPH > 250 mg/kg (gasoline) |
| Indirect                                  | Proximity to source area likely to be impacted with LNAPL                 | Soil gas probes located near (within 20 ft [6.1 m]) or within former underground storage tank (UST) fields or fuel dispenser areas |

Other potential indicators

| Indirect                                  | Fluorescence response in LNAPL range                                     | UV, LIF, or UVIF fluorescence above background levels (visual observation) |
| Indirect                                  | Organic vapor analyzer (e.g., photoionization detector)                  | >500 ppmV                                                                |
| Indirect                                  | PHC vapor, O₂ and CO₂ profiles                                          | PHC vapor and CO₂ concentrations in soil gas that show no decrease (or O₂ concentrations that show no increase) or remain relatively constant with distance from contamination source |
| Indirect                                  | Elevated aliphatic soil gas concentrations                               | For example, hexane soil gas concentrations > approximately 100,000 μg/m³ suggest LNAPL because dissolved plumes are primarily composed of soluble aromatic hydrocarbons (Lahvis et al., In prep.) |

Note: For two sites, #6-046 and #102 Chevron, there were long dissolved plumes (several hundred feet long) with elevated benzene concentrations (up to 12 mg/L) in groundwater that exceeded the above criteria, but when there was no evidence of LNAPL (it was also considered unlikely that the LNAPL body would have migrated this far). For these sites, the above criteria were overridden (i.e., site was designated as a dissolved source).
Table 7. Risk-Based Indoor Air Concentration for Primary Chemicals of Potential Concern

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Toxicity Endpoint</th>
<th>Risk-Based Indoor Air Concentration (μg/m³)¹</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>Carcinogenic</td>
<td>2.9 (1 x 10⁻⁵ ILCR); 0.29 (1 x 10⁻⁶ ILCR)</td>
<td>U.S. EPA IRIS²</td>
</tr>
<tr>
<td>Toluene</td>
<td>Non-carcinogenic</td>
<td>5,000 (RfC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>Non-carcinogenic</td>
<td>1,000 (RfC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Xylenes</td>
<td>Non-carcinogenic</td>
<td>100 (RfC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>Non-carcinogenic</td>
<td>3 (RfC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>Non-carcinogenic</td>
<td>700 (RfC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>MADEP Aliphatic C5-8</td>
<td>Non-carcinogenic</td>
<td>200</td>
<td>MADEP (2003)</td>
</tr>
</tbody>
</table>

¹ Assumes residential receptor, and continuous exposure over a lifetime.
² Midpoint of the range provided in U.S. EPA IRIS database.
³ ILCR = Incremental lifetime cancer risk; RfC = reference concentration.
⁴ IRIS database accessed February 2012.

Table 8. Summary of Results for Vertical Distance Method

<table>
<thead>
<tr>
<th>Dissolved Source</th>
<th>LNAPL Source—UST Sites</th>
<th>LNAPL—All Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>Most O₂ conc. &gt; 4%, and no O₂ &lt; 1%</td>
<td>Many data points with O₂ &lt; 4%, and O₂ &lt; 1% to 6 ft (1.8 m) separation</td>
</tr>
<tr>
<td>Benzene (100 μg/m³ threshold)</td>
<td>Pₘ &gt; 97% for 0 ft separation increasing to 99% at 5 ft (1.5 m)</td>
<td>Pₘ &gt; 61% for 0 ft separation increasing to ~ 95% for 15-ft (4.6-m) separation</td>
</tr>
<tr>
<td>Benzene (50 μg/m³ threshold)</td>
<td>Pₘ &gt; 94% to 95% for 0 ft to 5 ft (1.5 m)</td>
<td>Pₘ &gt; 57% for 0 ft separation increasing to ~ 93% for 15-ft (4.6-m) separation</td>
</tr>
<tr>
<td>Xylenes</td>
<td>One vapor concentration &gt; RBC, for separation distance of 3 ft (0.9 m)</td>
<td>&gt;10 vapor concentrations &gt; RBC, for separation distance up to 11 ft (3.4 m)</td>
</tr>
<tr>
<td>Hexane</td>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Five vapor concentrations &gt; RBC, for separation distance up to 4 ft (1.2 m)</td>
</tr>
<tr>
<td>C5-8 Aliphatic</td>
<td>Two vapor concentrations &gt; RBC, for separation distance up to 3 ft (0.9 m)</td>
<td>Five vapor concentrations &gt; RBC, for separation distance up to 3 ft (0.9 m)</td>
</tr>
<tr>
<td>C9-12 Aliphatic</td>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Eight vapor concentrations &gt; RBC, for separation distance up to 2 ft (0.6 m)</td>
</tr>
<tr>
<td>C9-10 Aromatic</td>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Four vapor concentrations &gt; RBC, for separation distance up to 2 ft (0.6 m)</td>
</tr>
</tbody>
</table>

The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
1 $P_{KM} = \text{Probability estimated using Kaplan-Meier method for exceeding threshold.}$

### Table 9. Summary of Results for Clean Soil (Davis) Method

<table>
<thead>
<tr>
<th>Source Scenario and Facility Type</th>
<th>Number Sites</th>
<th>Number Data Points</th>
<th>95th Percentile Clean Soil Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Method A</td>
</tr>
<tr>
<td>Dissolved</td>
<td>47</td>
<td>170</td>
<td>10.0 ft (3.0 m)</td>
</tr>
<tr>
<td>LNAPL (UST only)</td>
<td>53</td>
<td>172</td>
<td>13.9 ft (4.2 m)</td>
</tr>
<tr>
<td>LNAPL (all facilities)</td>
<td>60</td>
<td>216</td>
<td>20.0 ft (6.1 m)</td>
</tr>
</tbody>
</table>

Note: The above statistics include site data when no benzene groundwater concentration was available.

---

**Figure 1.** Conceptual Model Illustrating the Potential for Vapor Intrusion for a) Free-Phase LNAPL Source, b) Residual-Phase LNAPL Source, and c) Dissolved-Phase Source. (source Lahvis et al., In prep.; used with permission).
Figure 2. Vapor Intrusion Attenuation Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model for a Range of Source Total Hydrocarbon (benzene) Vapor Concentrations and Separation Distances for a Residential House Scenario (from Abreu et al., 2009).
Figure 3. Effect of Source Depth on Soil Gas Distribution and Vapor Intrusion Attenuation
Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model for a Source Total Hydrocarbon (Benzene) Vapor Concentration of 100 mg/L and Biodegradation Rate of 0.79 h\(^{-1}\) for a Residential House Scenario. Hydrocarbon and Oxygen Concentrations are Normalized by Source and Atmospheric Concentrations (from Abreu et al., 2009).
Figure 4. Vapor Intrusion Attenuation Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model as a Function of Separation Distance below Foundation and First-Order Biodegradation Rate for a Residential House Scenario (from Abreu et al., 2009).
Figure 5. Estimates of Indoor Air Benzene Concentrations Using BioVapor Model for Varied Effective Airflow through the Basement Foundation. Foundation Effective Airflow Statistics: 5th percentile = 0.3 L/min, 50th percentile = 3 L/min, 95th percentile = 30 L/min. Key model parameters: Vapor mixing height = 2.44 m; indoor air exchange rate = 0.25 h⁻¹; building footprint area = 100 m² (1,076 ft²) (from DeVaull, 2010).
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
Figure 8. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Only detectable benzene vapor concentrations shown.

Figure 9. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Data points shown are where both TPH vapor and oxygen concentrations were above detection limits. Shaded ellipse encompasses data that generally support the aerobic mineralization paradigm.
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
Figure 12. Vertical Distance Method–PHC Fraction and Hexane Data for Dissolved Sites.
Figure 13. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (UST only) Sites (KM = Kaplan-Meier).

Figure 14. Vertical Distance Method–PHC Fraction and Hexane Data for LNAPL (UST only) Sites.
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
Figure 17. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (all sites). Below detection limit concentrations replaced with half the detection limit for analysis.
Figure 18. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (UST sites). Below detection limit concentrations replaced with half the detection limit for analysis.
Figure 19. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold for Different Soil Types (coarse and fine grained). Below detection limit concentrations replaced with half the detection limit for analysis.

Figure 20. Results of Clean Soil (Davis) Method for Dissolved-Source Sites. 47 sites, N = 170.
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.

Figure 21. Results of Clean Soil (Davis) Method for LNAPL Source Sites (UST-only). 53 sites, N = 172.

Figure 22. Results of Clean Soil (Davis) Method for LNAPL Source Sites (all). 60 sites, N = 216.
Appendix A. PVI Database Data Dictionary

Attachment A-1. Table Structures as of April 17, 2012

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Long Integer</td>
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<td>Link to Buildings table</td>
</tr>
<tr>
<td>location_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Link to Locations table</td>
</tr>
<tr>
<td>horz_dist_to_bldg</td>
<td>Double</td>
<td>8</td>
<td>Horizontal distance, sample location to building (na for indoor samples)</td>
</tr>
<tr>
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<td>Text</td>
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<td>Horizontal distance unit</td>
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<td>Building identifier (aka, subsite)</td>
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<td>bldg_type</td>
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<td>Physical description of building (links to lt_Building_Types)</td>
</tr>
<tr>
<td>bldg_use</td>
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<td>Use of building (residential, commercial, industrial, school, etc.)</td>
</tr>
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<td>8</td>
<td>Area of the building footprint</td>
</tr>
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<td>Unit of measurement for footprint_area</td>
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<td>Building foundation types (lookup values in lt_Foundation_Types)</td>
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<td>Depth to base of foundation (below ground surface)</td>
</tr>
<tr>
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<td>20</td>
<td>Unit of measurement for depth to base of foundation</td>
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<td>Text</td>
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<td>Name of contact associated with data_provider</td>
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<td>Text</td>
<td>40</td>
<td>Contact street address and/or box number</td>
</tr>
<tr>
<td>data_contact_address2</td>
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<td>40</td>
<td>Site address, part two. Box number or other info.</td>
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<td>City</td>
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<td>data_contact_state</td>
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<td>Postal abbreviation for State</td>
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<td>Zip code</td>
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<td>Contact e-mail address</td>
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<td>Contact phone number</td>
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<td>time_stamp</td>
<td>Date</td>
<td>8</td>
<td>Date/time record was created</td>
</tr>
</tbody>
</table>

The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
### Field Name | Type | Size | Description
---|---|---|---
**Table: Documents**
`doc_id` | Long Integer | 4 | Unique ID for document
`site_id` | Long Integer | 4 | Link to Sites table
`ref_id` | Long Integer | 4 | Link to Reference table
`doc_name` | Text | 255 | Document descriptive name
`file_name` | Text | 255 | Physical file name
`doc_year` | Text | 4 | Document year (for bibliography)
`doc_desc` | Text | 255 | Description for the document
`doc_date` | Date | 8 | Document creation date
`doc_source` | Text | 255 | Document source
`author_org` | Text | 100 | Document author's organization
`author_citation` | Text | 255 | Author name in citation formats
`author_name` | Text | 50 | Document author's name
`Journal` | Text | 255 | Journal name in citation format
`Volume` | Text | 20 | Journal volume in citation format
`Pages` | Text | 20 | Journal pages in citation format
`author_phone` | Text | 20 | Document author's phone number
`doc_links` | Memo | 0 | Availability on the Internet, with website address (i.e., URL)
`doc_comments` | Memo | 0 | Other comments about the document (e.g., use, applicability)
`public_yn` | Text | 1 | Can this information be made available to the public? (Y=yes, N=no)
`doc_original_format` | Text | 100 | Original format of document
`date_QC_completed` | Date | 8 | Date that QC was completed
`time_stamp` | Date | 8 | Date/time record was created

### Table: Links
`Link_ID` | Long Integer | 4 | Unique ID for the links of the specified two location_xy_id.
`location_xy_id1` | Long Integer | 4 | First location of the linkage: probe location_xy_id
`location_xy_id2` | Long Integer | 4 | Second location of the linkage: non-probe location_xy_id
`distance_xy` | Double | 8 | Lateral distance between the two linked xy locations
`distance_xy_units` | Text | 10 | Unit of the lateral distance

### Table: Locations
`sample_location_id` | Long Integer | 4 | Location ID where sample was taken at 3D level (including depth z)
`site_id` | Long Integer | 4 | Link to Sites table
`building_id` | Long Integer | 4 | Link to Buildings table
`location_xy_id` | Long Integer | 4 | Unique ID for each sample location at 2D level, links locations laterally in Links table
`import_loc_id` | Text | 25 | 3D location XY ID assigned for import (Example: M129-M130, M207, M208)
`loc_name` | Text | 100 | Location xy name at 2D level
<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>samp_loc_name</td>
<td>Text</td>
<td>255</td>
<td>More specific name of sampling location; can vary by depth</td>
</tr>
<tr>
<td>sample_depth</td>
<td>Double</td>
<td>8</td>
<td>Sample depth, below land surface</td>
</tr>
<tr>
<td>sample_depth_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for sample depth</td>
</tr>
<tr>
<td>loc_type</td>
<td>Text</td>
<td>50</td>
<td>Location type (indoor air, outdoor air, probe, bulk soil, or well)</td>
</tr>
<tr>
<td>loc_int/ext</td>
<td>Text</td>
<td>20</td>
<td>Interior or exterior location</td>
</tr>
<tr>
<td>loc_desc</td>
<td>Text</td>
<td>255</td>
<td>Additional location description (e.g., floor; room use)</td>
</tr>
<tr>
<td>vz_soil_text_code</td>
<td>Text</td>
<td>10</td>
<td>Soil texture code (links to lt_Soil_Textures)</td>
</tr>
<tr>
<td>vz_alt_soil_desc</td>
<td>Text</td>
<td>255</td>
<td>Soil description (more specific than vz_soil_txt_code)</td>
</tr>
<tr>
<td>vz_alt_soil_grade</td>
<td>Text</td>
<td>255</td>
<td>Site soil gradation (V.Coarse, Coarse, Fine)</td>
</tr>
<tr>
<td>vz_porosity</td>
<td>Double</td>
<td>8</td>
<td>Vadose zone porosity</td>
</tr>
<tr>
<td>vz_porosity_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for vadose zone porosity</td>
</tr>
<tr>
<td>loc_comment</td>
<td>Memo</td>
<td>0</td>
<td>Comment/notes about latitude, longitude, vertical elevation (collection method, post processing, etc.)</td>
</tr>
<tr>
<td>time_stamp</td>
<td>Date</td>
<td>8</td>
<td>Date/time record was created</td>
</tr>
</tbody>
</table>

**Table: It_Building_Types**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bldg_type</td>
<td>Text</td>
<td>Physical description of building</td>
</tr>
</tbody>
</table>

**Table: It_Countries**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>country</td>
<td>Text</td>
<td>Country short name</td>
</tr>
<tr>
<td>country_name</td>
<td>Text</td>
<td>County name</td>
</tr>
</tbody>
</table>

**Table: It_Foundation_Types**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>foundation_type</td>
<td>Text</td>
<td>Building foundation types (lookup for Buildings table)</td>
</tr>
</tbody>
</table>

**Table: It_Hydrogeologic_Settings**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydro_setting_desc</td>
<td>Text</td>
<td>General Hydrogeologic setting description</td>
</tr>
</tbody>
</table>

**Table: It_Parameters**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter_id</td>
<td>Long Integer</td>
<td>Unique ID for each measurement parameter</td>
</tr>
<tr>
<td>parameter_abbrev</td>
<td>Text</td>
<td>Abbreviation for measured parameter (e.g., MEK, BP)</td>
</tr>
<tr>
<td>parameter_name</td>
<td>Text</td>
<td>Measured parameter (e.g., 2-butanone, barometric pressure)</td>
</tr>
<tr>
<td>cas_number</td>
<td>Text</td>
<td>Chemical Abstract System number (where applicable)</td>
</tr>
<tr>
<td>parameter_class</td>
<td>Text</td>
<td>Parameter class or grouping</td>
</tr>
<tr>
<td>organic_yn</td>
<td>Text</td>
<td>“Y” for organic chemicals, “N” for inorganic chemicals</td>
</tr>
<tr>
<td>HLC25</td>
<td>Double</td>
<td>Henry’s Law Constant at 25 degrees C (unitless)</td>
</tr>
<tr>
<td>DeltaH</td>
<td>Double</td>
<td>Enthalpy of vaporization, normal boiling point (cal/mol)</td>
</tr>
<tr>
<td>Tc</td>
<td>Double</td>
<td>Critical temperature (degrees Kelvin)</td>
</tr>
<tr>
<td>Tb</td>
<td>Double</td>
<td>Normal boiling point (degrees Kelvin)</td>
</tr>
<tr>
<td>comment</td>
<td>Text</td>
<td>Comment on parameter</td>
</tr>
<tr>
<td>sort_name</td>
<td>Text</td>
<td>Parameter name used for sorting</td>
</tr>
</tbody>
</table>

**Table: It.Sample_Media**

<table>
<thead>
<tr>
<th>Column</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>media</td>
<td>Text</td>
<td>Sample media type</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table: It_Soil_Textures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field Name</td>
<td>Type</td>
<td>Size</td>
<td>Description</td>
</tr>
<tr>
<td>soil_txt_code</td>
<td>Text</td>
<td>10</td>
<td>Soil texture code (links to Locations table)</td>
</tr>
<tr>
<td>soil_txt_name</td>
<td>Text</td>
<td>50</td>
<td>Soil texture name</td>
</tr>
<tr>
<td>soil_txt_desc</td>
<td>Text</td>
<td>255</td>
<td>Description of soil texture from VI database document</td>
</tr>
<tr>
<td><strong>Table: It_Stat_Types</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stat_type</td>
<td>Text</td>
<td>20</td>
<td>Statistic type</td>
</tr>
<tr>
<td><strong>Table: It_States</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>state_fips</td>
<td>Text</td>
<td>2</td>
<td>State fips code</td>
</tr>
<tr>
<td>state_name</td>
<td>Text</td>
<td>50</td>
<td>State name</td>
</tr>
<tr>
<td>state_abbrev</td>
<td>Text</td>
<td>4</td>
<td>State abbreviation</td>
</tr>
<tr>
<td><strong>Table: It_Units</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit_type</td>
<td>Text</td>
<td>20</td>
<td>Type or category for which the units are applicable</td>
</tr>
<tr>
<td>unit_code</td>
<td>Text</td>
<td>20</td>
<td>Reported unit (abbreviation)</td>
</tr>
<tr>
<td>unit_desc</td>
<td>Text</td>
<td>100</td>
<td>Description of unit (unabbreviated)</td>
</tr>
<tr>
<td>unit_pref</td>
<td>Boolean</td>
<td>1</td>
<td>Preferred unit for the unit_type (used for setting default value)</td>
</tr>
<tr>
<td><strong>Table: References</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ref_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Unique id for references</td>
</tr>
<tr>
<td>References_text</td>
<td>Text</td>
<td>255</td>
<td>Description of reference</td>
</tr>
<tr>
<td>time_stamp</td>
<td>Date</td>
<td>8</td>
<td>Date/time record was created</td>
</tr>
<tr>
<td><strong>Table: Results</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>test_result_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Unique ID for test result</td>
</tr>
<tr>
<td>import_result_id</td>
<td>Text</td>
<td>25</td>
<td>Result ID assigned by RTI for data imports</td>
</tr>
<tr>
<td>sample_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Sample ID that this test result is for - linked to Samples</td>
</tr>
<tr>
<td>parameter_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Link to lt_Parameters. Identifies measured parameter.</td>
</tr>
<tr>
<td>parameter_name</td>
<td>Text</td>
<td>50</td>
<td>Measured Parameter name (e.g., 2-butanone, Barometric Pressure)</td>
</tr>
<tr>
<td>result_value</td>
<td>Double</td>
<td>8</td>
<td>Analytical result, field measurement, or statistical calculation</td>
</tr>
<tr>
<td>result_unit</td>
<td>Text</td>
<td>15</td>
<td>Units of measurement for the result (and result_error_delta)</td>
</tr>
<tr>
<td>result_comment</td>
<td>Text</td>
<td>255</td>
<td>Result-specific comments</td>
</tr>
<tr>
<td>lab_anl_method_code</td>
<td>Text</td>
<td>35</td>
<td>Laboratory analytical method code</td>
</tr>
<tr>
<td>report_detection</td>
<td>Text</td>
<td>20</td>
<td>report detection limit</td>
</tr>
<tr>
<td>detect_flag_yn</td>
<td>Text</td>
<td>1</td>
<td>Must be either &quot;Y&quot; for detected analytes or &quot;N&quot; for non Detects</td>
</tr>
<tr>
<td>value_type</td>
<td>Text</td>
<td>12</td>
<td>Value type (&quot;actual&quot;, &quot;estimated&quot;, &quot;interpolated&quot; or &quot;calculated&quot;)</td>
</tr>
<tr>
<td>stat_type</td>
<td>Text</td>
<td>20</td>
<td>Statistic type reflected in the result_value (links to lt_Stat_Types)</td>
</tr>
<tr>
<td>stat_obs_date_first</td>
<td>Date</td>
<td>8</td>
<td>Earliest date of sample used to determine result_value</td>
</tr>
<tr>
<td>stat_obs_date_last</td>
<td>Date</td>
<td>8</td>
<td>Latest date of sample used to determine result_value</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>test_result_comment</td>
<td>Memo</td>
<td>0</td>
<td>Comment field</td>
</tr>
<tr>
<td>fixed_gas_method</td>
<td>Text</td>
<td>255</td>
<td>Method for fixed gases</td>
</tr>
<tr>
<td>time_stamp</td>
<td>Date</td>
<td>8</td>
<td>Date/time record was created</td>
</tr>
</tbody>
</table>

**Table: Samples**

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Unique ID for each sample</td>
</tr>
<tr>
<td>sample_location_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Location ID where sample was taken at 3 D level (including depth z)</td>
</tr>
<tr>
<td>original_sample_id</td>
<td>Text</td>
<td>40</td>
<td>Sample ID in original source</td>
</tr>
<tr>
<td>sample_medium</td>
<td>Text</td>
<td>20</td>
<td>Measured medium. (links to lt_Sample_Media)</td>
</tr>
<tr>
<td>sample_start_date</td>
<td>Date</td>
<td>8</td>
<td>Date sample collection began in (MM/DD/YYYY) format</td>
</tr>
<tr>
<td>sample_comment</td>
<td>Memo</td>
<td>0</td>
<td>Comments related to the sample</td>
</tr>
<tr>
<td>Headspace_yn</td>
<td>Text</td>
<td>1</td>
<td>Soil sample only: is this a headspace measurement? (Y, N)</td>
</tr>
<tr>
<td>gw_temp</td>
<td>Double</td>
<td>8</td>
<td>Ground water samples only: GW temperature at the time of sampling</td>
</tr>
<tr>
<td>gw_temp_units</td>
<td>Text</td>
<td>10</td>
<td>Ground water samples only: Units for GW temperature (i.e. °C)</td>
</tr>
<tr>
<td>ground_cover</td>
<td>Text</td>
<td>50</td>
<td>Soil Gas samples only: Ground cover (paved, grassy, etc.)</td>
</tr>
<tr>
<td>leak_test_yn</td>
<td>Text</td>
<td>1</td>
<td>Soil Gas samples only: Has the vapor probe been leak tested? (Y, N)</td>
</tr>
<tr>
<td>vz_moisture_content</td>
<td>Double</td>
<td>8</td>
<td>Vadose zone moisture content (measured value)</td>
</tr>
<tr>
<td>vz_moisture_content_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for vadose zone moisture content</td>
</tr>
<tr>
<td>Soil_TPH_paired_result_valu e</td>
<td>Double</td>
<td>8</td>
<td>Paired soil TPH results (Links by 3D location and sample Date)</td>
</tr>
<tr>
<td>Soil_TPH_paired_result_unit</td>
<td>Text</td>
<td>15</td>
<td>Units for paired Soil TPH result (and result_error_delta)</td>
</tr>
</tbody>
</table>

**Table: Sites**

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Type</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>site_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Unique ID for site</td>
</tr>
<tr>
<td>data_provider_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Company, agency, or individual submitting VI data. Links to the Data_Provider table.</td>
</tr>
<tr>
<td>original_site_id</td>
<td>Text</td>
<td>45</td>
<td>Site identifier in original source</td>
</tr>
<tr>
<td>site_city</td>
<td>Text</td>
<td>20</td>
<td>City of site</td>
</tr>
<tr>
<td>site_state_abbrev</td>
<td>Text</td>
<td>4</td>
<td>State abbreviation for State of site (links to lt_States)</td>
</tr>
<tr>
<td>site_country</td>
<td>Text</td>
<td>50</td>
<td>Country name (links to lt_Countries)</td>
</tr>
<tr>
<td>site_hydrology</td>
<td>Text</td>
<td>255</td>
<td>Hydrogeologic Setting (links to lt_Hydrogeologic_Settings)</td>
</tr>
<tr>
<td>site_vapor_src_type</td>
<td>Text</td>
<td>50</td>
<td>Type of contamination (e.g., gasoline)</td>
</tr>
<tr>
<td>site_vapor_src_origin</td>
<td>Text</td>
<td>255</td>
<td>Origin of the vapor source (UST, spill, landfill, etc.)</td>
</tr>
<tr>
<td>public_yn</td>
<td>Text</td>
<td>1</td>
<td>Can this information be made available to the public? (Y=yes, N=no)</td>
</tr>
<tr>
<td>time_stamp</td>
<td>Date</td>
<td>8</td>
<td>Date/time record was created</td>
</tr>
<tr>
<td>Field Name</td>
<td>Type</td>
<td>Size</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------------</td>
<td>------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>source_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Unique ID for sources</td>
</tr>
<tr>
<td>sample_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Link to Sample table</td>
</tr>
<tr>
<td>site_id</td>
<td>Long Integer</td>
<td>4</td>
<td>Link to Sites table</td>
</tr>
<tr>
<td>depth_to_water</td>
<td>Double</td>
<td>8</td>
<td>Depth to water table (below land surface) at time of sampling</td>
</tr>
<tr>
<td>depth_to_water_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for depth to water</td>
</tr>
<tr>
<td>depth_to_src</td>
<td>Double</td>
<td>8</td>
<td>Depth to vapor source at time of sampling (= GW depth for GW samples)</td>
</tr>
<tr>
<td>depth_to_src_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for depth to src</td>
</tr>
<tr>
<td>NAPL_direct_indication</td>
<td>Boolean</td>
<td>1</td>
<td>NAPL based on direct indication</td>
</tr>
<tr>
<td>NAPL_reported</td>
<td>Boolean</td>
<td>1</td>
<td>NAPL based on report</td>
</tr>
<tr>
<td>NAPL_inferred_prox</td>
<td>Boolean</td>
<td>1</td>
<td>NAPL inferred from proximity</td>
</tr>
<tr>
<td>NAPL_inferred_other</td>
<td>Boolean</td>
<td>1</td>
<td>NAPL inferred from other references</td>
</tr>
<tr>
<td>NAPL_inferred_other_comment</td>
<td>Text</td>
<td>255</td>
<td>Comments on NAPL inferred from other references</td>
</tr>
<tr>
<td>Thickness_Clean_Soil_Benzene_100_ug/m3</td>
<td>Double</td>
<td>8</td>
<td>Method 1: Thickness Clean Soil Benzene 100 ug/m³ Criteria</td>
</tr>
<tr>
<td>Thickness_Clean_Soil_Benzene_100_ug/m3 (Less than)</td>
<td>Double</td>
<td>8</td>
<td>Method 1: Thickness Clean Soil Benzene 100 ug/m³ Criteria (less than)</td>
</tr>
<tr>
<td>Thickness_Clean_Soil_Benzene_100_ug/m3 (Both)</td>
<td>Double</td>
<td>8</td>
<td>Method 1: Thickness Clean Soil Benzene 100 ug/m³ Criteria (both)</td>
</tr>
<tr>
<td>Thickness_Clean_Soil_Benzene_100_ug/m3 (Refined estimate)</td>
<td>Double</td>
<td>8</td>
<td>Method 2: Thickness Clean Soil Benzene 100 ug/m³ Criteria (Refined)</td>
</tr>
<tr>
<td>Thickness_Clean_Soil_Benzene_100_ug/m3 (Greater than)</td>
<td>Double</td>
<td>8</td>
<td>Thickness Clean Soil Benzene 100 ug/m³ Criteria (greater than)</td>
</tr>
<tr>
<td>Thickness_unit</td>
<td>Text</td>
<td>20</td>
<td>Unit of measurement for thickness</td>
</tr>
<tr>
<td>Benzene GW&gt;5000(ug/L)</td>
<td>Boolean</td>
<td>1</td>
<td>Calculated Benzene GW indicator by 3D and date linkages</td>
</tr>
<tr>
<td>TPH GW&gt;30000(ug/L)</td>
<td>Boolean</td>
<td>1</td>
<td>Calculated TPH GW indicator by 3D and date linkages</td>
</tr>
<tr>
<td>Benzene Soil&gt;10(ug/g)</td>
<td>Boolean</td>
<td>1</td>
<td>Calculated Benzene Soil indicator by 3D and date linkages</td>
</tr>
<tr>
<td>TPH Soil&gt;250(ug/g)</td>
<td>Boolean</td>
<td>1</td>
<td>Calculated TPH Soil indicator by 3D and date linkages</td>
</tr>
<tr>
<td>Source_type_calculated</td>
<td>Text</td>
<td>255</td>
<td>Source type (NAPL or Dissolved)</td>
</tr>
</tbody>
</table>
Appendix B. PVI Database Entity Relationship Diagram

PVI Database Diagram (draft)
April 17, 2012

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<table>
<thead>
<tr>
<th>Commenter</th>
<th>Charge Question</th>
<th>Guidance Section</th>
<th>Line Number</th>
<th>Details</th>
<th>Comment</th>
<th>EPA Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>EnviroGroup</td>
<td>[In reference to] the scientific appropriateness of the database for OUST’s purposes - The database is appropriate for application to USTs, but very weak in evaluation of diesel and high-ethanol fuels.</td>
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<td>The limited number of diesel sites is not viewed as a significant limitation because source petroleum hydrocarbon vapor concentrations at diesel sites are orders of magnitude lower than those at gasoline sites and therefore oxygen limitations and reduced bioattenuation are less of an issue than at gasoline sites. Therefore a focus on gasoline sites is conservative. One new site with a diesel source has been added to the database. Given the time-frame over which site data in the PVI database was obtained it is expected that some sites gasoline contains ethanol (10-15%). The limited data on ethanol is recognized as a limitation and there is on-going research that is expected to address this question. As warranted the findings of the research work should be incorporated in updated PVI guidance.</td>
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<td>EnviroGroup</td>
<td>[In reference to] whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST’s purposes - The analyses and methods are appropriate for OUST’s purposes, but some areas of incomplete analysis are present as described below.</td>
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<td>Additional analyses have been conducted to address these concerns</td>
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<td>EnviroGroup</td>
<td>[In reference to] whether the reported conclusions are adequately supported by the data and analyses. The conclusions for BTEX appear to be adequately supported by the data and analyses for UST sites. Additional data and analysis is needed for non-UST sites, for diesel sites, for high ethanol fuel sites, and for petroleum additives.</td>
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<td>Additional analyses have been conducted for non-UST, diesel and petroleum additives.</td>
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<td>EnviroGroup</td>
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<td>1</td>
<td>Yes</td>
<td>No revision warranted.</td>
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<td>EnviroGroup</td>
<td>The first three objectives appear to have been met. Additional review of published modeling studies pertaining to the effects of low permeability layers and impermeable surface cover appears to be warranted. The development and support for methods for lateral exclusion distance criteria is generally lacking. Additional data is required for sites known to have high ethanol fuels or diesel. Additional data is required to support utilization of this approach at non UST sites.</td>
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<td>2</td>
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<td>Additional analyses are conducted for diesel sites and for non-UST sites. In addition, modeling studies where low permeability soil layers are evaluated are summarized.</td>
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<td>EnviroGroup</td>
<td>The report does not address potential vapor intrusion issues related to fuel additives (e.g., MTBE, 1,2-dichloroethane, ethylene dibromide) or trimethylbenzene components of diesel. The report does not provide adequate data or analysis to evaluate the impact of biodegradation on methane generation from high ethanol content gasoline. Very limited data on diesel sources is included in the database (3 sites) and no separate evaluation of vapor intrusion behavior at such sites is included.</td>
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<td>Additional analyses have been conducted for MIBE and for diesel sites. There are limited data for 1,2-dichloroethane and ethylene dibromide so it is not possible to conduct similar exclusions analyses for these compounds, but a comprehensive summary of the published information on these chemicals is added as Appendix F.</td>
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<td>Commenter</td>
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<td>EnviroGroup</td>
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<td>The criteria for data acquisition for the underlying studies is described only to a limited extent. The data of Peargin and Kolhatkar (2011) is not mentioned as part of the database. To our knowledge, Davis has adequately screened the database that she used.</td>
<td>As we understand it, the data were collected over a period of years, beginning with a comprehensive set of data from Utah regulatory studies, that was, as mentioned by the commenter, adequately screened. Data were likely gathered in an opportunistic fashion, but because they were collected by Ms. Davis, were screened in a consistent manner as the Utah sites were. The end result was the most extensive set of data available for U.S. UST sites. The Peargin et al. Chevron dataset was not made available to us for compilation, but their publications have suggested largely consistent conclusions with the Davis/EPA dataset. It also is consistent with the large Australian dataset, which is a line of evidence that the data are adequate for its intended purpose to support EPA and state decisions on exclusion criteria. The Australian data were added to the most recent version of the database and were independently analyzed as described in a new appendix. A few other sites that became available since the original study were also added in the latest report and database, and additional detail was added to document the data acquisition and quality criteria used in the study.</td>
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<td>EnviroGroup</td>
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<td>The database does not contain adequate data or analysis to evaluate biodegradation of high ethanol content gasoline. The database does not contain adequate data or analysis to evaluate diesel release sites (only three sites have diesel). The database does not appear to be sufficiently large enough or representative of non-UST sites (there are only seven such sites in the database).</td>
<td>Two additional diesel and two additional non-UST sites have been added. With respect to ethanol, some additional text on its behavior based on recent literature was added, although the commented is right that data on high-ethanol content gasoline is either absent or not marked as such in the database. Some sites in the EPA PVI database where recent releases occurred probably had gasoline containing ethanol, but from the available information it is not possible to quantify how many.</td>
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<td>Yes.</td>
<td>No revision warranted</td>
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<td>EnviroGroup</td>
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<td>Soil moisture effects could use some additional data and evaluation at the low moisture content end of the spectrum. Insufficient information is provided to determine if oxygenated fuels behave differently. Evaluation of the impacts of impervious surface cover needs expansion for non-UST sites.</td>
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<td>EnviroGroup</td>
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<td>Fuel additives (e.g., MTBE, 1,2-dichloroethane, ethylene dibromide) are not addressed, although data for MTBE is available for 13 sites. Given the very low RBCs for 1,2-dichloroethane, this may be an important data gap for historic (leaded gasoline) fuel releases containing 1,2-DCA. API has numerous publications on the biodegradation of MTBE which might be cited. Naphthalene data is available for 18 sites in the database, but is not addressed, presumably due to it’s relatively low Henry’s Law constant. Trimethylbenzenes at diesel release sites are not addressed. These VOCs have fairly low Hazard Indexes and can be present at greater concentrations than benzene.</td>
<td>MBTE, naphthalene and trimethylbenzenes analyses added.</td>
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<td>EnviroGroup</td>
<td>2.4 438-437</td>
<td>The statement that “releases of fuel containing 10% ethanol are most likely included in the reviewed database” should be supported by data in Appendix C.</td>
<td>Existing text: “Note that releases of fuel containing 10% ethanol (E10) are most likely included in the reviewed database (this document, see Section 5.3) and in Lahvis et al. (In prep.).” revised as follows: “Note that some sites with releases of fuel containing 10% ethanol (E10) are most likely included in the reviewed database (this document, see Section 5.3) and in Lahvis et al. (In prep.). This issue is further addressed in Section 5.3, although data on gasoline composition is limited.”</td>
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<td>EnviroGroup</td>
<td>2.5 491-504</td>
<td>Former Refinery Site (Unknown location) (Luo et al., 2010): This empirical data presents strong evidence for the impact of background oxygen uptake in surface soils and for physically limited oxygen transport due to low permeability shallow soils. The latter is especially significant and should be expanded upon and considered in any screening criteria.</td>
<td>The screening criteria is revised to include discussion on the importance of the potential effect of low permeability shallow soils on soil vapor transport.</td>
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<td>EnviroGroup</td>
<td>2.5 512-517</td>
<td>UST Site, Stafford, New Jersey: This case study suggests that vapor intrusion from MTBE and 2,2,4-TMP might be more likely than benzene due to their higher solubility and possibly lower attenuation. This example should prompt further evaluation of MTBE in the database and collection of additional data on 2,2,4-TMP.</td>
<td>Analyses of MTBE and 2,2,4-TMP have been added. With one exception of one site (Stafford), MTBE vapors were attenuated to relatively low concentrations before reaching building. Attenuation of 2,2,4-TMP is described below.</td>
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<td>EnviroGroup</td>
<td>3 543-545</td>
<td>The statement regarding “available data suggest bioattenuation distances may be greater for aliphatic hydrocarbons compared with aromatic hydrocarbon compounds” should be expanded upon.</td>
<td>Added: For example, greater concentration attenuation between deep and shallow soil vapor was observed for benzene compared to 2,2,4-TMP at the Stafford site, where the ratio between deep and shallow soil vapor concentrations was 220 times lower for benzene compared to 2,2,4-TMP (Sanders and Hers, 2006), and at the North Battleford site, where the difference was 40 times (Hers et al., 2012)</td>
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<td>EnviroGroup</td>
<td>3.1 600-615</td>
<td>3-Dimensional Model Simulations (EPA 2012b): This section should have some figures to illustrate the lateral separation impact. In addition, the simulations for fine-grained, low permeability soils and “impermeable” ground cover should also be discussed.</td>
<td>Figures added. The applicable simulations from EPA 2012b have been summarized, and while it would be helpful to have additional simulations that address additional different ground cover scenarios, they are not available.</td>
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<td>EnviroGroup</td>
<td>6.2 828-829</td>
<td>Database Structure: Information on the release date and ethanol content of the fuel would also be important to include.</td>
<td>This information is not available</td>
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<td>EnviroGroup</td>
<td>6.2 834-836</td>
<td>Database Structure: Information on the lateral distance between soil gas probes and buildings is included in the database, but was not evaluated in the analysis.</td>
<td>An analysis between distance between soil gas probes and buildings is not considered relevant because the database is not being used as a predictive tool to estimate indoor air concentrations. Note that the distance between soil gas probes and monitoring wells was relatively small and not considered a significant factor (median distance = 5 ft., average distance = 8.3 ft, N=229)</td>
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<td>EnviroGroup</td>
<td>6.3 874-875</td>
<td>Database Structure: The statement that “some sites in the database where recent releases have occurred likely have gasoline containing ethanol” should be documented. Possibly an estimated release date could be added.</td>
<td>There is limited documentation on ethanol content in fuels. Not feasible to add a release date.</td>
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<td>EnviroGroup</td>
<td>6.3 876-878</td>
<td>Database Structure: Note that few large buildings are included in the database, so the applicability to large buildings may be limited. The citation to Table 3 should be changed to Table 4.</td>
<td>Added to text “Thus, the applicability of the database to large buildings may be limited.”</td>
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<td>EnviroGroup</td>
<td>Tables 1701-1704</td>
<td>Table 6 Note that two sites footnoted on Table 6 have dissolved plumes with benzene at 12 mg/L (100% of effective solubility). Do these two sites fall with 95% probabilities by the separation distance method? Note that the sensitivity analysis for the Vertical Distance Method, in Section 8.2 (lines 1191-1196), does not extend beyond 10 mg/L benzene in groundwater and thus does not include values representative of these two sites.</td>
<td>These two sites fall within the 95% probability. There was rapid attenuation of benzene vapour concentrations at these sites.</td>
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<td>EnviroGroup</td>
<td>7.1.3</td>
<td>968-970</td>
<td>Proximity to Fuel Storage/Dispensing Facilities: This section discusses the use of a threshold distance of 20 ft &quot;to approximately correspond to the exclusion criteria distance that was estimated for LNAPL sites, as subsequently indicated in this report&quot;. No such lateral exclusion distance is discussed at a later point in the report.</td>
<td>The point is not to comment on lateral distance but simply a distance that would be appropriate for screening of sites. Text simplified.</td>
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<td>EnviroGroup</td>
<td>Figures</td>
<td>1747</td>
<td>Figure 8 This figure needs a legend identifying the red values (presumably benzene in ug/m3) and the blue values (presumably oxygen in %). Area 2 is not discussed.</td>
<td>Legend added. Area 1A adequately describes method, Area 2 does not need to be discussed.</td>
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<td>EnviroGroup</td>
<td>8.1</td>
<td>1140-1143</td>
<td>Exploratory Data Analysis: The report notes a poor correlation between groundwater and soil vapor concentrations (of benzene). This suggests that caution is needed when using groundwater benzene concentrations as a screening criteria for identification of LNAPL plumes.</td>
<td>Agreed. This point is made in report discussion and conclusions.</td>
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<td>EnviroGroup</td>
<td>8.1</td>
<td>1156-1161</td>
<td>Exploratory Data Analysis: The report notes that methane data are available for 23 sites, but no separate analysis was undertaken to determine if sites with high methane concentration demonstrated different behavior than those with low concentrations.</td>
<td>Methane analysis added.</td>
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<td>EnviroGroup</td>
<td>8.2.1</td>
<td>1214-1215</td>
<td>Vertical Distance Method: The notation that source separation distances increase to approximately 30 feet for non-UST LNAPL sources should be reiterated in the conclusions.</td>
<td>Agreed. This point is made in report discussion and conclusions.</td>
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<td>EnviroGroup</td>
<td>8.2.1</td>
<td>1218-1219</td>
<td>Vertical Distance Method: Is there an explanation for the apparent lack of biodegradation of 2,2,4-TMP at the two sites illustrated on Figure 16 (lines 1779-1780)?</td>
<td>Comment addressed in footnote #3.</td>
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<td>EnviroGroup</td>
<td>8.2.2</td>
<td>1233-1235</td>
<td>Influence of Surface Cover: It should be noted that the upper probability achieved for the pavement cover case in Figure 17 (line 1781) is less than 95%, even at a 30 foot separation distance. It is not true that the pavement and building scenario &quot;yielded similar results&quot; based on Figure 17.</td>
<td>Revised.</td>
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<td>EnviroGroup</td>
<td>8.2.3</td>
<td>1257-1261</td>
<td>Influence of Soil Type: It would be helpful if the results from modeling were discussed here, along with some discussion of theoretical expectations. The modeling studies by EPA (2012) generally showed some capping effect for surficial, low permeability soils. More detailed analysis of the impact of soil stratigraphy would be helpful.</td>
<td>Statement added on case study results by Luo et al (2010) where layered system may have influenced observed attenuation.</td>
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<tr>
<td>EnviroGroup</td>
<td>Figures</td>
<td>1791</td>
<td>Figure 19 The lack of plotted data points for fine-grained soils beyond a separation distance of 12 feet for the NAPL case implies lack of data in the database. Is this correct? If so, extrapolating results of this analysis to sites with fine-grained soils and NAPL may be problematic.</td>
<td>Added. The evaluation of data trends is limited by absence of fine-grained data beyond 14 ft separation distance</td>
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<td>EnviroGroup</td>
<td>8.3</td>
<td>1271-1277</td>
<td>2nd bullet It should be noted that the required thickness of clean soil for LNAPL sources increases with increasing groundwater concentration according to figure 21 (line 1797).</td>
<td>No revision warranted - this is stated.</td>
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<td>EnviroGroup</td>
<td>9.2</td>
<td>1338-1339</td>
<td>The exclusion of fractured rock unsaturated zones should be reiterated in the conclusions.</td>
<td>Revised.</td>
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<td>EnviroGroup</td>
<td>9.3</td>
<td>1351-1354</td>
<td>Exclusion Distance Assessment Framework: Could a deep soil gas concentration threshold be utilized for identifying LNAPL? Soil concentrations appear to provide the most reliable indicator. The vertical distance method indicates a small probability for vapor concentrations above thresholds for distances as little as 0 ft; the report should discuss how capillary rise affects this observation (if the building is within the capillary fringe, is the groundwater considered to be in contact with the building)?</td>
<td>The text has been revised to indicate that deep soil gas, while not correlated to dissolved groundwater concentrations, can be used as a line of evidence to identify NAPL. The height of the capillary fringe is also mentioned as a consideration when estimating inclusion distances.</td>
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<td>EnviroGroup</td>
<td>9.5</td>
<td>1375-1381</td>
<td>Lateral Exclusion Distance: This section suggests that lateral exclusion distances should be larger than vertical exclusion distances, especially for non-UST sites and that they should be similar to vertical distances for UST sites. This is at odds with the limited statements in the remainder of the document that suggest no lateral exclusion distance.</td>
<td>The discussion has been revised to be more generic indicating that practically lateral distances should be greater than vertical distances because of site investigation limitations and data density, but that recommendations on lateral distances goes beyond scope of this report. The ORD issue paper on lateral inclusion zone will address this issue (Wilson et al. In Prep.).</td>
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<td>EnviroGroup</td>
<td>10</td>
<td>1390-1453</td>
<td>Conclusions: The report suggests that more detailed PVI assessment may be warranted at large building sites, such as apartment complexes or commercial/industrial buildings. This is a very subjective factor that could make application of an exclusion distance difficult. Can the database or modeling studies provide any more insight into a building size criterion?</td>
<td>The database is limited to small to moderate sized buildings. It may be possible to define an approximate building size range where based on the data there do not appear to be concerns for oxygen limitations, but there is little basis for establishing a single &quot;bright line&quot; size threshold for concerns. EPA is conducting modeling that may help provide a more quantitative basis that together with this analysis could be used to establish thresholds.</td>
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<tr>
<td>McAary</td>
<td>General Comment</td>
<td>If the data used in the analysis are all high quality and if the uncertainty in the calculated exclusion distances are negligible (neither of which have been demonstrated), the bottom line is that dissolved phase source can be neglected unless there is a very shallow water table and NAPEL sources can be neglected if the building is more than 30 feet away (which is already a fairly typical exclusion distance). This could be summarized in a much, much shorter document. There is far too much redundancy, and at the same time, far too many vague statements. What is needed is to get to the point, do so in comprehensive detail, and clearly state the uncertainties in the outcome.</td>
<td>Based on input from other reviewers and EPA, the document length is considered appropriate. It is noted that there are several comments by this reviewer requesting additional details or explanation, so the comment on document length is inconsistent.</td>
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<td>McAary</td>
<td>General Comment</td>
<td>It is not enough to simply focus on exclusion distances. The report refers to &quot;screening criteria&quot; in the title, and &quot;screening methods&quot; in the text, as if these are interchangeable and the exclusion distance is the only component. This is not true. If petroleum hydrocarbons behave significantly differently than chlorinated solvents, then it is fair to treat them differently during a PVI assessment; however, this has many implications for the scope and methods of assessment, which have been noted throughout the edited document. For example, I find a landfill gas meter is invaluable for assessing soil vapor conditions at a hydrocarbon site and seldom informative at chlorinated solvent sites. If hydrocarbons degrade and therefore do not travel far, then the sample spacing required to minimize the risk of failing to identify a hot-spot would have to be much closer than for persistent chlorinated solvent vapors. The list goes on and on. The draft OUST Guidance does not address all of the implications raised in this document, and it is not clear whether the two are intended to be complimentary or not. Either way, one of the documents needs to provide guidance on the site characterization that is sufficiently detailed to distinguish the extent of NAPL, and for buildings that are not excluded, the scope and methods of data collection needed to make a determination whether PVI poses a risk or not. At present, this is a major gap.</td>
<td>This document provides more than exclusion distances but also provides a framework for inclusionary criteria and information on petroleum hydrocarbon behaviour. Guidance on assessment approach and methods for screening of PVI sites is addressed in separate EPA OUST guidance document.</td>
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<td>McAlary</td>
<td>General Comment</td>
<td>There are certain conditions that have been excluded (preferential pathways, fractured rock, large buildings, etc.). It is important to incorporate methods of dealing with these circumstances in the screening process. If any of these occur, is indoor air sampling needed? Or would it be necessary to collect vertical profiles of soil vapor concentrations through the floor of each building? If no guidance is provided to inform the regulators, practitioners and owners how to proceed, then the document really hasn’t advanced the status quo.</td>
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<td>The conditions have been discussed from a technical perspective. Guidance on assessment approach and methods for screening of PVI sites is addressed in separate EPA OUST guidance document.</td>
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<td>McAlary</td>
<td>General Comment</td>
<td>There are far too many instances in the report where a topic is discussed in a sentence or two that really needs a couple of paragraphs or pages to be sufficiently detailed for the average regulator or consultant. Methane can be a dominant contribution to oxygen demand, so it needs much more extensively discussed and incorporated in the screening process. Oxygen is the reason hydrocarbons can be degraded, yet the correlation between O2 and TPH in the database is not consistent with theoretical expectations, and that indicates either a poor conceptualization or poor data quality. Lots of the sites in the database don’t even have oxygen or methane data, which I would consider to be essential for verifying data quality. There is no discussion at all regarding whether samples were collected from temporary probes or properly sealed soil vapor implants, which in my experience is a critical determinant to data quality in all soil types except uniform medium to coarse sand.</td>
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<td>The correlation between O2 and TPH is consistent with expectations with only a few outliers. Major revision has been made to Section 8 to support this. Approximately 60% of sites have O2 and CO2 data. Extensive information provided on data quality. The data quality is considered relatively high for most soil gas samples.</td>
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<td>McAlary</td>
<td>General Comment</td>
<td>Considering the extent of the comments and the significance of the omissions, this reviewer recommends a major revision.</td>
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<td>Major revisions made.</td>
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<td>McAlary</td>
<td>Comment on General Charge Question</td>
<td>(In reference to) the scientific appropriateness of the database for OUST’s purposes - I consider the database to be dubious at best. While lots of sites are included, the distribution is very skewed so a small number of sites contribute the majority of the data. Practitioners have over the period that this data was collected used a wide range of sampling and analytical methods, and standards of QA/QC and care, so without knowing who collected and analyzed the samples, I can’t have a lot of confidence in the results. Temporary probes are common, but in my experience, they leak a lot and especially should not be used in low permeability materials, but there is not enough information to be able to tell whether or to what extent this occurred. There are indications of questionable data quality (soil gas samples with high TPH and O2, which is not expected in nature, and is expected if a sample with high TPH and low O2 concentrations was subject to addition of atmospheric air from a leaking fitting or seal). Furthermore, there is a huge amount of scatter (i.e., poor correlations) in the data, so any values calculated must also consider the associated error bars, which would be huge.</td>
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<td>Extensive information is provided on data quality. The data quality is considered relatively high for most soil gas samples. When taken in broader context, the USEPA and Australian database (as well as evaluation by Peargin and Kolhatkar) show similar trends for exclusion distances.</td>
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<tr>
<td>McAlary</td>
<td>Comment on General Charge Question</td>
<td>(In reference to) whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST’s purposes - The analysis essentially concludes that dissolved hydrocarbons only pose a risk if the source/building separation is very small and NAPL can pose a risk to about 30 feet, with the caveat that sites with preferential pathways, fractured rock, large buildings, etc. are not included. If that is all that the report will be used for, the analyses are appropriate.</td>
<td></td>
<td></td>
<td>No revision warranted</td>
<td></td>
</tr>
<tr>
<td>Commenter</td>
<td>Charge Question</td>
<td>Guidance Section</td>
<td>Line Number</td>
<td>Details</td>
<td>Comment</td>
<td>EPA Resolution</td>
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<tr>
<td>McAlary</td>
<td>1</td>
<td>General Charge Question</td>
<td>34</td>
<td>In reference to whether the reported conclusions are adequately supported by the data and analyses - The data is not highly reliable, as stated above.</td>
<td>No, it is repetitive and vague and much, much longer than it needs to be to support the outcome. The database is missing several key components that are essential to verifying the integrity of the data.</td>
<td>Data reliability framework has been added</td>
</tr>
<tr>
<td>McAlary</td>
<td>2</td>
<td>General Charge Question</td>
<td>68</td>
<td>The comment on one hand indicates that the document is much longer than needed but indicates components are missing. To address the second part of this comment, there is an enhanced discussion in text on data quality.</td>
<td>No, the report does not address the final objective: “Identify methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.” In my opinion, there needs to be a robust and consistent method for site assessment that forms the foundation for that selection. If a site is poorly characterized, it doesn’t matter how good the decision criteria or exclusion distances are. Far too many people take it for granted that site assessment is true, accurate and complete, and in my experience, it is far more complicated than that. It would be acceptable to refer to another guidance document if one existed that meets this need, but the OUST draft guidance also does not address all of the implications raised in this draft document.</td>
<td>The database report identifies criteria upon which sites may be screened but details with respect to application of the criteria and methods are addressed in the OUST draft guidance.</td>
</tr>
<tr>
<td>McAlary</td>
<td>3</td>
<td>General Charge Question</td>
<td>91</td>
<td>The database report identifies criteria upon which sites may be screened but details with respect to application of the criteria and methods are addressed in the OUST draft guidance.</td>
<td>No, please add details of whether probes were temporary, PRT, or implants, whether purging was monitored to ensure steady readings, whether a shut-in test was performed and whether a helium test was performed. If you don’t know how many soil gas samples had atmospheric air leaks, you don’t really know what caused the attenuation. A mass balance on O2 and CO2 might help. Not clear why the last bullet is part of the Charge Questions. If exclusion criteria are adopted as concluded in this draft report, will attenuation factors still be needed? I would expect the only sites remaining would be basements with dissolved hydrocarbons and buildings with a foundation within 30 ft of NAPL, and it seems pre-emptive mitigation would be appropriate in either case. That’s not specifically stated anywhere, which is another reason why this document is incomplete.</td>
<td>No revision warranted.</td>
</tr>
<tr>
<td>McAlary</td>
<td>4</td>
<td>General Charge Question</td>
<td>123</td>
<td>Detailed information on probe design and leak testing at each site was added to the report, including cases where the information was not available in original sources. Discussion of mitigation actions (preemptive or not) are beyond the scope of the report.</td>
<td>There are enough sites, but the data is skewed to a small number of sites with a large number of samples, and the data quality has not been adequately defended, so I would say no.</td>
<td>No response warranted.</td>
</tr>
<tr>
<td>McAlary</td>
<td>5</td>
<td>General Charge Question</td>
<td>154</td>
<td>Detailed information on probe design and leak testing at each site was added to the report, including cases where the information was not available in original sources. Discussion of mitigation actions (preemptive or not) are beyond the scope of the report.</td>
<td>No. Considering the uncertainties, the outcomes (exclusion distances) should be expressed with a range of possible error (i.e., X +/- Y), not as a single value.</td>
<td>No revision made. The different number of data points per site is an unavoidable outcome of the empirical analysis and is not considered a significant limitation. The fact remains that there are measurements from from approximately 74 sites. There is an enhanced discussion in text added on data quality.</td>
</tr>
<tr>
<td>McAlary</td>
<td>6</td>
<td>General Charge Question</td>
<td>186</td>
<td>No revision made. It is not possible to attribute uncertainty and error bars to exclusion distances. However, the probability analysis conducted provides a range of outcomes for different source-separation distances.</td>
<td>No. No, but it may not matter much. Most guidance uses an exclusion distance of 30 feet anyway, and that’s pretty much the same value as determined in this draft report.</td>
<td>No response warranted.</td>
</tr>
<tr>
<td>McAlary</td>
<td>7</td>
<td>General Charge Question</td>
<td>204</td>
<td>No. No, but it may not matter much. Most guidance uses an exclusion distance of 30 feet anyway, and that’s pretty much the same value as determined in this draft report.</td>
<td>No response warranted.</td>
<td>No response warranted.</td>
</tr>
<tr>
<td>McAlary</td>
<td>8</td>
<td>General Charge Question</td>
<td>236</td>
<td>No response warranted.</td>
<td>No response warranted.</td>
<td>No response warranted.</td>
</tr>
<tr>
<td>Commenter</td>
<td>Charge Question</td>
<td>Guidance Section</td>
<td>Line Number</td>
<td>Details</td>
<td>Comment</td>
<td>EPA Resolution</td>
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<tr>
<td>McAlary</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>I provided two additional papers with carefully collected data that would add to the existing database. John Wilson of EPA Lab in Oklahoma is also interested in this subject and may have other resources. 1) Effects of Alternate Petroleum Hydrocarbon Sources in the Vadose Zone on the Vapor Intrusion Pathway beneath a Residential Community (Paul Michalski, Shannon Thompson, Charlie DeWolf, Paul Nicholson, Todd McAlary; and 2) A CASE STUDY ON THE INFLUENCE OF AEROBIC BIODEGRADATION ON VAPOR INTRUSION AT A FORMER REFINERY PROPERTY (Todd McAlary, Paul Nicholson, David Bertrand, Hester Groenevelt and Robert Ellinger (2010)</td>
<td>Data from the first paper already in the database. Data from the second report is added.</td>
</tr>
<tr>
<td>McAlary</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>It’s not really clear to me why this report is needed. How is it different than the OUST Guidance, and why isn’t it simply combined with the OUST guidance? In my review of Table 3 of the current draft OUST Guidance, I’m not sure anything further is an improvement, and this draft raises far more questions than it answers.</td>
<td>Introductions provides additional clarification on purpose of the two documents.</td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 100</td>
<td>Source Zone Identificatio n Methods</td>
<td>Add O2/CH4, FID, soil staining, odor, and Radon as evidenced by mineral precipitates</td>
<td>Soil staining, odours and CH4 added. Radon not considered standardized approach for source zones.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 105 &amp; 110</td>
<td>Exploratory Data</td>
<td>Not everyone uses the term Exploratory Data</td>
<td>Exploratory data analysis is defined in the document and executed as defined. No revision made as it is not an incorrect term per se.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 108</td>
<td>Soil Vapor Concentrati on Thresholds</td>
<td>Move to in between 7.1.2 Soil Concentration Data and 7.1.3 Proximity to Fuel Storage Dispensing Facilities</td>
<td>No revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 120 &amp; 121</td>
<td>Exclusion Distance Assessment Framework &amp; Lateral Exclusion Distances</td>
<td>This is good, but not enough. There should also be recommendations for what kind of data is needed to support the initial characterization and what spacing and frequency is acceptable. Also add recommendations for follow-up actions (further characterization or mitigation) when exclusion is not supported.</td>
<td>No revision - this recommendation goes beyond scope of this report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 176</td>
<td></td>
<td>How many ND values had elevated reporting limits? These should not be considered “clean.”</td>
<td>No revision made. The purpose here is to show general relation between groundwater and soil vapor concentrations. Raised reporting limits is not relevant for this analysis.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Table of Contents 179-180</td>
<td></td>
<td>Oxygen below detection almost never happens.</td>
<td>The report includes an enhanced discussion on measurements methods and data quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>219-220</td>
<td></td>
<td>This has at least three components: 1) What data are necessary and sufficient for screening? 2) What criteria screen as positive or negative? 3) What follow-on actions are necessary when positive? It seems like the focus is only on item #2.</td>
<td>The main focus is item #2 but item #1 is indirectly addressed. The rationale for not addressing #3 is provided in the text.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>1.1 234</td>
<td></td>
<td>Compared to chlorinated compounds; therefore screening PHCs using the same methodology as CI VOCs is overly conservative and risks waste of resources.</td>
<td>Text added &quot;compared to chlorinated hydrocarbons; therefore, screening for PHCs using the same methodology as chlorinated hydrocarbons is overly conservative&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Elaborate on how and why this is useful, how it fits into a screening program and how it improves on the existing status quo.

An exclusion distance approach potentially improves upon existing regulatory frameworks based on extensive site investigation for soil vapor intrusion studies in that it provides for a more efficient approach. It also focuses resources on inclusionary sites with significant potential for vapor intrusion issues.

McAlary 1.1 240
Start a new paragraph after "negligible." Combine this new paragraph with the next paragraph that starts at line 243.

Revision made.

McAlary 1.1 247
End sentence and add period after "Davis 2009." 

Revision made.

McAlary 1.2 265 & 276
"assessment framework" and "set of criteria" in line 265. These are two different things. Need to make sure you addressed both of them in the "key part" line 276.

This report addresses a key part of this framework: the evaluation PHC vapor attenuation and identification and justification of exclusion distances between contamination and receptors that can be used to quickly assess whether the PVI pathway is complete. However, the scope of this study did not include development of the detailed framework and criteria that will be needed to apply these exclusion distances, which are described in separate guidance on PVI being prepared by US EPA.

McAlary 1.2 278-280
Why not? These are inexorably linked. If PHCs degrade and therefore don’t migrate as far, samples would need to be more closely-spaced to avoid missing a hot-spot!

Beyond scope of this report.

McAlary Endnote 2
[In reference to "measureable"] Labs can quantify to parts per trillion. That’s not necessary or appropriate.

Reference deleted

McAlary Endnote 2
[In reference to "measureable"] Above RBSLs Reference deleted

McAlary General Comment
See comment in Introduction. If you intend to provide a new screening methodology, the criteria for decision-making is only one piece.

The intention is not to describe the details of a new screening methodology.

McAlary 2.1 313
Add "light, non aqueous phase liquids or" before LNAPLs

No revision made - already defined

McAlary 2.1 General Comment
Need to also discuss methanogenesis, CH4 impact on O2 demand, potential for explosions, etc.

Text already addressed these points, but new section written to emphasize this issue

McAlary 2.1 315 Add "partially" after LNAPL.

Revision made

McAlary 2.1 318 Add "or as water percolates through residual LNAPL in the vadose zone." after "groundwater"

Revision made

McAlary 2.1 320
[In reference to sentence starting with "Melthane"] This should not be under this heading. Create a new section, and cover the anaerobic processes more completely.

Revision made

McAlary 2.1 323
[In reference to fuel oxygenates] Need a tie-in sentence. How is this relevant?

Minor revision made to indicate fuel oxygenates present in addition to PHC. Tie sentence considered not needed

McAlary 2.1 329
[In reference to "greatly reduced"] Vague: use more specific terminology, eg: 1,000-fold reduction over 1m or so.

Revised to indicate orders-of-magnitude concentration attenuation, indicating 1000 fold attenuation is much too specific and not appropriate

McAlary 2.1 331, 348 & 349
Is it just one process or many? [as implied by different species in line 348 and direct metabolism and co-metabolism in line 349]

Changed to plural

McAlary 2.1 333
If this doesn't get published, why not spell out the flux balance concept here? [ref. Lahvis et al. in prep]

No change - not considered warranted because Lahvis article accepted

McAlary 2.1 335 & 345
[In reference to “DeVaull, 2007b” & “Zobell...”] Are there no other citations for rates?

Citation added - This section is already well referenced with additional citations for rates at end of Section 2.2

McAlary 2.1 335 & 337
[In reference to “typically” line 335 and “orders of magnitude” line 337] Vague.

No change made - Not considered vague, see response to comment on line 329

McAlary 2.1 338 Is advection important?

Advection deleted to simplify concept

McAlary 2.2 344-362 General Comment
[with ref to 2.2 discussion lines 344-362] Lots of information here, and no discussion of whether any of these factors need to be measured (and if so, how?), or if not, why not.

No revision made - Given that this is CSM discussion, a discussion of which factors should or should not be measured is not considered warranted for this section of report

McAlary 2.2 362
Does Leeson and Hinchee, 1996 address rates?

Reference added
<table>
<thead>
<tr>
<th>Commenter</th>
<th>Charge</th>
<th>Guidance</th>
<th>Line Number</th>
<th>Details</th>
<th>Comment</th>
<th>EPA Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>McAlary</td>
<td>2.2</td>
<td>Section 2.2 in its entirety (Lines 343-379)</td>
<td>363-370</td>
<td>This section needs to be restructured. Currently there are 3 paragraphs. The first talks about everything, without saying what matters, the second nothing matters, and the third says what REALLY matters, without saying what is needed to provide enough data on these factors.</td>
<td>No change made. Restructuring not considered necessary, see response to comments on lines 344-362 (Column G, Row 85)</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.2</td>
<td></td>
<td>375-376</td>
<td>[Add] and supply (i.e., flux balance); Added: &quot;and supply (i.e., flux balance)&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.2</td>
<td>In reference to &quot;(properties)&quot; porosity and moisture content (not sure which other properties matter)</td>
<td>378</td>
<td></td>
<td>Added: &quot;e.g., soil porosity and moisture&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.2</td>
<td>Need to say how each of these must be characterized as part of a PVI screening process!</td>
<td>374-379</td>
<td>What is an acceptable level of uncertainty?</td>
<td>No change made. Given that this is CSM discussion, recommendation of which parameters must be characterized is not considered warranted.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.3</td>
<td>Far better to add a table and show all this with numbers.</td>
<td>381-394</td>
<td></td>
<td>No revision made - This section describes processes so it is not clear how this could be summarized in table with numbers. Some language was added to illustrate the first principal that the more soluble hydrocarbons in dissolved plumes are also smaller and more volatile than those in NAPL.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.3</td>
<td>Explain lower biodegradation rates</td>
<td>388</td>
<td></td>
<td>Reference to lower biodegradation rates deleted</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.3</td>
<td>Replace &quot;study&quot; with studies and define &quot;meta analyses and database evaluations&quot;</td>
<td>403</td>
<td>The distribution of LNAPL sources and presence of residual NAPL within the unsaturated soil zone (i.e., in release zones) compared to LNAPL at the water table can influence the volatilization potential. For LNAPL sources at the water table, the position of the water table relative to the smear zone can be important, and seasonally higher volatilization rates can occur when the water table is low and below a portion of the smear zone.</td>
<td>Revised as &quot;case studies and database evaluations&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>Compare and contrast this to the list in lines 374-379. Why have both?</td>
<td>409-445</td>
<td>The discussion under lines 409 to 445 provides factors that can increase the potential for vapor intrusion and provides a more detailed discussion than the bullets under lines 374-379, which are intended to provide overview of factors that may affect vapor intrusion, and that both can increase or decrease the potential for vapor intrusion. For these reasons, both sections are needed.</td>
<td></td>
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</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>Define (preferential pathway)</td>
<td>414</td>
<td></td>
<td>Revision made</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>Need ΔP in addition to high gas K</td>
<td>416-418</td>
<td>No revision made - Diffusion may also be important</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>What about wet clay (outside building) and dry, dessicated and fractured clay beneath the building?</td>
<td>419-431</td>
<td>Revised to include clay layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>Add * in the range of ___ to ___&quot; after &quot;measured rates&quot;</td>
<td>426</td>
<td>Rates added</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>Create new sentence after &quot;zones&quot;</td>
<td>433</td>
<td>Revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>In reference to &quot;(most likely)&quot; Vague</td>
<td>436</td>
<td>Revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>General Comment on Section</td>
<td>439-441</td>
<td>Some amount of data is pretty critical. No revision warranted for this section of the report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>General Comment on Section</td>
<td>444</td>
<td>Methane would be produced under anaerobic conditions. We are not aware of published data for UST sites where there was significant pressure build-up due to methane generation, including sites with buildings.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.4</td>
<td>CH4 flux vs O2 flux. When does CH4 win? Effect of barometric inversions.</td>
<td>444-445</td>
<td>Barometric pressure fluctuations are a separate issue and could enhance vapor transport at sites with deep water table (10's of metres) with coarse-grained soils, but such sites are also conducive for aerobic biodegradation to reduce concentrations below levels of concern before reaching receptors.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5</td>
<td>Add McAlary et al 2011, Michaelski et al 2010</td>
<td>452</td>
<td></td>
<td>McAlary et al 2011 added</td>
<td></td>
</tr>
<tr>
<td>Commenter</td>
<td>Charge Question</td>
<td>Guidance Section</td>
<td>Line Number</td>
<td>Details</td>
<td>Comment</td>
<td>EPA Resolution</td>
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<tr>
<td>McAlary</td>
<td>2.5.1</td>
<td></td>
<td>464</td>
<td>At what depths?</td>
<td>Added &quot;compared to similar depths below the building&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.2</td>
<td></td>
<td>477</td>
<td>(In reference to &quot;benzene, toluene, and xylene&quot;) And nothing else?</td>
<td>Correct</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.3</td>
<td></td>
<td>488</td>
<td>Not near the saw-cut expansion joints during times of positive ΔP</td>
<td>Revision made</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.4</td>
<td>490 &amp; 491</td>
<td>488</td>
<td>Change &quot;unknown&quot; to &quot;confidential&quot;</td>
<td>Revision made</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.4</td>
<td></td>
<td>498</td>
<td>&quot;the observed behavior&quot; vague</td>
<td>Added: &quot;and elevated shallow PHC concentrations&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.4</td>
<td></td>
<td>504</td>
<td>Add &quot;for ______&quot; after &quot;these reasons&quot;</td>
<td>Added &quot;for the observed soil vapor behavior&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.5</td>
<td></td>
<td>508</td>
<td>(In reference to &quot;sharp rise&quot;) I've also seen sites (Michaelski et al 2010) where vapor concentrations increase during periods of low water table. Explain why both can occur.</td>
<td>Added: &quot;through soil gas pumping (note that there are sites where the opposite effect is observed where soil vapor concentrations rise when the water table falls below LNAPL source zones)&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.6</td>
<td></td>
<td>517</td>
<td>(In reference to sentence ending with &quot;greater solubility&quot;) Do you mean slower degradation rates?</td>
<td>Revision made: &quot;Compared to benzene, it was inferred that MTBE attenuated to a lesser degree because of its lower degradation rate and 2,2,4-TMP to a lesser degree because of its lower solubility (biodegradation occurs in the water phase)&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.6</td>
<td>General Comment on Section</td>
<td></td>
<td>So why was this one building worse? Does that factor also need to be characterized?</td>
<td>Revision made: &quot;No PVI was detected at a nearby slab-at-grade building above residual LNAPL or other buildings above a dissolved groundwater source.&quot; Context provided to indicate why conditions worse.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.7</td>
<td>General Comment on Section</td>
<td></td>
<td>Expand soil type, source depth, building size, etc</td>
<td>No additional data available.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.8</td>
<td></td>
<td>529</td>
<td>(In reference to &quot;up to 500 m (1,640 ft) from the release&quot;) i.e. beyond the NAPL distribution.</td>
<td>Available information suggests that 500 m from location of release, and not NAPL (which likely extends significant distance from the release)</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>2.5.8</td>
<td>529-530</td>
<td></td>
<td>Surely, there's more than just PID data.</td>
<td>No additional data available.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.0</td>
<td>532-538</td>
<td></td>
<td>One sentence does not a paragraph make. [Combine with next paragraph at 539-547]</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.0</td>
<td></td>
<td>541</td>
<td>Why just these three [benzene, toluene, and xylene]? Ethylbenzene? MTBE? 124 TMB?</td>
<td>BTX replaced with petroleum hydrocarbon vapors</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.0</td>
<td></td>
<td>551-552</td>
<td>Vague wording.</td>
<td>Added &quot;through prediction of distances over which PHC vapor concentration attenuation occurs for varying site conditions&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.0</td>
<td></td>
<td>557</td>
<td>[Remove the word &quot;subsequent.&quot; Add &quot;The model has been used in several studies (A&amp;J 2005, A et al 2009, US EPA 2012.&quot; In its place. Next sentence starts with &quot;Three-dimensional&quot;)</td>
<td>Revised</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.0</td>
<td></td>
<td>558</td>
<td>Replace &quot;studies&quot; with &quot;scenarios&quot;</td>
<td>Revised</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td></td>
<td>572</td>
<td>(Replace &quot;cycling is a relevant condition&quot; with) fluctuations occur (very common)</td>
<td>No revision considered warranted. The text acknowledges this is relevant condition and additional emphasis (&quot;very&quot;) not warranted.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td></td>
<td>577</td>
<td>What would be necessary and sufficient data collection to confirm or refute whether this condition is important for a given site? This should be part of the screening process.</td>
<td>No revision made - out of context for this section</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td></td>
<td>583</td>
<td>(In reference to 10 mg/L) Does that include methane? It should.</td>
<td>No revision made - this is in reference to dissolved sites. Elevated methane concentrations were only measured at a few NAPL sites.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td>General Comment on Section</td>
<td></td>
<td>Simulators likely overestimate PVI potential? Can't say this without considering CH4.</td>
<td>Added: &quot;The model simulations (and source concentrations chosen) implicitly assume that methane does not represent a significant oxygen demand in addition to that represented by petroleum hydrocarbons.&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td></td>
<td>590</td>
<td>Compare to Michaelski et al 2010</td>
<td>No revision made - out of context for this section</td>
<td></td>
</tr>
<tr>
<td>Commenter</td>
<td>Charge</td>
<td>Guidance Section</td>
<td>Line Number</td>
<td>Details</td>
<td>Comment</td>
<td>EPA Resolution</td>
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<tr>
<td>McAlary</td>
<td>3.1.1</td>
<td>594-597</td>
<td>This is a good example of vague wording being clarified with a quantitative statement. Please do the same where comment &quot;vague&quot; is used elsewhere</td>
<td>No revision made - Text is &quot;There are significant reductions in attenuation factors when aerobic biodegradation is included, relative to the non-biodegradation case; for example, for a separation distance of 5 ft (1.5 m), there is an approximate three orders-of-magnitude reduction in the attenuation factor with biodegradation at a first-order decay rate of 0.79 h⁻¹.&quot; The word &quot;significant&quot; is given context through a specific example with quantitative comparison. The use of the word &quot;approximate&quot; is considered appropriate given the accuracy of model simulations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.2</td>
<td>813-615</td>
<td>Another key point is that currently almost nobody collects vertical profiles of soil vapor concentrations below buildings. Should this be incorporated into the new PVI screening protocol? If not, why not?</td>
<td>No revision made - out of context for this section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.3</td>
<td>General Comment on Section</td>
<td>What if saturation was near 100% for a month (wet spring)? See McAlary et al 2011.</td>
<td>Added paragraph: &quot;It is acknowledged that available modeling address a limited number of capping scenarios and additional work in this area would be valuable. The capping scenario inputs are considered reasonably representative. For clay soils, saturations could be greater than 60% over short time periods (i.e., weeks) but the fine-grained layer modeled is relatively thick (1 m).&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.4</td>
<td>635</td>
<td>Replace &quot;unknown&quot; with &quot;confidential&quot;</td>
<td>Revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.1.4</td>
<td>637-639</td>
<td>This indicates that it is essential to document the geology and soil moisture profile as part of a PVI screening process.</td>
<td>No revision made - out of context for this section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.2</td>
<td>642</td>
<td>Insert &quot;1-D&quot; after &quot;results for a&quot;</td>
<td>Revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.2</td>
<td>655</td>
<td>What's the value for the non-degradation scenario?</td>
<td>Attenuation factors for non-degrading case added</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.3</td>
<td>673</td>
<td>Replace &quot;source&quot; with &quot;deeper soil&quot;</td>
<td>Revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.3</td>
<td>676</td>
<td>Are you assuming building acts like an accordion? i.e., Q soil in = Q soil out?</td>
<td>No revision made - addressed in next paragraph</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.3</td>
<td>678</td>
<td>[In reference to &quot;conceptually easier&quot;] Why?</td>
<td>Added: &quot;because of common usage soil gas advection rate or Q_{soil} parameter in modeling studies&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.3</td>
<td>680-681</td>
<td>[with ref to converted] How?</td>
<td>Added: &quot;through consideration of density of air and oxygen content of air&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.3</td>
<td>General Comment on Section</td>
<td>Qsoil in = Qsoil out?Justify (net neutral building with ΔP cycles from wind gusts, etc)</td>
<td>The phenomena described may occur but contextually is not the key assumption. The point is that there is air moving to below the below that supplies oxygen to the subsurface.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.4</td>
<td>687-688</td>
<td>Disagree quite strongly. You can calculate a source vapor concentration, multiply by a modeled α factor and compare to RBSLs for indoor air very easily. In fact, you should correlate measured and modeled exclusion distances.</td>
<td>Disagree with comment in that the uncertainty and sensitivity in model predictions is not easy to develop correlations for purpose that appears to be described (semi-site specific framework for predictive purposes). When there is good site specific data, model predictions can be compared to measured values. Revision made: &quot;The results of the modeling studies for LNAPL sources cannot easily and precisely be correlated to distances (or exclusion distances) where PVI is unlikely to occur in part because of the sensitivity of the model predictions to key factors (i.e., source vapor concentration, separation distance, biodegradation rate constant, assumptions of oxygen diffusion through building foundation).&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.4</td>
<td>695-696</td>
<td>I'm not aware of any good data to show the surface capping effect and the model input were not validated, only estimated.</td>
<td>Agree that there is limited data for capping scenario. No revision made.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>3.4</td>
<td>697-700</td>
<td>Need to follow through with protocols for site characterization.</td>
<td>No revision made</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>4.0</td>
<td>712</td>
<td>How many of these [25 sites] were sampled from temporary probes vs slurry-sealed probes?</td>
<td>Added: &quot;A rigorous quality assurance/quality control program was followed for data collection including installation of properly sealed permanent probes and leak tracer tests.&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>4.0</td>
<td>722-723</td>
<td>Can you check again and add now?</td>
<td>No revision made, beyond scope of this work to add data.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>4.0</td>
<td>732</td>
<td>How many μg/m³?</td>
<td>Revision made - thresholds in μg/m³ added</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
McAlary 4.0 General Comment on Section Add papers by McAlary and Michaelski. EPA Resolution: McAlary paper and Oklahoma site data already included.

McAlary 5.0 General Comment on Section Re-sequence and groom. EPA Resolution: Revision made - see below.

McAlary 5.0 738-741 Three ideas [should be]. three sentences. EPA Resolution: Revision made - see below.

McAlary 5.0 738-747 [Reviewer suggests this re-squencing] Most states exclude sites from the need for VI assessments if they are more than a specified distance from the source of vapor contamination. These are defined as "exclusion distances" in this report, generally the 100-ft (30-m) lateral distance. Guidance for New Hampshire, New Jersey, Connecticut, and Massachusetts includes a 15- to 30 ft (4.6- to 9.1-m) exclusion distance for aerobically biodegradable chemicals. The technical justification for the exclusion distance criteria is relatively limited or not provided in the guidance by these jurisdictions. Guidance on vertical and lateral exclusion distances for PHCs based on detailed evaluations of empirical data and/or modeling studies is a recent development.

Revision made - Most regulatory approaches states exclude sites from the need for VI assessments if they are more than a specified distance from the source of vapor contamination. Distances applied in this context are defined as "exclusion distances" in this report. A default distance adopted by many states is 100-ft (30-m) in the lateral, and in some cases, vertical direction. However, guidance for New Hampshire, New Jersey, Connecticut, and Massachusetts specifies a 15- to 30 ft (4.6- to 9.1-m) exclusion distance for aerobically biodegradable chemicals. The technical justification for exclusion distance criteria is relatively limited or not provided in guidance by these jurisdictions. This is understandable given that detailed evaluations of empirical data and/or modeling studies to support exclusion distances is a recent development.

McAlary 5.0 749 Create a new sentence after "approach" starting with "Guidance" EPA Resolution: Revision made.

McAlary 5.0 754 It isn't "free," really. Better to stick with one term: NAPL. EPA Resolution: This is NJDEP terminology. Quotations added.

McAlary 6.1 805 is this ["Davis" database] publically available? If so, where? EPA Resolution: No revision made - the EPA database supercedes the Davis database. The EPA database is posted at http://www.epa.gov/oust/cat/pvi/index.htm

McAlary 6.1 817 Describe "checks" in more detail. EPA Resolution: Information on QA/QC added.

McAlary 6.2 Add bullet: "Probe design, purging procedure, soil gas permeability and leak-check procedures." Without this, I have very little confidence in the data. EPA Resolution: Information on QA/QC added.

McAlary 6.2 847-848 This also claims that any method or evidence of QA/QC is enough, regardless of how detailed or whether it was followed. That's not enough detail for me. EPA Resolution: Information on QA/QC added.


McAlary 6.2 General Comment on Section Temporary probes? Low K Soils? The two should never be used together, yet they often are. EPA Resolution: Information on type of probe added.

McAlary 6.3 881,883, & 885 [In reference to "most" (881), "many" (883), "a majority" (883), and "fewer" (885)] Why not say #/# (i.e. quantify). EPA Resolution: Added: "(all statistics with respect to number of sites with data is provided in Table 5)"


McAlary 7.1.2 963-964 And soil gas samples were within what distance of this evidence? EPA Resolution: It was not possible to quantify the distance for all sites, but typically boreholes where soil samples were obtained to infer whether LNAPL was present were the same borehole where the soil gas probe was installed, or were within a few ten's of feet. This was added to the text.

McAlary 7.2 989-992 Earlier, it seemed benzene was the focus. Consider moving this up front. EPA Resolution: No revision made.

McAlary 7.2 "[And other factors]" Vague. EPA Resolution: Revised to be more specific.

McAlary 7.2 1001-1003 Based on how many rounds of water level monitoring, on average? EPA Resolution: Added: "where multiple monitoring events were available (on average, there was about two events per site)."

McAlary 7.2 1035-1036 It isn't "unimpacted" and it isn't "clean." These terms are misleading. Better to say "soil with no NAPL." EPA Resolution: Text added: i.e., soil without NAPL.

McAlary 7.2 This has significant implications for the scope of the data collection part of a PVI assessment. You are saying vertical profile data MUST be collected with resolution (spacing) EPA Resolution: No revision made - this recommendation is beyond the scope of this report.

McAlary 7.2 show this with a figure. EPA Resolution: No revision made - this is shown (Figure 8).
<table>
<thead>
<tr>
<th>Commenter</th>
<th>Charge Question</th>
<th>Guidance Section</th>
<th>Line Number Details</th>
<th>Comment</th>
<th>EPA Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>McAlary</td>
<td>7.2.3</td>
<td>1051-1054</td>
<td>What was the rationale? Why not take a semi-log plot of [benzene] vs distance, fit a line and use the fitted line to tell you the distance?</td>
<td>Added: The method provides for a conservative estimate of the attenuation distance because for any shallow concentration above 40 µg/m³, the full distance to this vapor sample location is used.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.2.3</td>
<td>1055</td>
<td>Because?</td>
<td>Added: &quot;because a minimum distance is required for concentration attenuation to occur.&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.2.3</td>
<td>1059-1061</td>
<td>Exactly why a semi-log plot would be a better choice.</td>
<td>Possibly better, but method this complex not warranted. Text added: The method provides for a conservative estimate of the attenuation distance because for any shallow concentration above 40 µg/m³, the full distance to this vapor sample location is used.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.2.3</td>
<td>1069-1073</td>
<td>Move this paragraph to line 1056</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>1075</td>
<td>Need to add a &quot;topic sentence&quot;</td>
<td>Revision made: This section describes the rationale for establishing risk-based soil vapor concentrations of potential concern, to which measured soil vapor concentrations are compared to determine when an important part of the analysis was defining a soil vapor concentration threshold when soil PVI may would typically not be of potential concern.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>1094-1105</td>
<td>Combine paragraphs.</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>1097</td>
<td>Add &quot;spatial and temporal&quot; before &quot;variability&quot;</td>
<td>Revised to be the same.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>1099 &amp; 1102</td>
<td>[In reference to “95th” and “90th”] Why not use the same?</td>
<td>Agreed that radon studies could be cited but there are already several studies that provide information on attenuation factors. Inclusion of radon studies not considered warranted.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>1109</td>
<td>[In reference to “exposure amortization”] Not everyone will know this term, so define.</td>
<td>Added: &quot;and for consistency with previous database evaluations by Davis (2009) and Lahvis et al. (In prep.).&quot; While there is slight inconsistency in approach, it is considered to not detract from the overall results and useful of the analysis. Also the practical considerations with respect to benzene detection limits are unavoidable and real, and require flexibility and slightly different approach.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>7.3</td>
<td>General Comment</td>
<td>You defend α ~0.01 as reasonably conservative, then don’t use that for the one chemical that is your primary focus. Seems odd.</td>
<td>See above.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1120</td>
<td>[In reference to “a proportion”] Why not be specific and say 25% or whatever? There are many instances when the wording is vague.</td>
<td>Revision made: replace statement on on proportion has low concentration with &quot;but the difference in the distribution between LNAPL and dissolved sites is smaller than expected&quot;.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1118-1124</td>
<td>Elevated reporting limits?</td>
<td>No, not the reason.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1127</td>
<td>[In reference to “there is no apparent correlation for dissolved-source data”] Why is this? Is it because of some processes? Or data quality?</td>
<td>Added: &quot;The reason for the lack of correlation for dissolved-source data and relatively consistent, low soil vapor concentrations is inferred to be biodegradation.&quot;</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1127</td>
<td>[In reference to &quot;weak&quot;] Just say r²?</td>
<td>Regression coefficient [R²=0.08] added.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1132</td>
<td>Add from the measured groundwater concentration after &quot;partitioning&quot;</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1129-1134</td>
<td>This is reasonably attributable to biodegradation</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1138</td>
<td>[In reference to “predicted concentrations by Henry’s Law”] Why not just be specific: &quot;groundwater concentration multiplied by Henry’s Constant&quot;</td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1</td>
<td>1138-1139</td>
<td>[Starting with “which is consistent” to the end of the sentence] Good. But the previous paragraph needs a &quot;tie-in&quot; sentence like this too.</td>
<td>No revision made.</td>
<td></td>
</tr>
<tr>
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<tr>
<td>McAlary</td>
<td>8.1 1144-1157</td>
<td>It's not really clear why this paragraph is located here, it needs a better topic sentence and tie-in sentence to clarify the relevance to the preceding and following paragraphs.</td>
<td></td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1144-1145</td>
<td>[In reference to &quot;has been hypothesized as&quot;] This wording sounds too academic.</td>
<td></td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1146</td>
<td>[after &quot;low oxygen&quot;] add concentrations where there are</td>
<td></td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1147</td>
<td>[after (near atmospheric)] add concentrations where there are</td>
<td></td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1148</td>
<td>[In reference to &quot;high natural oxygen demand&quot;] Define what this means. Were there any such sites in the database?</td>
<td></td>
<td>Revision made.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1150-1151</td>
<td>[considerable scatter in the data] Why is this? When the data don't match theory is one of them dubious? If the O2 concentration is really low, a portable meter of ten reads 1% or more. Is this a limitation of the equipment?</td>
<td></td>
<td>There may some limitation associated with portable equipment.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1151</td>
<td>(Figure 9) Plot as both linear-linear and log-log scales.</td>
<td></td>
<td>Revision made</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>8.1 1152-1154</td>
<td>Do these data points pass the quality screen? If so, why?</td>
<td></td>
<td>Major section added: The oxygen versus TPH vapor concentration data indicates general trends that are consistent with expected behavior. For dissolved sources, there is no data indicating depleted oxygen consistent with expected low oxygen demand. For LNAPL sources, relatively low oxygen concentrations (defined here as less than 4 percent) occur when TPH vapor concentrations exceed approximately 1 x 10^6 ug/m^3 (1 mg/L), but there are a few data points where both oxygen and TPH vapor concentrations are elevated. To provide context for interpretation of this data, it is important to recognize that: Relatively high TPH vapor concentrations are required before the oxygen depletion is resolvable. Ambient oxygen (21%v/v or 280 g/m^3) has a measured resolution of about 2%v/v. With a 0.3 g-HC/g-O2 consumption ratio based on stoichiometric considerations, this suggests a hydrocarbon level at which significant oxygen consumption should be resolvable of about (280 x (2 / 21) x 0.3 = 8 g/m^3 or 8.6 ug/m^3 (defined as the sensitivity threshold) on Figure 9. Volume averaging of soil gas is an inevitable result of active soil gas sampling and the dimension of the soil gas probe and sand pack, which often ranges between 0.15 and 0.3 m. Volume averaging can result in TPH vapor and oxygen concentrations that are both elevated. Volume averaging of soil gas is an inevitable result of active soil gas sampling and the dimension of the soil gas probe and sand pack, which often ranges between 0.15 and 0.3 m. Volume averaging can result in TPH vapor and oxygen concentrations that are both elevated. Soil gas samples that are obtained within or straddle the biodegradation zone may have moderately elevated concentrations of both TPH vapors and oxygen (5-10%). There are several case studies with detailed soil gas profiles that demonstrate this behavior (Hers et al., 2000; Fischer et al., 1996; Ririe et al., 2002). Some leakage of oxygen concentration can occur through the process of sampling or analysis; however, this is not considered to have caused a significant bias in results for the reasons described below. Focusing on the quadrant of Figure 9 where TPH vapor concentrations exceed the sensitivity threshold and oxygen concentrations exceed 4%, there are only 26 data points (0% of the data) that fall within this region. Upon closer examination, many of these data points were from Hal's site in Utah (Figure 9). Approximately half of the Hal's data from this quadrant were determined to be high quality data based on internally consistent oxygen versus TPH vertical profile data, the other half were generally deep soil gas probes (Response continued below...)</td>
<td></td>
</tr>
</tbody>
</table>
where oxygen was elevated suggesting possible leakage (possible due to water table effects). Overall, the number of data points with possible concerns relating to leakage is inferred to be very small. In the case of Ha's site, the data with possible leakage was for small exclusion distances, and thus has no bearing the overall conclusions respecting distances in this report.

Data added

Rationale added.

Revised

Revised

Revised

Revised

Revised

Revised.

Revised

Revised.

No revision made

Revised

Section shortened.

This section re-structured and clarified.

No revision made – separate analysis warranted.

Example site conditions added.
<table>
<thead>
<tr>
<th>Commenter</th>
<th>Charge</th>
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<th>Line Number</th>
<th>Details</th>
<th>Comment</th>
<th>EPA Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>McAlary</td>
<td>9.1</td>
<td>1294</td>
<td></td>
<td>&quot;large buildings or a capping effect based on geologic conditions.&quot; Your analysis (8.2.2) did not support this statement very well or maybe just wasn't very clearly worded.</td>
<td>Revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.1</td>
<td>1299-1302</td>
<td></td>
<td>This has implications for PVI assessment scope.</td>
<td>Agreed.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1308</td>
<td></td>
<td>[overly conservative] By how much?</td>
<td>Not possible to quantify by how much.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1311</td>
<td></td>
<td>[too far apart.] How far is too far? This has implications for the site characterization too.</td>
<td>Revised to indicate 5-10 ft.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1312-1319</td>
<td></td>
<td>Seems familiar, check for redundancy. The topic of whether an oxygen shadow develops under a building has not really been addressed in detail and it should be. Show the O2 profile data and do O2 flux calculations.</td>
<td>Revised to indicate 5-10 ft.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1320-1324</td>
<td></td>
<td>Pretty vague and unconvincing.</td>
<td>Text revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1328-1330</td>
<td></td>
<td>You shouldn't just assume the reader is familiar with these topics and gloss over them.</td>
<td>Revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1331</td>
<td></td>
<td>[in reference to &quot;uncertainty&quot;] Specifically, what is uncertain?</td>
<td>Revised to remove reference to uncertainty.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1333</td>
<td></td>
<td>[in reference to &quot;methanogenesis and associated oxygen demand?&quot;]</td>
<td>Reference to methanogenesis added.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1334-1335</td>
<td></td>
<td>[in reference to &quot;not necessarily&quot;] Vague.</td>
<td>Revised, clearer definition provided.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.2</td>
<td>1339</td>
<td></td>
<td>Need to make sure these conditions are carried through.</td>
<td>Agreed.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.3</td>
<td>1344-1345</td>
<td></td>
<td>[in reference to &quot;PVI is unlikely to occur unless a dissolved source is very close to a building foundation.&quot;] Except for preferential pathways, fractured rock, naturally high f0c, large footprint buildings?</td>
<td>Not considered warranted for dissolved sites.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.3</td>
<td>1352-1354</td>
<td></td>
<td>Poorly worded and hard to follow.</td>
<td>Revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.4</td>
<td>1358-1361</td>
<td></td>
<td>[in reference to &quot;This framework could include groundwater concentration thresholds for benzene, but given the uncertainty in the relation between groundwater and soil vapor concentrations, this should not be the primary factor for screening sites.&quot;]</td>
<td>2 ideas, [needs] 2 sentences.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.4</td>
<td>1360</td>
<td></td>
<td>[in reference to &quot;uncertainty&quot;] Is it just a poor correlation? Or is it uncertainty in the data quality? I don't usually see a poor correlation, unless there is a fresh water lens.</td>
<td>It mainly reflects a combination of uncertainty in data quality and poor correlation because of factors such as variable biodegradation, variable geology, and factors related to investigation (e.g., screen length, position). Revised text.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.4</td>
<td>1367</td>
<td></td>
<td>[in reference to &quot;for LNAPL source&quot;] Only for LNAPL? Wouldn't you need to show dissolved sources as PVI case studies indicate LNAPL is of primary concern.</td>
<td>Yes - these factors have not been demonstrated for dissolved sources as PVI case studies indicate LNAPL is of primary concern.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.4</td>
<td>1371</td>
<td></td>
<td>[in reference to &quot;significant&quot;] What specifically makes a preferential pathway significant?</td>
<td>Revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.4</td>
<td>1371-1373</td>
<td></td>
<td>Seems I've read this several times, but each time, it is just a passing comment.</td>
<td>Disagree, appropriate emphasis given. Word methanogenesis added.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.5</td>
<td>1379-1380</td>
<td></td>
<td>[in reference to &quot;uncertainty associated with delineating a PHC source near existing or future buildings&quot;] Describe exactly what makes this uncertain. Is it data density? Data quality? Poor knowledge of the processes?</td>
<td>Revised to indicate why, i.e., practical limitations associated with site investigation.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.5</td>
<td>1380</td>
<td></td>
<td>[in reference to &quot;large&quot;] by how much?</td>
<td>Not possible to indicate by how much.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>9.6</td>
<td>General Comment on Section</td>
<td>Virtually all of section 9 is either vague or redundant. I would suggest a complete rewrite. It needs to answer several basic questions, see &quot;Global Comments.&quot;</td>
<td>Revised.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>10.0</td>
<td>1391</td>
<td></td>
<td>[in reference to &quot;typically high&quot;] Vague. [replace with] &quot;overly&quot;</td>
<td>Revised.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>10.0</td>
<td>1395</td>
<td></td>
<td>[in reference to &quot;screening evaluation methods&quot;] To me, a &quot;screening evaluation method&quot; includes sample collection and analysis protocols, sample spacing and frequency specifications and criteria for decision making. All of this is completely missing and the document is incomplete without it.</td>
<td>Revised to indicate screening approach</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>10.0</td>
<td>1396</td>
<td></td>
<td>[in reference to &quot;characterizing PVI&quot;] Not really. The impression I get is that all of the sites were simply assumed to be well-characterized.</td>
<td>Revised to &quot;evaluating&quot; instead of &quot;characterizing&quot;</td>
<td></td>
</tr>
</tbody>
</table>
Therefore, you must also provide guidance on what methods and scope and QA/QC and criteria are necessary and sufficient to accomplish this. Beyond scope of this report.

This analysis was not conducted, comment out of context

No revision made - correct as is.

Yes. This is addressed in concluding paragraph.

Important to have three categories

Statement that risk driver is sufficient. This statement not intended to preclude assessment for other compounds. No revision considered warranted.

Revised.

Revised. See previous sections.

Revised.

Revised.

Revised. Screening framework provided.

Revised.

Table 1 includes petroleum sites where vapor intrusion was documented. Although these studies include cases where the subslab samples were quite high there is quite a large attenuation between the source and subslab at these sites and there are no indoor air samples that demonstrate that the VI pathway is complete and that VI is actually occurring. Given that crucial piece of evidence is missing and there are already several refinery sites in the table, we don't think adding these sites is appropriate or necessary.

Table 1 includes petroleum sites where vapor intrusion was documented. Although these studies include cases where the subslab samples were quite high there is quite a large attenuation between the source and subslab at these sites and there are no indoor air samples that demonstrate that the VI pathway is complete and that VI is actually occurring. Given that crucial piece of evidence is missing and there are already several refinery sites in the table, we don't think adding these sites is appropriate or necessary.

No revision needed for Ohio count.

No revision warranted.

Revised.

Revised.

Revised.

Revised.

Beyond scope of this report.

No revision warranted.

Revised.

Legend added

Legend added

This is shown on Figure 8. The point of Figure 7 is to show the difference between dissolved and NAPL sites.
McAlary Figures

1754 Figure 8 [In reference to "only detectable benzene vapor concentrations shown."] Why not plot non-detect values as a different symbol?
Not considered warranted.

McAlary Figures

1759-1760 Figure 9 What is the n=2 for these plots? Is there even a negative slope? How closely do the data agree with theoretical expectations? What does that say about your ability to use these data to build an argument?

Issues addressed

McAlary Figures

Figure 9 [In reference to "shaded ellipse encompasses data that generally support the aerobic mineralization paradigm."] Not sure I even agree with this. The ellipse implies a linear relation or a semi-log plot, which implies a first-order relationship, but stoichiometrically, it should be linear. What is the explanation for all the other data? Is it a data quality issue? Shouldn't the ellipse be on both Fig. 9 plots?

Issues addressed. The comment on ellipse and inference of first-order relation overinterprets the data and intended purpose. There is uncertainty in the data and for reasons described in report a "perfect" linear relationship would not be expected, especially when data from different sites are combined. Ellipse is less meaningful on dissolved plots because TPH vapor concentrations are relatively low and thus oxygen depletion will be less than for LNAPL case.

McAlary Figures

Figure 9 [In reference to NAPL plot on the right side of the page] Do you really expect 100,000 ug/m³ TPH with 20% O2?

Issues addressed

McAlary Figures

Figure 10 Not really clear why these are included or what they add to the analysis.
Rationale added in text

McAlary Figures

Figure 11 [In reference to axis labels] Two axis labels

No revision made - not clear what comment is about

McAlary Figures

Figure 11 What is the uncertainty in the calculated values? Looking at the scatter in the data, I'd guess it is very high. What does it mean if the outcome is 5ft +/- 50ft?

The probability analysis does not allow for estimation of error bars, but the nature of the analysis in that it provides probabilities as a function of distance provides some insight on uncertain. As data becomes more limited, there is greater variability in the slope of the probability versus distance relation. As the number of data points increases, the relation becomes smoother. The complementary database efforts and different methods used for the analysis, all which point to similar exclusion distances, suggest that the data is not subject to the high level of uncertainty. The greatest uncertainty is likely associated with capturing geologic variability and layering, which is intrinsically difficult to do when dealing with empirical analysis.

McAlary Figures

Figure 12 MTBE? Naphthalene? TMBs? TBA?

MBE, naphthalene, TMBs added. No TBA data.

McAlary Figures

Figure 13 Same comment as for dissolved source: what are the error bars on the calculated probabilities?

See above

McAlary Figures

Figure 14 MTBE? Naphthalene? TMBs? TBA?

MBE, naphthalene, TMBs added. No TBA data.

McAlary Figures

Figure 15 Error bars?

See above comment

McAlary Figures

Figure 16 BVC

Added to figure.

McAlary Figures

Figure 17 [In reference to graph on top of page] Does this support the argument that buildings and pavement contribute to an O2 shadow? If so, what are the implications for PVI site assessment scope and methods?

Beyond scope of this section.

McAlary Figures

Figure 17 [In reference to graph on top of page, for each surface cover listed in legend] n=_____

Added.

McAlary Figures

Figure 17 [In reference to the data points on the bottom graph that are less than 0] What does negative distance mean?

Soil vapor probe within source zone.

McAlary Figures

Figure 17 [In reference to graph on bottom of page] Considering the scatter, what are the error bars on the probabilities?

See above comment

McAlary Figures

1782-1785 Figure 17 [In reference to Figure 17 caption] Could plot them as open symbols.

No revision considered warranted.

McAlary Figures

Figure 18 [In reference to graph on top of page, for each surface cover listed in legend] n=_____. Added.

McAlary Figures

Figure 18 [In reference to the data points on the bottom graph that are less than 0] What does negative distance mean?

See above comment

McAlary Figures

Figure 18 [In reference to legend bottom graph] Sequence

Revised

McAlary Figures

Figure 18 No O2 values approaching atmospheric seems very unlikely.

The available data have been plotted.

McAlary Figures

Figure 19 Error bars?

See above comment
<table>
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<tr>
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<th>Comment</th>
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</tr>
</thead>
<tbody>
<tr>
<td>McAlary</td>
<td>Figures</td>
<td></td>
<td>Figure 20</td>
<td>Should there be a positive slope to the correlation? If not, why not? If so, does the data support theory? If not, what does the discrepancy tell us?</td>
<td>Should there be a positive correlation in that the clean soil distance should increase at high groundwater concentrations (i.e., at groundwater concentrations that are representative of LNAPL sources). Greater clean soil distances are observed for higher groundwater concentrations. The text describes this relationship.</td>
<td></td>
</tr>
<tr>
<td>McAlary</td>
<td>Figures</td>
<td></td>
<td>Figure 22</td>
<td>[In reference to title add] -NAPL (All) Revised</td>
<td>We appreciate the positive review of document structure and organization. We did not add a glossary in this draft as terms like &quot;attenuation factor&quot; are well used and understood in the VI practitioner community. Acronyms are defined on first use within the text.</td>
<td></td>
</tr>
<tr>
<td>Widdowson</td>
<td></td>
<td></td>
<td>1</td>
<td>Overall, the report is very clearly written in most aspects. The document is well-organized and is crafted in a logical manner. The scope of the report is robust. The text describes this relationship.</td>
<td>Overall, the report is very clearly written in most aspects. The document is well-organized and is crafted in a logical manner. The scope of the report is robust. The text describes this relationship. Other suggestions for improving the clarity of the report are inclusion of a Glossary of Terms and a List of Acronyms. For example, the term &quot;vapor attenuation factor&quot; or &quot;attenuation factor&quot; is used repeatedly but never adequately defined.</td>
<td></td>
</tr>
<tr>
<td>Widdowson</td>
<td></td>
<td></td>
<td>2</td>
<td>The report provides a thorough presentation of the scientific issues related to the stated objectives. As indicated in my response to Question 1, the lack of a thorough description of the conceptual site model hinders in complete presentation of the science. The report does not adequately address hydrologic factors such as drought conditions and atmospheric pressure changes that may impact the potential for a complete PVI pathway. Furthermore, the conceptual site model is based on an assumed steady-state depth to the water table and on sites with no perched water table. The report does not address these issues and impacts on PVI potential.</td>
<td>The report contains five objectives designed for the development of exclusion distances. • Objective 1 is achieved. The empirical database assembled for the report built upon a previous study by Davis (2009). Additional data from sites in Maine is included. Data from a total of 70 sites are evaluated. • Objective 2 is achieved. The data are checked against original sources and assembled electronically. • Objective 3 addressed when and under what conditions there is the potential for a complete PVI pathway at a site. As noted on page 2, a complete PVI pathway is defined as measurable indoor petroleum hydrocarbon vapor concentrations that come from a subsurface contamination source. Two case studies are presented where a complete PIV pathway’s noted. In one case (Section 2.5.2), building depressurization is noted as a factor. However, in the Discussion, this factor is not mentioned. Conditions for increased potential for PVI are listed in Section 2.4. Clarification of all conditions in Section 10 would be helpful. • Objective 4 is achieved. The report summarizes pertinent modeling studies on PHC vapor transport and intrusion. • Objective 5 is achieved. The report provides a coherent discussion of methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.</td>
<td></td>
</tr>
<tr>
<td>Widdowson</td>
<td></td>
<td></td>
<td>3</td>
<td>The report provides a thorough presentation of the scientific issues related to the stated objectives. As indicated in my response to Question 1, the lack of a thorough description of the conceptual site model hinders in complete presentation of the science. The report does not adequately address hydrologic factors such as drought conditions and atmospheric pressure changes that may impact the potential for a complete PVI pathway. Furthermore, the conceptual site model is based on an assumed steady-state depth to the water table and on sites with no perched water table. The report does not address these issues and impacts on PVI potential.</td>
<td>Revisions made: &quot;A literature search conducted on soil moisture effects did not indicate other studies specifically addressing vadose zone attenuation of PHC vapors under dry conditions. However, the empirical databases for this project include sites in dry climates including Utah and several areas of Australia, and thus are considered the most direct indicator for the influence of soil moisture&quot; and &quot;Atmospheric Pressure Changes. Atmospheric pressure changes could result in transient advective soil gas flow at sites with deep water tables and coarse-grained soils; however, such processes are not expected to result in longer-term conditions where there would be significant differences in the aerobic biodegradation profile, compared to a diffusion only transport paradigm.&quot;</td>
<td></td>
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</table>

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<table>
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<tr>
<td>Widdowson</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>The underlying studies are well summarized, but the criteria for data acquisition during are not fully described in this report. As noted in Table 5, oxygen (soil gas) data is not available at all sites. However, the absence of this data does not preclude the notion that attenuation of vapor concentrations in the vadose zone can be reasonably attributed to aerobic biodegradation. The phenomenon of aerobic biodegradation in the vadose zone is so widely observed at petroleum-contaminated sites that excluding these studies is not warranted.</td>
<td>While studies without oxygen but with petroleum hydrocarbon vapor data were ranked of lower confidence with respect to the CSM, these studies were still used, and were not excluded.</td>
</tr>
<tr>
<td>Widdowson</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>As shown in Table 3, the assembled database is derived from 9 states accounting for 67 of the 70 sites. These locations reflect a range of hydrogeologic settings throughout the U.S. The database is dominated (75% of the 67 sites in the U.S.) by data from 3 states, but these states represent 3 distinct geologic regions of the country. Although UST sites make up the bulk of the database (90% of the 70 sites), the database is adequate in size. The database includes a large number of benzene and oxygen soil vapor records and pair benzene soil vapor and groundwater concentration data. Benzene data is included in 65 of the 70 sites. Subslab vapor samples were obtained at over 50% of the sites. Based on the information pertaining to foundation type in Table 4, the database sufficiently representative of subsurface conditions. However, it would be useful to include data on depth to the water table and surface cover here.</td>
<td>No revision made - depth to water table could be added but not considered really needed. Surface cover varies from probe to probe and can not be practically added.</td>
</tr>
<tr>
<td>Widdowson</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>A description of the statistical methods employed in the study is lacking in the report. The report should include a rationale for use of the Kaplan-Meier non-parametric method. It would be helpful to include this information to explain methods and assumptions employed with appropriate citations, above and beyond the limited description on page 27. This could easily be included in an appendix.</td>
<td>An appendix on K-M is not considered warranted but additional information added: &quot;the Kaplan-Meier method has been shown in recent literature to be the preferred method in many cases for estimating statistical parameters (e.g., mean, median, standard deviation), makes no underlying assumptions about the data because it is a non-parametric method, and can be used with multiple reporting limits.&quot;</td>
</tr>
<tr>
<td>Widdowson</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>The preponderance of evidence from not just this study but also similar studies cited in this report (see Section 9.6) demonstrate that establishing a vertical distance of separation between a source of petroleum vapor contamination and an overlying receptor that include biodegradation is based on sound scientific principles. There is no indication that the findings of the report lack scientific integrity. Regarding factors that influence or potential influence biodegradation, as noted in my response to Question 3, the report does not adequately address hydrologic factors. Water table elevation is subject to change with rainfall events and prolonged drought. The extent to which a water table rises or falls over time is site specific depending on the intensity and duration of recharge events, land cover, plant type and soil properties. The report did not address how temporal variability in the depth to the water table is considered. A related issue is the potential for perched water tables at some sites. In some cases, perched saturated zones are seasonal and may be discontinuous with space across a site.</td>
<td>Discussion on temporal variability on water table height added to discussion.</td>
</tr>
<tr>
<td>Widdowson</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>Reasons provided for application of the proposed vertical separation distances to other common fuel constituents and additives vary. Several fuel constituents and additives are addressed in the case studies. Data for these compounds are commonly collected at the database study sites (Table 5), but the number of data is less frequent. Besides benzene, other database constituents are analyzed (see page 26-27), but the report primarily addresses naphthalene and 2,2,4-TMP on this issue. Therefore, a thorough explanation of the rationale for applying the proposed vertical separation distances for benzene and other fuel constituents and additives is lacking.</td>
<td>Revised to address this concern</td>
</tr>
<tr>
<td>Commenter</td>
<td>Charge Question</td>
<td>Guidance Section</td>
<td>Line Number</td>
<td>Details</td>
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<tr>
<td>Widdowson</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>The report provides an adequate list of references including field studies that pertain to the attenuation of petroleum hydrocarbon soil vapors. Some possible exceptions are the work performed at the U.S. Geological Survey study site at Laurel Bay, SC. MTBE vapor transport was evaluated at this UST site. A complete bibliography for this work is available at <a href="http://toxics.usgs.gov/bib/bib-MTBE.html">http://toxics.usgs.gov/bib/bib-MTBE.html</a>. A study of naphthalene vapor transport and attenuation in the vadose zone published by Marr et al. in 2006 (Environmental Science &amp; Technology, vol. 40, no. 17) may also prove useful.</td>
<td>Marr et al. was reviewed and does not provide soil gas data needed for the PVI database analysis. The USGS research at the Laurel Bay site was likewise reviewed but is limited to groundwater transport and volatilization rates at water table, and does not address MTBE transport within the unsaturated soil zone.</td>
</tr>
<tr>
<td>Widdowson</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>1) Going forward, some notion of “best practices” for the collection of data, what data to collect and how frequently, and methods for data analysis is warranted. This includes the need for technical guidance on methods to verify benzene attenuation and confirm oxygen levels in soil gas. 2) As mentioned previously, the notion of a vertical exclusion is based on a static water table. Some consideration for a site-specific evaluation of the temporal variability in the depth to the water table is recommended.</td>
<td>Beyond scope of this report to specify best practices, but the need for such practices is emphasized.</td>
</tr>
</tbody>
</table>
Response to General Peer Review Charge Questions:

- the scientific appropriateness of the database for OUST’s purposes:

  The database is appropriate for application to USTs, but very weak in evaluation of diesel and high-ethanol fuels.

- whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST’s purposes; and

  The analyses and methods are appropriate for OUST’s purposes, but some areas of incomplete analysis are present as described below.

- whether the reported conclusions are adequately supported by the data and analyses.

  The conclusions for BTEX appear to be adequately supported by the data and analyses for UST sites. Additional data and analysis is needed for non-UST sites, for diesel sites, for high ethanol fuel sites, and for petroleum additives.

Response to Peer Review Specific Charge Questions

1. Is the report written in a manner that is clear, robust, and transparent for its intended purpose?

   Yes.

2. Does the report meet its stated objectives (listed above) for which it was conducted? If not, please indicate any identified gaps.

   The first three objectives appear to have been met. Additional review of published modeling studies pertaining to the effects of low permeability layers and impermeable surface cover appears to be warranted. The development and support of methods for lateral exclusion distance criteria is generally lacking. Additional data is required for sites known to have high ethanol fuels or diesel. Additional data is required to support utilization of this approach at non UST sites.

3. Are there any additional scientific issues relating to the stated objectives that are not addressed in the report?

   The report does not address potential vapor intrusion issues related to fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide) or trimethylbenzene components of diesel. The report does not provide adequate
data or analysis to evaluate the impact of biodegradation on methane generation from high ethanol content gasoline. Very limited data on diesel sources is included in the database (3 sites) and no separate evaluation of vapor intrusion behavior at such sites is included.

4. **Are the criteria for data acquisition during the underlying studies (i.e., Davis, Eremita, Peargin and Kolhatkar) and into the assembled database adequately described?** Do these criteria ensure that the estimated attenuation in vapor concentrations in the vadose zone at each site:
   - can be reasonably attributed to aerobic biodegradation (versus other explanations); and
   - is an appropriate value for predicting potential indoor air concentrations in nearby buildings?

The criteria for data acquisition for the underlying studies is described only to a limited extent. The data of Peargin and Kolhatkar (2011) is not mentioned as part of the database. To our knowledge, Davis has adequately screened the database that she used.

5. **Is the assembled database adequately large and sufficiently representative of subsurface conditions and indoor air concentrations for purposes of reliably determining presumptive criteria for each of the following scenarios:**
   - petroleum releases from USTs; and
   - petroleum releases from other sites (e.g., refineries, terminals, transmission pipelines)?

The database does not contain adequate data or analysis to evaluate biodegradation of high ethanol content gasoline.

The database does not contain adequate data or analysis to evaluate diesel release sites (only three sites have diesel).

The database does not appear to be sufficiently large enough or representative of non-UST sites (there are only seven such sites in the database).

6. **Are the statistical methods applied to the data appropriate for the data set and for the comparison being made?**

Yes

7. **Are the findings of the report of adequate scientific integrity to support establishment of a vertical distance between a source of petroleum vapor contamination and an overlying receptor in determining whether an UST site could pose a significant health risk to building occupants?** Have all the factors that influence, or potentially influence, biodegradation (e.g., soil moisture,
Soil moisture effects could use some additional data and evaluation at the low moisture content end of the spectrum. Insufficient information is provided to determine if oxygenated fuels behave differently. Evaluation of the impacts of impervious surface cover needs expansion for non-UST sites.

8. **Does the Golder/RTI Report provide a sound basis for applying the proposed vertical separation distances for aromatic and aliphatic petroleum hydrocarbons (e.g., benzene) to other common fuel constituents (e.g., naphthalene) and fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide)?**

Fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide) are not addressed, although data for MTBE is available for 13 sites. Given the very low RBCs for 1,2-dichloroethane, this may be an important data gap for historic (leaded gasoline) fuel releases containing 1,2-DCA. API has numerous publications on the biodegradation of MTBE which might be cited. Naphthalene data is available for 18 sites in the database, but is not addressed, presumably due to it’s relatively low Henry’s Law constant. Trimethylbenzenes at diesel release sites are not addressed. These VOCs have fairly low Hazard Indexes and can be present at greater concentrations than benzene.

9. **Are you aware of additional references or other resources that could be added to the report, or would be useful in meeting the stated objectives of the report? Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?**

The two studies below provide extensive multimedia data on a diesel spill and evaluation of attenuation. Addition of data from this site to the database would be useful to provide support for the application of the conclusions presented to diesel sites.


**Specific Comments**

1. **Section 2.4 – lines 436-437:** The statement that “releases of fuel containing 10% ethanol are most likely included in the reviewed database” should be supported by data in Appendix C.

2. **Section 2.5 – Former Refinery Site (Unknown location) (Luo et al., 2010), lines 491-504:** This empirical data presents strong evidence for the impact of background oxygen uptake in surface soils and for physically limited oxygen transport due to low
permeability shallow soils. The latter is especially significant and should be expanded upon and considered in any screening criteria.

3. **Section 2.5 – UST Site, Stafford, New Jersey, lines 512-517**: This case study suggests that vapor intrusion from MTBE and 2,2,4-TMP might be more likely than benzene due to their higher solubility and possibly lower attenuation. This example should prompt further evaluation of MTBE in the database and collection of additional data on 2,2,4-TMP.

4. **Section 3.0 – lines 543-545**: The statement regarding “available data suggest bioattenuation distances may be greater for aliphatic hydrocarbons compared with aromatic hydrocarbon compounds” should be expanded upon.

5. **Section 3.1 3-Dimensional Model Simulations (EPA 2012b), lines 600-615**: This section should have some figures to illustrate the lateral separation impact. In addition, the simulations for fine-grained, low permeability soils and “impermeable” ground cover should also be discussed.

6. **Section 6.2 Database Structure, lines 828-829**: Information on the release date and ethanol content of the fuel would also be important to include.

7. **Section 6.2 Database Structure, lines 834-836**: Information on the lateral distance between soil gas probes and buildings is included in the database, but was not evaluated in the analysis.

8. **Section 6.3 Database Content, lines 874-875**: The statement that “some sites in the database where recent releases have occurred likely have gasoline containing ethanol” should be documented. Possibly an estimated release date could be added.

9. **Section 6.3 Database Content, lines 876-878**: Note that few large buildings are included in the database, so the applicability to large buildings may be limited. The citation to Table 3 should be changed to Table 4.

10. **Section 7.1 Source Zone Identification Methods**: Note that two sites footnoted on Table 6 (lines 1701 – 1704) have dissolved plumes with benzene at 12 mg/L (100% of effective solubility). Do these two sites fall with 95% probabilities by the separation distance method? Note that the sensitivity analysis for the Vertical Distance Method, in Section 8.2 (lines 1191-1196), does not extend beyond 10 mg/L benzene in groundwater and thus does not include values representative of these two sites.

11. **Section 7.1.3 Proximity to Fuel Storage/Dispensing Facilities, lines 968-970**: This section discusses the use of a threshold distance of 20 ft “to approximately correspond to the exclusion criteria distance that was estimated for LNAPL sites, as subsequently indicated in this report”. No such lateral exclusion distance is discussed at a later point in the report.

12. **Section 7.7 Clean Soil Method, Figure 6 (lines 1746-1747)**: This figure needs a legend identifying the red values (presumably benzene in ug/m³) and the blue values (presumably oxygen in %). Area 2 is not discussed.

13. **Section 8.1 Exploratory Data Analysis, lines 1140-1143**: The report notes a poor correlation between groundwater and soil vapor concentrations (of benzene). This suggests that caution is needed when using groundwater benzene concentrations as a screening criteria for identification of LNAPL plumes.

14. **Section 8.1 Exploratory Data Analysis, lines 1158-1161**: The report notes that methane data are available for 23 sites, but no separate analysis was undertaken to
determine if sites with high methane concentration demonstrated different behavior than those with low concentrations.

15. **Section 8.2.1 Vertical Distance Method, lines 1214-1215:** The notation that source separation distances increase to approximately 30 feet for non-UST LNAPL sources should be reiterated in the conclusions.

16. **Section 8.2.1 Vertical Distance Method, lines 1218-1219:** Is there an explanation for the apparent lack of biodegradation of 2,2,4-TMP at the two sites illustrated on Figure 16 (lines 1779-1780)?

17. **Section 8.2.2 Influence of Surface Cover, lines 1233-1235:** It should be noted that the upper probability achieved for the pavement cover case in Figure 17 (line 1781) is less than 95%, even at a 30 foot separation distance. It is not true that the pavement and building scenario “yielded similar results” based on Figure 17.

18. **Section 8.2.3 Influence of Soil Type, lines 1257-1261:** It would be helpful if the results from modeling were discussed here, along with some discussion of theoretical expectations. The modeling studies by EPA (2012) generally showed some capping effect for surficial, low permeability soils. More detailed analysis of the impact of soil stratigraphy would be helpful.

19. **Section 8.2.3 Influence of Soil Type, Figure 19 (line 1791):** The lack of plotted data points for fine-grained soils beyond a separation distance of 12 feet for the NAPL case implies lack of data in the database. Is this correct? If so, extrapolating results of this analysis to sites with fine-grained soils and NAPL may be problematic.

20. **Section 8.3, 2nd bullet, lines 1271-1277:** It should be noted that the required thickness of clean soil for LNAPL sources increases with increasing groundwater concentration according to figure 21 (line 1797).

21. **Section 9.2, line 1338-1339:** The exclusion of fractured rock unsaturated zones should be reiterated in the conclusions.

22. **Section 9.3 – Exclusion Distance Assessment Framework, line 1351-1354:** Could a deep soil gas concentration threshold be utilized for identifying LNAPL? Soil concentrations appear to provide the most reliable indicator. The vertical distance method indicates a small probability for vapor concentrations above thresholds for distances as little “as 0 ft;” the report should discuss how capillary rise affects this observation (if the building is within the capillary fringe, is the groundwater considered to “be in contact” with the building?)

23. **Section 9.5 Lateral Exclusion Distance, lines 1375-1381:** This section suggests that lateral exclusion distances should be larger than vertical exclusion distances, especially for non-UST sites and that they should be similar to vertical distances for UST sites. This is at odds with the limited statements in the remainder of the document that suggest no lateral exclusion distance.

24. **Section 10 Conclusions:** The report suggests that more detailed PVI assessment may be warranted at large building sites, such as apartment complexes or commercial/industrial buildings. This is a very subjective factor that could make application of an exclusion distance difficult. Can the database or modeling studies provide any more insight into a building size criterion?
Vapor Intrusion at a Diesel LNAPL Site

Principal Investigators: James B. Cowart, P.E. and Lindsay Breyer, CIH

A Vapor Intrusion evaluation at the City of Mandan, ND was conducted during the following Site Conditions:
- Approximately 1.5 to 3.0 million gallons of weathered diesel LNAPL was present over an area of 657,000 sq. ft. and was up to 6.88 ft. apparent thickness.
- Overlying the LNAPL area were 4.5 city blocks with approximately thirty 1-2 story commercial and residential structures with basements.
- Groundwater was present at approximately 20 ft. below ground surface, although the nearby Heart River had caused groundwater fluctuations of 5-10 ft.
- Lithology at the site consisted of coarse grained clayey sands to 2-3 ft. depth; sandy clays to a 11-12 ft. depth; and fine grained sands greater than 17 ft. depth.
- Moisture in the soils ranged from 24 to 31%, and density averaged 95 lbs/cu.ft.

Hydrocarbons were profiled in Diesel LNAPL, soils and soil-gas (deep & shallow), and indoor/outdoor air media.
- Media were analyzed for Volatile and Semi-volatile Organic Compounds, Diesel Range Organics, C2-C10 Hydrocarbons, and Fixed Gases. 15 compounds were identified as Preliminary Contaminants of Concern (PCCCs).
- Actual deep soil-gas (taken at approximately 19 ft. bgs in the capillary zone within 1 ft. of LNAPL, correlated well (r^2=0.94) with soil-gas predicted from LNAPL (using Raoult’s Law).
- Concentrations of the PCCC vapors ranged generally as follows:
  - Deep soil gas 10,000 to 100,000 ppm.
  - Shallow soil gas 100 to 1,000 ppm.
  - Indoor air and outdoor air 0.3 to 3.0 ppm, not including outliers such as toluene.

CONCLUSIONS:
- Deep soil-gas concentrations above the LNAPL (19 ft. bgs) generally obeyed Raoult's Law.
- Shallow soil-gas concentrations (taken at 8 ft. bgs at base- ment level) were 10-500 times less concentrated than deep soil-gas (i.e., attenuation factor 1 x 10^-1 to 5 x 10^-2).
- Indoor air concentrations were typically 100-1,000 times less concentrated than shallow soil-gas (i.e., attenuation factor 1 x 10^-2 to 1 x 10^-3).
- Cumulative vapor intrusion attention factors (deep soil-gas to indoor air) were generally 1 x 10^-2 to 5 x 10^-2, and likely were greater if “background” hydrocarbons had been subtracted.
1. Site Description

This report presents some of the results of a screening level assessment of the vapor intrusion exposure pathway for hydrocarbon contaminants in the subsurface in Mandan, North Dakota. A large pool of free diesel product exists as a light nonaqueous phase liquid (LNAPL) under a portion of the downtown Mandan area. The LNAPL has been estimated to contain between 1.5 and 3 million gallons of diesel fuel. The thickness of free product is reported to be as much as 6.88 feet in some locations with an area of approximately 657,000 square feet.

The presence of diesel fuel in the subsurface has also resulted in contamination of groundwater in the vicinity of the spill. Groundwater is present at a depth of approximately 20 feet below ground surface, and the flow is generally toward the southeast. The depth to groundwater and the direction of groundwater flow change seasonally in response to river stages in the nearby Heart River and precipitation. Recorded fluctuations in the water levels for wells within the study area ranged from 5 to 10 feet between 1990 and 2000.

The horizontal extent of the LNAPL is reported to vary with fluctuations in the water table, resulting in a “smear zone” of contaminated soil around the perimeter of the LNAPL. Groundwater flow has resulted in the transport of contaminants outside the area of the LNAPL.

A detailed geochemical evaluation of the LNAPL at Mandan was previously completed by the U.S. Geological Survey in 2001. This study included the analysis of samples from the LNAPL for a wide variety of compounds. Diesel-related compounds detected in the LNAPL included alkyl benzenes, alkanes, polynuclear aromatic hydrocarbons (PAHs), and other compounds associated with diesel fuel. Target analytes detected in the volatile fraction included benzene, toluene, ethylbenzene, m&p-xylene, o-xylene, isopropylbenzene, n-propylbenzene, 1,3,5-trimethylbenzene, 2-ethylbenzene, 1,2,4-trimethylbenzene, sec-butylbenzene, p-isopropylosuene, 1,2,3-trimethylbenzene, n-butylbenzene, 1,2,3,5-tetramethylbenzene, 1,2,3,4-tetramethylbenzene, and naphthalene.

Because of their volatile nature, these compounds have the potential to evaporate from the LNAPL, soil and groundwater; migrate through the soil gas; and enter nearby buildings through cracks and other penetrations in the foundations as well as to enter utilities such as manholes, sanitary sewers and storm sewers. Some of these compounds can increase the risk of cancer in exposed individuals. Others are not considered to be carcinogens but can cause non-cancer health effects, depending on the level of exposure.
This project was conducted in order to perform a screening level evaluation of the vapor intrusion pathway. It included the collection of soil samples, groundwater samples, free product samples, soil gas samples, indoor air samples, and outdoor air samples. The results were evaluated in accordance with guidelines and regulations developed by the EPA, OSHA, and other agencies.

2. Building Information

A number of businesses and residences are located above the areas of known diesel contamination in Mandan. Occupants of these buildings are potentially exposed to diesel-related contaminants via the vapor intrusion pathway. This study was a screening-level evaluation that included sampling in and near a small number of commercial and residential buildings above and near the LNAPL. The buildings includes an apartment building, law office, vacuum repair shop, furniture store, financial services office, bank, law enforcement center, and a library.

In general, the buildings were older one- to two-story structures with basements. Most of the basements contained a poured slab, although a few contained small areas with dirt floors. Some of the buildings are interconnected with old steam tunnels. All contained natural gas heating systems.

Outdoor sources of petroleum-related compounds included vehicle traffic in the vicinity, a nearby railroad refueling facility, and a refinery. An active soil vapor extraction system was shut down approximately one week prior to conducting the sampling. Potential indoor sources included paint, petroleum products, cleaning chemicals, and similar materials. To the extent possible, sampling was conducted in locations where these materials were not being actively used.

Soil borings were conducted for the purposes of collecting samples for geotechnical testing and analysis of diesel-related contaminants. The lithology encountered in the soil boring locations generally consisted of medium- to dark-brown silty sands and fine to very coarse grained clayey sands to a depth of about 2 to 3 feet. This layer was underlain by medium-brown low to high plasticity sandy clays with tan/white/rust mottling to a depth of 11 to 17 feet. Poorly graded fine-grained sands were observed below the sandy clay interval.

3. Sampling and Analysis Methods

A Sampling and Analysis Plan (SAP) and Quality Assurance Project Plan (QAPP) were developed for this project prior to conducting field activities. The sampling and analytical methods used for this study are summarized in Table 1 below.

Soil samples were collected during the installation of soil gas monitoring wells. A shallow soil sample was collected at approximately basement level (8 feet below ground surface). A deep soil sample was collected just above the capillary fringe or about 16 feet below ground surface. The borings were completed as soil gas monitoring wells using 1/8-inch stainless steel tubing.
connected to a stainless steel mesh filter equipped with a 1/8-inch vapor inlet opening. Monitoring points were installed at two different depths in each location.

### Table 1. Methodology

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Soil</th>
<th>Groundwater</th>
<th>Soil Gas</th>
<th>Indoor/Outdoor Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Organic Compounds (VOCs)</td>
<td>EPA 8260B</td>
<td>EPA 8260B</td>
<td>EPA TO-15</td>
<td>EPA TO-15</td>
</tr>
<tr>
<td>Semivolatile Organic Compounds (SVOCs)</td>
<td>EPA 8270C</td>
<td>EPA 8270C</td>
<td>EPA TO-13¹</td>
<td>EPA TO-13¹</td>
</tr>
<tr>
<td>Diesel Range Organics (DRO)</td>
<td>EPA 8015M</td>
<td>EPA 8015M</td>
<td>EPA TO-13 Mod.</td>
<td>EPA TO-13 Mod.</td>
</tr>
<tr>
<td>C₂ to C₁₀ Hydrocarbons</td>
<td>NA</td>
<td>NA</td>
<td>EPA TO-3</td>
<td>EPA TO-3</td>
</tr>
<tr>
<td>Fixed Gases²</td>
<td>NA</td>
<td>NA</td>
<td>ASTM D1946</td>
<td>ASTM D1946</td>
</tr>
</tbody>
</table>

¹Includes only the polynuclear aromatic hydrocarbons (PAHs)
²Methane, nitrogen, oxygen, carbon dioxide, carbon monoxide

Approximately two weeks after installation of the soil gas monitoring wells, soil gas samples were collected. Sampling was conducted at depths of approximately 8 and 16 feet below ground surface. Prior to sampling, the tubing and well annulus was purged by removing 1.5 to 2 volumes of air with a battery-operated personal air sampling pump. Field readings were then obtained with a photoionization detector (PID) and combustible gas indicator (CGI). These readings were collected to ensure that soil gas was being sampled rather than short-circuiting to the atmosphere. Soil gas samples for EPA method TO-15 were collected over 1 to 2 hour intervals using evacuated SUMMA canisters equipped with a 1-hour flow regulator. These canisters were also analyzed for C₂ to C₁₀ hydrocarbons using EPA method TO-3 and for fixed gases (methane, nitrogen, oxygen, carbon dioxide, carbon monoxide) using ASTM D1946. Samples for Polynuclear Aromatic Hydrocarbons were collected in accordance with EPA Method TO-13 using a personal air sampling pump to draw soil gas through a PUF/XAD-2 cartridge.

Groundwater samples were collected using a low-flow purge technique. Standing water in the wells was purged with a bladder-type pump. The pH, temperature, conductance, and dissolved oxygen were monitored. When the parameters stabilized, samples were collected for analysis of VOCs, SVOCs, and other parameters. Where present, free product was sampled using disposable plastic bailers. Depth to groundwater (or free product) ranged from 18.25 to 19.32 feet below ground surface.

Indoor air samples were collected using SUMMA canisters for TO-15, TO-3, and ASTM D1946. PUF/XAD-2 cartridges were used in conjunction with personal air sampling pumps to collect PAHs and diesel-range organics. Sampling duration was approximately 24 hours. Building owners were interviewed at the time of indoor air sample collection, and each sample location was inspected by the sampling team. A questionnaire/inspection form was completed for each location. Outdoor air samples were collected in three locations. An indoor sample from a building outside the area of known contamination was also collected.
QA/QC protocols included the collection of field duplicates and field blanks. All analytical data was reviewed by an independent chemist and analytical data was validated by following CLP guidelines.

4. Alpha Information

Attenuation factors were calculated for the vapor intrusion pathway and are summarized in Table 2 below. One set of factors was calculated from the data for sampling locations above the LNAPL. A second set of factors was calculated for locations outside the LNAPL but with the area of known contamination (the so-called “smear zone”). Soil vapor concentrations above the LNAPL are expected to be controlled by the vapor pressure of the components of the LNAPL. The soil vapor concentrations in the “smear zone” are expected to be controlled by volatilization of contaminants absorbed onto the soil matrix. The data used to calculate the attenuation factors is summarized in Tables 3 and 4. No attempt was made to correct the data for “background.”

The results were also compared to the screening levels published in the EPA Draft Vapor Intrusion Guidance. Several compounds were detected at concentrations above the screening levels in the various media sampled. The results are summarized in Table 5.

### Table 2. Attenuation Factors

<table>
<thead>
<tr>
<th>Compound</th>
<th>Locations Above LNAPL</th>
<th>Locations Outside LNAPL But Above Contaminated Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,4-Trimethylbenzene</td>
<td>0.0127</td>
<td>0.0077</td>
</tr>
<tr>
<td>1,3,5-Trimethylbenzene</td>
<td>0.0194</td>
<td>0.0153</td>
</tr>
<tr>
<td>4-Isopropyltoluene</td>
<td>NA</td>
<td>0.1000</td>
</tr>
<tr>
<td>Benzene</td>
<td>NA</td>
<td>0.0186</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>0.0631</td>
<td>0.0031</td>
</tr>
<tr>
<td>Isopropylbenzene</td>
<td>0.0281</td>
<td>0.0155</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>0.0033</td>
<td>0.0609</td>
</tr>
<tr>
<td>n-Butylbenzene</td>
<td>NA</td>
<td>0.0333</td>
</tr>
<tr>
<td>n-Propylbenzene</td>
<td>0.0242</td>
<td>0.0057</td>
</tr>
<tr>
<td>sec-Butylbenzene</td>
<td>0.0132</td>
<td>0.0564</td>
</tr>
<tr>
<td>Toluene</td>
<td>NA</td>
<td>0.0206</td>
</tr>
<tr>
<td>Xylenes (total)</td>
<td>0.0572</td>
<td>0.0045</td>
</tr>
<tr>
<td>1,2,3-Trimethylbenzene</td>
<td>NA</td>
<td>0.0194</td>
</tr>
<tr>
<td>2-Ethyltoluene</td>
<td>NA</td>
<td>0.0720</td>
</tr>
<tr>
<td>4-Ethyltoluene</td>
<td>NA</td>
<td>0.0094</td>
</tr>
<tr>
<td>Methane</td>
<td>NA</td>
<td>0.0870</td>
</tr>
<tr>
<td>Average</td>
<td>0.0276</td>
<td>0.0331</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.0033</td>
<td>0.0031</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.0631</td>
<td>0.1000</td>
</tr>
</tbody>
</table>
### Table 3. Monitoring Results for Locations Above LNAPL

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average LNAPL ug/L</th>
<th>Deep Soil ug/kg</th>
<th>Shallow Soil ug/kg</th>
<th>Deep Soil Gas ug/m³</th>
<th>Shallow Soil Gas ug/m³</th>
<th>Average Indoor Air ug/m³</th>
<th>Average Outdoor Air ug/m³</th>
<th>&quot;Background&quot; Indoor Air ug/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=2</td>
<td>n=1</td>
<td>n=1</td>
<td>n=1</td>
<td>n=1</td>
<td>n=6</td>
<td>n=3</td>
<td>n=1</td>
</tr>
<tr>
<td>1,2,4-Trimethylbenzene</td>
<td>7,500,000</td>
<td>21000</td>
<td>19</td>
<td>95,000</td>
<td>730</td>
<td>1.9</td>
<td>0.51</td>
<td>2.8</td>
</tr>
<tr>
<td>1,3,5-Trimethylbenzene</td>
<td>1,545,000</td>
<td>6700</td>
<td>27</td>
<td>30,000</td>
<td>460</td>
<td>1.0</td>
<td>&lt;2</td>
<td>0.71</td>
</tr>
<tr>
<td>4-Isopropyltoluene</td>
<td>NA</td>
<td>1800</td>
<td>13</td>
<td>2,600</td>
<td>260</td>
<td>1.1</td>
<td>&lt;2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Benzene</td>
<td>&lt;200,000</td>
<td>1000</td>
<td>6.6</td>
<td>8,600</td>
<td>160</td>
<td>3.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>666,000</td>
<td>1400</td>
<td>6.6</td>
<td>42,000</td>
<td>130</td>
<td>1.7</td>
<td>0.57</td>
<td>1.3</td>
</tr>
<tr>
<td>Isopropylbenzene</td>
<td>228,000</td>
<td>460</td>
<td>1.2</td>
<td>6,400</td>
<td>99</td>
<td>0.69</td>
<td>&lt;2</td>
<td>0.76</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>2,655,000</td>
<td>9100</td>
<td>4.9</td>
<td>8,700</td>
<td>530</td>
<td>1.0</td>
<td>&lt;2.6</td>
<td>&lt;2.6</td>
</tr>
<tr>
<td>n-Butylbenzene</td>
<td>NA</td>
<td>4100</td>
<td>12</td>
<td>12,000</td>
<td>400</td>
<td>0.59</td>
<td>&lt;2.2</td>
<td>0.78</td>
</tr>
<tr>
<td>n-Propylbenzene</td>
<td>952,000</td>
<td>2000</td>
<td>6.6</td>
<td>23,000</td>
<td>130</td>
<td>0.58</td>
<td>0.28</td>
<td>1.2</td>
</tr>
<tr>
<td>sec-Butylbenzene</td>
<td>296,000</td>
<td>1300</td>
<td>12</td>
<td>3,900</td>
<td>220</td>
<td>0.33</td>
<td>&lt;2.2</td>
<td>0.56</td>
</tr>
<tr>
<td>Toluene</td>
<td>&lt;200,000</td>
<td>1000</td>
<td>6.6</td>
<td>6,500</td>
<td>130</td>
<td>55.3</td>
<td>8.6</td>
<td>79</td>
</tr>
<tr>
<td>Xylenes (total)</td>
<td>2,780,000</td>
<td>6800</td>
<td>7.4</td>
<td>159,000</td>
<td>720</td>
<td>7.4</td>
<td>2.4</td>
<td>5.1</td>
</tr>
<tr>
<td>1,2,3-Trimethylbenzene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>36,000</td>
<td>700</td>
<td>1.6</td>
<td>&lt;2</td>
<td>1.9</td>
</tr>
<tr>
<td>2-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>25,000</td>
<td>1,800</td>
<td>0.76</td>
<td>0.18</td>
<td>0.9</td>
</tr>
<tr>
<td>4-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>89,000</td>
<td>840</td>
<td>1.6</td>
<td>0.53</td>
<td>2</td>
</tr>
<tr>
<td>Methane</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>23%</td>
<td>2.00%</td>
<td>0.0036%</td>
<td>0.0056%</td>
<td>0.0003%</td>
</tr>
</tbody>
</table>

Averages exclude non-detects
### Table 4. Monitoring Data for Locations Outside LNAPL, Above Soil Contamination

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average Groundwater ug/L (n=3)</th>
<th>Average Deep Soil ug/kg (n=3)</th>
<th>Average Shallow Soil ug/kg (n=3)</th>
<th>Average Deep Soil Gas ug/m³ (n=3)</th>
<th>Average Shallow Soil Gas ug/m³ (n=3)</th>
<th>Average Inside Air ug/m³ (n=6)</th>
<th>Average Outside Air ug/m³ (n=3)</th>
<th>&quot;Background&quot; Indoor Air ug/m³ (n=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,4-Trimethylbenzene</td>
<td>43</td>
<td>12033</td>
<td>1.4</td>
<td>100,333</td>
<td>2,707</td>
<td>7.1</td>
<td>1.0</td>
<td>2.8</td>
</tr>
<tr>
<td>1,3,5-Trimethylbenzene</td>
<td>&lt;10</td>
<td>4100</td>
<td>&lt;6.7</td>
<td>29,667</td>
<td>1,003</td>
<td>1.3</td>
<td>2.0</td>
<td>0.71</td>
</tr>
<tr>
<td>4-Isopropyltoluene</td>
<td>NA</td>
<td>735</td>
<td>&lt;6.7</td>
<td>3,300</td>
<td>290</td>
<td>0.53</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Benzene</td>
<td>98</td>
<td>100</td>
<td>&lt;6.7</td>
<td>15,700</td>
<td>34</td>
<td>16.3</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>76</td>
<td>1203</td>
<td>&lt;6.7</td>
<td>61,333</td>
<td>473</td>
<td>6.6</td>
<td>0.57</td>
<td>1.3</td>
</tr>
<tr>
<td>Isopropylbenzene</td>
<td>18</td>
<td>327</td>
<td>&lt;6.7</td>
<td>7,367</td>
<td>300</td>
<td>1.5</td>
<td>2.0</td>
<td>0.76</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>392</td>
<td>5333</td>
<td>1.7</td>
<td>22,000</td>
<td>1,055</td>
<td>1.9</td>
<td>2.4</td>
<td>&lt;2.6</td>
</tr>
<tr>
<td>n-Butylbenzene</td>
<td>NA</td>
<td>2333</td>
<td>&lt;6.7</td>
<td>15,500</td>
<td>652</td>
<td>1.2</td>
<td>2.2</td>
<td>0.78</td>
</tr>
<tr>
<td>n-Propylbenzene</td>
<td>28</td>
<td>1400</td>
<td>&lt;6.7</td>
<td>24,667</td>
<td>551</td>
<td>2.4</td>
<td>0.85</td>
<td>1.2</td>
</tr>
<tr>
<td>sec-Butylbenzene</td>
<td>&lt;10</td>
<td>1500</td>
<td>&lt;6.7</td>
<td>4,533</td>
<td>300</td>
<td>1.4</td>
<td>2.2</td>
<td>0.56</td>
</tr>
<tr>
<td>Toluene</td>
<td>&lt;10</td>
<td>&lt;1300</td>
<td>&lt;6.7</td>
<td>773</td>
<td>59</td>
<td>40.0</td>
<td>8.6</td>
<td>79</td>
</tr>
<tr>
<td>Xylenes (total)</td>
<td>25</td>
<td>1167</td>
<td>&lt;6.7</td>
<td>69,687</td>
<td>1,047</td>
<td>8.9</td>
<td>2.4</td>
<td>5.1</td>
</tr>
<tr>
<td>1,2,3-Trimethylbenzene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>41,333</td>
<td>1,153</td>
<td>2.5</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>2-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>25,333</td>
<td>802</td>
<td>1.2</td>
<td>0.79</td>
<td>0.9</td>
</tr>
<tr>
<td>4-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>45,667</td>
<td>1,253</td>
<td>2.8</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>Methane</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>17%</td>
<td>0.85%</td>
<td>0.0058%</td>
<td>0.0056%</td>
<td>0.0003%</td>
</tr>
</tbody>
</table>

Averages exclude non-detects
Table 5. Detection of Diesel-Related Compounds in Various Media

<table>
<thead>
<tr>
<th>Compound</th>
<th>Soil*</th>
<th>Groundwater</th>
<th>Deep Soil Gas</th>
<th>Shallow Soil Gas</th>
<th>Indoor Air</th>
<th>Background Indoor Air</th>
<th>Outdoor Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Toluene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Xylenes (total)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1,2,3-Trimethylbenzene</td>
<td>NA</td>
<td>NA</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1,2,4-Trimethylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1,3,5-Trimethylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>n-Propylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Isopropylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4-Ethyltoluene</td>
<td>NA</td>
<td>NA</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>n-Butylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sec-butylbenzene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>p-Isopropyltoluene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2-Methylnaphthalene</td>
<td>X</td>
<td>X</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Acenaphthene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fluorene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Anthracene</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

X = Compound detected in one or more samples from this medium  
Highlighting indicates one or more samples exceeds EPA screening level  
NA = Compound not included in analyte list  
*Screening levels not available for soil samples

5. Conclusions

The observed attenuation factors of diesel-related compounds for deep soil gas to shallow soil gas averaged about 0.03 to 0.04. For shallow soil gas to indoor air, the attenuation factors were 0.03 to 0.08. Attenuation factors for individual compounds varied by an order of magnitude or more.

Methane was found in potentially explosive concentrations in the subsurface at this site. Methane has the potential to accumulate to hazardous concentrations in underground structures such as sewers and utility vaults.

The concentrations of diesel-related compounds in indoor air were relatively low, although several compounds exceeded the screening level established in the EPA vapor intrusion guidance.

Further evaluation of the site is recommended to more fully evaluate the impacts of subsurface diesel contamination on indoor air.
EnviroGroup Limited
James B. Cowart, P.E.
Curriculum Vitae

EXPERTISE

- Indoor Air/Vapor Intrusion Assessment & Mitigation
- Water Quality, Industrial Process Wastewater and Watersheds
- Mining and Oil and Gas Permitting & Reclamation
- CERCLA/RCRA Hazardous Waste Investigation, Feasibility, Design, Remedial Action
- Expert Testimony and Litigation Support

EDUCATION and CERTIFICATIONS

M.S., Civil/Environmental Engineering, University of Miami, Florida, 1995
M.F.A., Photography, University of Florida, Florida, 1974
B.S., Engineering, U.S. Military Academy, West Point, New York, 1967
Registered Professional Engineer, Colorado, Wyoming and Kansas, 2011
USEPA Certification for Indoor Air Vapor Intrusion Training, 2003
MSHA Underground and Surface Mining 40-hour Training, 1996
Registered Petroleum Storage Tank Consultant # 5182, State of Colorado, 1993
OSHA HAZWOPER 40-hour Training, 1985

SUMMARY OF EXPERIENCE

Mr. Cowart has 38 years of experience in the environmental disciplines of water, wastewater, water resources, solid waste, indoor air pollution, hazardous waste, environmental assessments and impact statements, due diligence, and assessment and remediation of soils and groundwater. He has worked closely with clients in numerous industries including mining, propulsion, organic chemicals, pesticides, timber products, printing and publishing, foods, beverages, fish processing, oil and gas, transportation, metals finishing, pharmaceuticals, pyrotechnics, airports, dry cleaners and commercial development. He has provided technical assistance to Federal, State and County agencies. He has international experience in South Africa, Botswana, Peru, Chile, Colombia, Mexico and Japan. In addition, Mr. Cowart has four years of engineering management experience with the U.S. Army Signal Corps and three years of graduate schooling and teaching positions.

Mr. Cowart has served as a project engineer, principal engineer, project manager or director, division manager, branch office manager, chief operating officer, vice president and board of directors’ member in several environmental consulting companies. He has managed approximately 1,000 projects ranging from very small up to $15 million in size, involving over 500 man-years of work. Mr. Cowart has authored more than a dozen papers, and provided litigation support as well as deposition or testimony in more than 20 cases. He serves on the board of directors for several non-profit organizations.

EMPLOYMENT HISTORY

Senior Project Manager, EnviroGroup Limited, Centennial, Colorado, 2009 to present.
Principal Engineer, Walsh Environmental Scientists and Engineers, LLC. Boulder, Colorado, 1993 to 2009.
INDOOR AIR/ VAPOR INTRUSION INVESTIGATION & MITIGATION PROJECTS

VAPOR INTRUSION ASSESSMENT & MITIGATION, RIVER POINT AT SHERIDAN, COLORADO
Mr. Cowart was Project Director for the Voluntary Cleanup (VCUP) and redevelopment of a 130 acre former landfill in Sheridan, Colorado. A Vapor Mitigation Plan for this site was prepared by Mr. Cowart and approved by the Colorado Department of Public Health and Environment in 2006. Vapor assessment and mitigation of $4 to $6 million are being performed for 800,000 square feet of commercial buildings, including Target and Costco, as well as parking lots and utilities, in order to protect public health and safety from explosive levels of methane and other toxic gases. This is currently the largest vapor mitigation project in the U.S.

VAPOR INTRUSION ASSESSMENT & MITIGATION, HEADQUARTERS: CDOT, DENVER, COLORADO
Mr. Cowart was Program Manager from 1997-2001 for the first large, complex vapor intrusion related hazardous waste investigation and remediation in the U.S. at the CDOT Headquarters in Denver, Colorado. Leaking underground storage tanks on-site contaminated groundwater with solvents, which in turn led to air quality impacts to 750 occupants of apartment buildings and single family residences above the groundwater plume. For this project, Mr. Cowart directed a RCRA Facilities Investigation, an Interim Measures Action consisting of soil vapor extraction at 30 structures, a Baseline Risk Assessment which established Preliminary Remediation Goals, a Long Term Corrective Measures Plan, and an Operations & Maintenance and Monitoring program which provides for more than $20 million for treatment of indoor air over the next 20 years. This site was regulated by the Colorado Department of Public Health and Environment.

VAPOR INTRUSION ASSESSMENT, ELECTRONICS FACILITY, CENTENNIAL, COLORADO
Mr. Cowart was Project Manager from 1999-2004 for an indoor air quality assessment of chlorinated solvents, including trichloroethylene (TCE) at a former Honeywell electronics assembly facility in Centennial, Colorado. Plans were developed and implemented for soil gas and indoor air sampling at on-site commercial and at 49 off-site residential locations. The USEPA RCRA Division concluded that the human health impacts at the site were “under control” and indoor air monitoring was discontinued.

VAPOR INTRUSION MITIGATION DESIGN, INDUSTRIAL BUILDING, PARK CITY, KS
EnviroGroup prepared the design of a subslab depressurization system, using gravel and pipe connected to blower systems, to mitigate vapors at a 42,000 square foot industrial warehouse in Park City, KS. Mr. Jim Cowart, P.E. is Sr. Project Manager and Registered Professional Engineer for the system.

VAPOR INTRUSION MITIGATION DESIGN, COMMERCIAL BUILDING, LYNDHURST, OH
EnviroGroup prepared the design of a subslab depressurization system, using gravel and pipe connected to blower systems, to mitigate vapors at a 3,876 square foot commercial bank building in Lyndhurst, OH. Mr. Jim Cowart, P.E. is Sr. Project Manager and Registered Professional Engineer for the system.

VAPOR INTRUSION MITIGATION DESIGN REVIEW, CITY OF SHERIDAN, COLORADO
For the City of Sheridan, Colorado, EnviroGroup provided vapor mitigation design review for the Chick-fil-A, Steak n’ Shake and Texas Roadhouse restaurant building permit located at the River Point Mall in Sheridan, Colorado. Also for the City of Sheridan, Mr. Cowart provided design review for permit approval of the methane control systems in sanitary and stormwater utilities. Mr. Jim Cowart, P.E. is Sr. Project Manager.

VAPOR INTRUSION EXPERT DEPOSITION, PCE IN GROUNDWATER, SECURITY, COLORADO
Mr. Cowart provided expert witness services for plaintiffs concerned about potential human health cancer risks from indoor air in 3,000 residences overlying a tetrachloroethylene (PCE)-contaminated groundwater plume in Security, Colorado. Mr. Cowart prepared expert reports and was deposed three times during 2003 to 2006, before a judgment was issued in 2007.

VAPOR INTRUSION ASSESSMENT & EXPERT TESTIMONY, DIESEL SPILL, MANDAN, NORTH DAKOTA
Mr. Cowart directed sampling of groundwater, soil vapor, soil, indoor air, and outdoor air during 2002-2004 in order to assess the potential human health impacts in indoor air located over this 3 million gallon diesel spill in the City of Mandan, North Dakota. On behalf of selected residents, Mr. Cowart has been deposed twice and testified in court as an expert concerning the potential for diesel-related contaminants in groundwater to have migrated through soil vapor into indoor air.

VAPOR INTRUSION MITIGATION, COMMERCIAL BUSINESS CENTER, ARVADA, COLORADO
Mr. Cowart directed the design and installation of a 22,000 sq. ft. passive subsurface vapor mitigation system, protecting against explosive methane gas, at the Ralston Business Center in Arvada, Colorado.
VAPOR INTRUSION MITIGATION, TRUCKING FACILITY, ADAMS COUNTY, COLORADO
Mr. Cowart directed the design and installation of a 10,000 sq. ft. passive subsurface vapor mitigation system, protecting against explosive methane gas, at the Voyager Express trucking facility in Westminster, Colorado.

VAPOR INTRUSION MITIGATION, COMMUNITY CENTER, FT. COLLINS, COLORADO
Mr. Cowart directed the design and installation of a 30,000 sq. ft. active subsurface vapor mitigation system, protecting against explosive methane gas and volatile compounds, at the Aztlan Community Center, Ft. Collins, Colorado.

VAPOR INTRUSION MITIGATION DESIGN, CHEYENNE, WYOMING
For the Wyoming Department of Environmental Quality, Mr. Cowart is designing vapor mitigation systems for several large commercial buildings impacted by PCE volatilizing from groundwater.
WATER QUALITY, INDUSTRIAL WASTEWATER and WATERSHEDS

BOULDER CREEK WATERSHED INITIATIVE

Mr. Cowart is on the Board of Directors of the Boulder Creek Watershed Initiative in Boulder, Colorado. The overall goals of the BCWI include assessment, restoration and public education on water quantity, water quality, invasive species and endocrine disruptors. Funding has been provided through the Colorado Department of Public Health and Environment for a one year study of bacterial parameter contamination. The total suite of constituents collected and analyzed is: air and water temperature, dissolved oxygen, pH, conductivity, total coliform, e-coli bacteria, UV 254 optical brighteners, TOC, LAS (Linear alkylbenzene sulphonate), Nonphenols (ELISA), B estrodial(ELISA), bacteroids and, chemometrics (NO3, NO2, NH3). Additionally, physical habitat evaluations were performed.

SURFACE WATER ASSESSMENT, LEFTHAND WATERSHED, JAMESTOWN, COLORADO

Surface water in the Little James Creek segment of the South Platte River in Colorado was characterized over a one-year period. Stormwater runoff and acid mine drainage was impacting receiving stream water quality. Approximately 12 surface water sites were sampled for flow and chemistry, as well as 6 sites for macroinvertebrates. Results were compared to drinking water, aquatic life, recreation and irrigation water quality standards. Mr. Cowart was the project manager.

USE ATTAINABILITY ANALYSIS, FE WARREN AFB, CHEYENNE, WYOMING

Surface water at FE Warren Air Force Base (AFB) was sampled and analyzed in order to evaluate whether it is in compliance with recently promulgated and proposed Wyoming Department of Environmental Quality (WDEQ) standards. Crow Creek, Diamond Creek and Unnamed Tributary were sampled in winter, low-flow conditions over five days in accordance with a Field Sampling Plan. Laboratory analyses were performed on approximately 40 parameters in accordance with a Quality Assurance Project Plan. These data were used in a Draft Use Attainability Analysis by FE Warren AFB. Mr. Cowart was the project manager.

REMOVAL OF 1, 4-DIOXANE FROM GROUNDWATER AT REFIELD SITE, DENVER, CO

EnviroGroup is responsible for permitting and design of wastewater treatment to remove 1, 4-dioxane from groundwater extraction wells at the Redfield Site, Denver, Colorado. Both UV/Peroxide and UV/Titanium Dioxide processes are being evaluated. Mr. Jim Cowart, P.E. is Sr. Project Manager.

NPDES PERMITTING FOR LEAD/ZINC/SILVER MINE NEAR CREEDE, CO

EnviroGroup is responsible for permitting of wastewater discharges from a historical mine in Creede, Colorado. Treatability studies are being conducted for mine dewatering and future mine ore milling discharges to surface water. Mr. Jim Cowart, P.E. is Sr. Project Engineer.

REMOVAL OF NITRATE FROM GREENHOUSE WASTEWATER, BRUSH, COLORADO

Mr. Cowart is responsible for permitting and design of wastewater management systems to remove nitrate-nitrogen from discharges to surface water at the Brushco Farms tomato greenhouse in Brush, Colorado.

TREATABILITY STUDY FOR ACID MINE DRAINAGE, BURLINGTON MINE, COLORADO

Mr. Cowart managed a treatability study for acid mine drainage, using static and dynamic testing of the Anoxic Limestone Drain technology, at the Burlington Mine site near Jamestown, Colorado. Dissolved zinc and manganese concentrations were reduced, while pH and alkalinity were increased, so as to compare the effluent with Colorado water quality standards.

REMOVAL OF METALS FROM ADIT DISCHARGE, CALAIS MINE, CARIBOU, COLORADO

The Calais Mine is a gold/silver resource in Caribou Colorado where underground mining began in the 1880’s. The mine currently has a draining adit which is permitted by the State of Colorado NPDES program. Flows of 10-100 gallons per minute are regulated for pH, and metals such as zinc, cadmium and lead. Mr. Cowart has conducted several wastewater treatability studies of the discharge, including: natural zeolites, immobilized ligands, and electrocoagulation. Lime neutralization is currently utilized. The receiving stream, Coon Trail Creek, is monitored monthly to ensure that water quality standards are met.

PRECIPITATION OF HEAVY METALS FROM GROUNDWATER, COPPER MINE, CUBA, NEW MEXICO

For the USDA Forest Service, Mr. Cowart conducted a treatability study and prepared a conceptual design for the removal of heavy metals, such as copper, from acidic groundwater at the former Nacimiento Mine site in Cuba, New Mexico. The acidic groundwater was titrated with various bases in order to determine optimum precipitation conditions. Polishing treatment was evaluated using an immobilized ligand to preferentially adsorb metals of concern. A conceptual design and capital and annual cost estimate was prepared for a 105 gpm groundwater extraction and treatment system, with discharge to either groundwater or surface water.

For the U.S. Environmental Protection Agency, Mr. Cowart directed over 75 man-years of work during a 10-year period in order to establish wastewater treatment effluent guidelines and standards for industries discharging into surface waters or publicly-owned treatment works. The industries addressed were those of pesticide chemicals, fruits and vegetables, edible oils, malt beverages, wines, soft drinks, distilled spirits, sugar cane processing, fish processing, hydrolyzed vegetable protein, and pectin. Wastewater treatment units which were evaluated and incorporated into designs included activated carbon and resin adsorption; steam stripping; chemical oxidation by hydrolysis; ion exchange; ultrafiltration; metals precipitation; oil/water separation including dissolved air flotation; activated sludge, aerated lagoons, and rotating biological contractors; sand filtration; anaerobic digestion; wet air oxidation of sludge; and thermal treatment and land application of sludges.

OIL PRODUCTION WASTEWATER CONSULTING, COLOMBIA, OCCIDENTAL PETROLEUM

Mr. Cowart provided consulting services to an American oil company at their 200,000-barrel per day oil and gas extraction facility in northeast Colombia. Alternatives were evaluated for the control and treatment of 250 pounds of phenols contained in approximately 50 million gallons per day of produced water, which is discharged into nearby surface water. Mr. Cowart evaluated chemical oxidation, microbial-assisted biological oxidation, and physical treatment technologies for the removal of phenols, hydrocarbons, and oil and grease in wastewater so that stringent toxicity-based receiving water standards could be met. He also reviewed plant design and suggested operational modifications that would reduce the amount of contaminants that need treatment.


For the US EPA Industrial Environmental Research Laboratory (IERL) at Research Triangle Park, North Carolina, Mr. Cowart served as project manager for a wastewater treatability study of pesticide wastewater using hydrolysis, chemical oxidation, and ultra-violet photolysis studies. As project manager for the IERL at Cincinnati, Ohio, he managed a study for the development of analytical methods of pesticides in wastewater.

WASTEWATER TREATMENT DESIGN, PESTICIDE FACILITY, NAPLES, FLORIDA

For the Collier Mosquito Control District, Mr. Cowart served as project manager for the design of oil/water separation and hydrolysis treatment facilities for spills and stormwater from a vehicular, fixed-, and rotary-winged aircraft, RCRA-hazardous material pesticide storage, formulation, application, and maintenance facility.
MINING AND OIL AND GAS PERMITTING AND RECLAMATION

SPCC PLANS, O&G SITES, WESTERN COLORADO.
EnviroGroup provided certification of SPCC plans at a major company with oil and gas well pads, compressor stations and water treatment facilities in the Piceance Basin, Colorado. Hundreds of sites are covered in the SPCC plans prepared in accordance with USEPA regulations at 40 CFR 112 due November 10, 2011. Mr. Jim Cowart, P.E. is Sr. Project Manager and Registered Professional Engineer for the plans.

O&G PRODUCED WATER FACILITY PERMITTING, DEBEQUE, COLORADO.
EnviroGroup has provided a wide variety of services for the acquisition of air, wastewater, groundwater and solid waste permits for a 1,000 barrel per day oil and gas produced water evaporation disposal facility. Air services include air emissions testing, Reasonably Available Control Technology evaluation and Air Pollution Emissions Notice submittals to agencies. Groundwater services include a Groundwater Characterization Report and a Groundwater Corrective Action Plan submittals to agencies. Solid waste services include preparation of an Engineering Design and Operation Plan for expansion of the evaporation ponds to greater than 3,000 barrels per day. Mr. Jim Cowart, P.E. is Sr. Project Manager.

SHALE OIL PILOT PLANT DESIGN, PICEANCE BASIN, COLORADO.
Mr. Jim Cowart, P.E. served as Sr. Engineer for the environmental design of a pilot plant for the American Shale Oil Company, Rifle, Colorado. AMSO, in a joint venture with TOTAL on BLM leased land, designed a shale oil gas and liquids processing facility, including separators, steam stripping and incineration, in order to evaluate full-scale application.

SPCC PLANS, COMMERCIAL DIESEL FUEL SITES, DENVER, COLORADO.
EnviroGroup provided certification of SPCC plans at a major fuel/oil distributor with facilities in Denver, Colorado. Mr. Jim Cowart, P.E. is Sr. Project Manager and Registered Professional Engineer for the plans.

VOLUNTARY CLEANUP at BURLINGTON MINE, JAMESTOWN, COLORADO
At the former Burlington Fluorspar Mine Site near Jamestown, Colorado, Mr. Cowart was project manager for the reclamation design and construction oversight for this Voluntary Cleanup (VCUP). This 13-acre facility contained over 10,000 feet of underground tunnels, adits and shafts. Acid rock drainage was generated from approximately 35,000 cubic yards of waste rock, and acid mine drainage from underground workings was discharging to a nearby creek. The reclamation included: diversion of a 220 cfs surface water stream; consolidation of waste rock in a neutralized and capped repository; closure of subsidence pits, shafts and adits, and grading/drainage; and revegetation of the site. This project won the Colorado Mined Land Reclamation Board (MLRB) Hard Rock Reclamation Award for 2005.

REMEDIAL INVESTIGATION/FEASIBILITY STUDY, CAPTAIN JACK CERCLA MINE SITE, WARD, COLORADO.
Mr. Cowart served as Senior Engineer for an RI/FS at a collection of abandoned mine sites in California Gulch, Lefthand Canyon Watershed, near Ward, Colorado. Oversight is by the Colorado Department of Public Health & Environment and USEPA, Region 8 in Denver, Colorado.

REMEDIAL INVESTIGATION, CALIFORNIA GULCH CERCLA SITE, LEADVILLE, COLORADO
At a mining and smelting Superfund site in Colorado, Mr. Cowart served as senior engineer for the portions of the Remedial Investigation (RI) related to defining background metals in soils and for the chemical evaluation of metals sources.

FEASIBILITY STUDY AND REMEDIAL DESIGN, NACIMIENTO COPPER MINE CERCLA SITE, CUBA, NEW MEXICO
Mr. Cowart is project manager for this CERCLA Feasibility Study (FS) and Remedial Design (RD) at an abandoned copper mine site on USDA Forest Service property near Cuba, New Mexico. Approximately 25 million gallons of groundwater are contaminated with acidic solutions from historic in-situ leaching mining processes. A variety of remedial alternatives were evaluated including natural attenuation, groundwater pumping, ex-situ metals precipitation and ligand polishing treatment, with discharge of treated effluent to recharge galleries, surface water or an on-site pit lake. A remedial design has been prepared to include groundwater extraction, neutralization and metals precipitation, polishing treatment by immobilized ligand, and discharge to the surface.
ENVIRONMENTAL LIABILITY EVALUATION, TONOPAH MINE, NEVADA
For Antofagasta Minerals of Chile, Mr. Cowart conducted an environmental liability evaluation in preparation for purchase of the Tonopah copper mine in Nevada. An inspection was performed of historic pit-lake, heap leach, tailings and other processing areas. Visits were made to the BLM and Nevada DEP to evaluate regulatory compliance. Existing bonding was reviewed for adequacy. A confidential opinion was developed to estimate potential costs for reclamation.

ENVIRONMENTAL LIABILITY EVALUATION, EMERALD ISLE & ZONIA MINES, ARIZONA
For Ascendant Copper of Denver, Colorado Mr. Cowart conducted an environmental liability evaluation in preparation for purchase of the Emerald Isle & Zonia copper mines in Arizona. An inspection was performed of historic pit-lake, heap leach, PLS pond, raffinate pond, and other processing areas. Visits were made to the BLM and Arizona DEQ to evaluate the Aquifer Protection Permit and other regulatory compliance issues. Existing bonding was reviewed for adequacy. A confidential opinion was developed to estimate potential costs for reclamation.

HUMAN HEALTH RISK EVALUATION, CHUQUICAMATA COPPER MINE, ATACAMA DESERT, CHILE
For Codelco, the state-owned mining company in Chile, Mr. Cowart and a team of toxicologists evaluated the potential human health risks to on-site workers and off-site families at the Chuquicamata mining and smelter site, the largest copper mine in the world. The primary pathway of concern was arsenic in smelter and windblown tailings inhaled and ingested by workers and families resulting in elevated levels in blood and urine. Engineering controls, best management practices and health and safety practices were recommended to management.

PERMITTING OF HARD ROCK GOLD MINE, CARIBOU, COLORADO
Mr. Cowart has managed the acquisition of Federal, State and County permits for the Calais Resources 200 ton per day underground gold/silver mine in Caribou, Colorado. Point-source discharges of adit drainage containing zinc and other dissolved metals have been permitted through the Colorado Pollution Discharge Elimination System (CPDES); mining operations and reclamation have been permitted with the Colorado Department of Reclamation and Mine Safety (DRMS); and local Special Use permits have been obtained from the Boulder County Land Use Department. These permits allow underground mining, surface milling, underground tailings backfill, stormwater management, treatment of wastewater, and other associated mine operations to be implemented at this historic mining district west of Nederland, Colorado.

RISK-BASED SOILS CLEANUP, TOWN OF RICO, COLORADO
EnviroGroup is working cooperatively with the Town of Rico and Atlantic Richfield to develop the technical basis for a State-approved Voluntary Cleanup of the streets, alleys, lots, right-of-ways and stormwater drainage which have been impacted with lead from historic mining operations.
RCRA/HAZARDOUS WASTE PROJECTS

RCRA INTEGRATED CORRECTIVE ACTION, DRY CLEANER, AURORA, COLORADO

At the former JH Cleaners site in Aurora, Colorado Mr. Cowart is directing an Integrated Corrective Action Plan for PCE contaminated soils and groundwater. A site characterization has been conducted to determine the level and extent of PCE-related contamination in soils, soil gas, groundwater and indoor air. A Corrective Action Plan is being prepared to include aerobic bioremediation of soils, anaerobic bioremediation of groundwater, and a radon-type vapor mitigation system to ensure that future building occupants are not exposed to excess PCE-related risk. The site is regulated by the Colorado Department of Public Health and Environment.

RCRA INDOOR AIR QUALITY, ALLIANT TECHSYSTEMS SITE, LITTLETON, COLORADO

Mr. Cowart was Project Manager from 1999-2004 for an indoor air quality assessment of chlorinated solvents at this former Honeywell electronics assembly facility. This site was regulated under a Consent Order from the RCRA Division, U.S. Environmental Protection Agency, Region VIII. Plans were developed and implemented for soil gas and indoor air sampling at on-site commercial and at 49 off-site residential locations. Community relations meetings were held to explain the purpose and findings of studies. Based on evaluations of groundwater, soil gas and indoor air data, the USEPA concluded that the human health impacts at the site were “under control” and indoor air monitoring was discontinued.

RCRA INDOOR AIR QUALITY, COLORADO DEPARTMENT OF TRANSPORTATION, DENVER, COLORADO

Mr. Cowart was Program Manager from 1997-2001 for an indoor air-quality related hazardous waste investigation and remediation at the CDOT Headquarters in Denver, Colorado. Leaking underground storage tanks on-site contaminated groundwater with solvents, which in turn led to air quality impacts inside roughly 100 apartment buildings and single family residences above the groundwater plume. For this project, Mr. Cowart directed a RCRA Facilities Investigation, an Immediate Response Action consisting of soil vapor extraction at 30 structures, a Baseline Risk Assessment which established Preliminary Remediation Goals, and a Corrective Measures Plan which provides for more than $20 million for treatment of indoor air over the next 20 years. This site was regulated by the Colorado Department of Public Health and Environment.

RCRA SOIL AND GROUND WATER TREATMENT, COLORADO DEPARTMENT OF TRANSPORTATION, DENVER

At the Colorado Department of Transportation headquarters site, Denver, Colorado, Mr. Cowart was senior engineer for a RCRA Corrective Measures Plan and Corrective Action which involved remediation of soils, soil vapor, and ground water contaminated by waste solvents. Groundwater extraction, air stripping and vapor incineration systems were installed and operated to remove dissolved solvents.

RCRA QUALITY CONTROL ENGINEER, ROCKY MOUNTAIN ARSENAL BASIN F, RCRA CLOSURE, DENVER

For the Army Corps of Engineers, Mr. Cowart acted as the independent registered engineer to certify the RCRA closure of $70 million facilities including Basin F waste ponds, tank farm, and submerged quench incinerator, which contained pesticides, munitions, and chemical warfare wastes.

RCRA INDOOR AIR QUALITY, CITY OF MANDAN, NORTH DAKOTA

Mr. Cowart was Project Manager in 2002-2004 for a vapor intrusion and indoor air quality assessment of approximately 12 square blocks of commercial and residential buildings in Mandan, North Dakota which are located over an estimated 3 million gallons of diesel fuel floating on the groundwater table. The State determined that RCRA regulations applied. Multi-media samples were taken of floating product, soil gas, soil, indoor and outdoor air. Results were evaluated to determine if there were short- or long-term human health risks for occupants of the buildings.

EXPERT CONSULTANT FOR RCRA WASTE CODE DEVELOPMENT, US EPA

For the U.S. Environmental Protection Agency's Office of Solid and Hazardous Waste, Mr. Cowart served as an expert for the development of listed RCRA hazardous wastes from non-specific sources, which appeared in Code 40 of Federal Regulations (CFR) 261.31 May 19, 1980, for waste numbers K031 through K099 in the pesticides industry.

RCRA WASTE GENERATION EVALUATION, FLORIDA DER

For the Florida Department of Environmental Regulation and South Florida Regional Planning Council, Mr. Cowart directed the inventory of more than 33,000 businesses to determine RCRA hazardous waste generator characteristics and requirements under 40 CFR 262 and Chapter 17 of the Florida Administrative Code.
STATEWIDE RCRA CHARACTERIZATION AND SITING STUDY, FLORIDA DER
For the Florida Department of Environmental Regulation, Mr. Cowart served as senior engineer for a statewide RCRA hazardous waste characterization and siting study conducted pursuant to the siting and permitting process in Chapter 17 of the Florida Administrative Code and 40 CFR 264 for owner/operators of hazardous waste treatment, storage, and disposal facilities.

GROUND WATER REMEDIAL ACTION, PRATT AND WHITNEY RCRA SITE, PALM BEACH COUNTY, FLORIDA
Mr. Cowart served as project manager for this RCRA Corrective Action (CA) consisting of the design and installation of a 26 well product recovery system for several feet of PCB/jet-fuel contaminated ground water. The product recovery system, which was designed in 1985, was one of the early low-flow pneumatic systems installed.

RCRA CLOSURE, ELECTROPLATING FACILITY IMPOUNDMENT, TAMPA, FLORIDA
For Sanitary Dash, Mr. Cowart served as senior engineer for a RCRA clean closure of a surface impoundment receiving wastewaters from an electroplating facility in Tampa.

RCRA PART B PERMITTING, CORRECTIVE MEASURES STUDIES, AND CORRECTIVE ACTION, FLORIDA
For Safety Kleen mineral spirits distribution and recycling centers in South Florida, he served as senior project engineer for RCRA Corrective Measures Studies and Corrective Actions related to contamination of soil and ground water, and for RCRA Part B permitting for new facilities.

RCRA PERMITTING, PESTICIDE FACILITY, NAPLES, FLORIDA
The Collier Mosquito Control District has an RCRA-hazardous material pesticide storage, formulation application, and maintenance facility for both vehicles and aircraft. Mr. Cowart served as project manager for environmental design, RCRA-generator permitting; spill prevention and countermeasure control plan development; and ground water and stormwater permitting for this facility.

RCRA ASSESSMENT AND REMEDIAL ACTION PLANS, U.S. ZINC GALVANIZING, FLORIDA
For this industrial facility, Mr. Cowart directed the removal of RCRA liquids and sludges, conducted an assessment of metals in soils using electromagnetic and resistivity geophysical techniques, performed an assessment of ground water, and prepared remedial action plans in accordance with Metro Dade County Florida hazardous waste regulations.

COMPREHENSIVE RCRA AND ENVIRONMENTAL SERVICES, UNITED STATES SUGAR CORPORATION, CLEWISTON, FLORIDA.
Over a 3-year period, Mr. Cowart served as project manager for comprehensive environmental services including assessment and remediation of 12,000 tons of Bunker C-impacted soils, design of solids separation and oil/water separators for 2,400 gallon per minute wastewater discharges, decontamination of a 2, 4-D pesticide formulation warehouse, assessment and remediation of MSMA-pesticide impacted soils at a chemical storage facility. In addition, he prepared waste management protocols and performed RCRA facility inspections.
CERCLA/SUPERFUND HAZARDOUS WASTE PROJECTS

REMEDIAL INVESTIGATION/FEASIBILITY STUDY, CAPTAIN JACK CERCLA MINE SITE, WARD, COLORADO.
Mr. Cowart served as Senior Engineer for an RI/FS at a collection of abandoned mine sites in California Gulch, Lefthand Canyon Watershed, near Ward, Colorado. Oversight is by the Colorado Department of Public Health & Environment and the USEPA, Region 8 in Denver, Colorado.

REMEDIAL INVESTIGATION, WILSON'S CONCEPT'S CERCLA SITE, FLORIDA
Mr. Cowart served as senior project engineer for a Remedial Investigation (RI) of an electronics and metal finishing facility CERCLA site in Broward County, Florida.

REMEDIAL INVESTIGATION, CALIFORNIA GULCH CERCLA SITE, LEADVILLE, COLORADO
At a mining and smelting Superfund site in Colorado, Mr. Cowart served as senior engineer for the portions of the Remedial Investigation (RI) related to defining background metals in soils and for the chemical evaluation of metals sources.

FEASIBILITY STUDY, 58TH STREET MUNICIPAL LANDFILL CERCLA SITE, DADE COUNTY, FLORIDA
Mr. Cowart served as project manager for the portion of the Feasibility Study (FS) at this Superfund landfill site that involved geophysical studies, groundwater modeling, and capping alternatives.

FEASIBILITY STUDY AND REMEDIAL DESIGN, NACIMIENTO COPPER MINE CERCLA SITE, CUBA, NEW MEXICO
Mr. Cowart was project manager for this CERCLA Feasibility Study (FS) and Remedial Design (RD) at an abandoned copper mine site on USDA Forest Service property near Cuba, New Mexico. Approximately 25 million gallons of groundwater were contaminated with acidic solutions from historic in-situ leaching mining processes. A variety of remedial alternatives were evaluated including natural attenuation, groundwater pumping, ex-situ metals precipitation and ligand polishing treatment, with discharge of treated effluent to recharge galleries, surface water or an on-site pit lake. A remedial design was being prepared to include groundwater extraction, neutralization and metals precipitation, polishing treatment by immobilized ligand, and discharge to the surface.

REMEDIAL DESIGN, PIONEER SAND CERCLA SITE, PENSACOLA, FLORIDA
Mr. Cowart served as senior project engineer for a Remedial Design (RD) incorporating air injection, leachate treatment, and an engineered cap at an abandoned borrow pit/industrial fill area in Pensacola, Florida.

SITE INVESTIGATION, ANACONDA ALUMINUM CERCLA SITE, DADE COUNTY, FLORIDA
Mr. Cowart served as project manager for a Site Investigation at this aluminum anodizing facility. A percolation pit had received wastewater containing metals which were precipitated with caustic soda.

EXPERT DEPOSITION, THOMPSON HAYWARD CERCLA SITE, FRESNO, CALIFORNIA
At the Thompson Hayward Agriculture and Nutrition CERCLA Site in Fresno County, California for litigation filed in Wilmington, Delaware in North American Phillips Corp. vs. Aetna, Mr. Cowart was deposed for eight days as an expert in pesticide formulation and packaging industry operations and waste management practices. The case was settled out of court.
PERMITTING, SITE ASSESSMENTS AND REMEDIATION, AT NON-HAZARDOUS AND BROWNFIELDS AND VOLUNTARY CLEANUP SITES

RISK-BASED SOILS CLEANUP, TOWN OF RICO, COLORADO
EnviroGroup is working cooperatively with the Town of Rico and Atlantic Richfield to develop the technical basis for a State-approved Voluntary Cleanup of the streets, alleys, lots, right-of-ways and stormwater drainage which have been impacted with lead from historic mining operations. Mr. Jim Cowart, P.E. is Sr. Project Engineer.

PHASE 1 ENVIRONMENTAL SITE ASSESSMENT, CENTENNIAL, COLORADO
EnviroGroup prepared a Phase I Environmental Site Assessment of the American Sporting Goods Corporation facility located at 10730 Production Avenue, Fontana, California. The Assessment was prepared in conformance with the American Society for Testing and Materials (ASTM) Practice E1527-05. Mr. Jim Cowart, P.E. is Sr. Project Manager.

PHASE 1 ENVIRONMENTAL SITE ASSESSMENT, FONTANA, CALIFORNIA
EnviroGroup prepared a Phase I Environmental Site Assessment of the former Circle K Store, currently Walgreens facility, located at 16950 East Smoky Hill Road, Centennial, Colorado. The Assessment was prepared in conformance with the American Society for Testing and Materials (ASTM) Practice E1527-05. Mr. Jim Cowart, P.E. is Sr. Project Manager.

EVALUATION OF LOWRY LANDFILL COSTS, DENVER, CO
EnviroGroup evaluated the reasonableness of the future Design, Remedial Action, and Operations and Maintenance cost estimates at the Lowry Landfill in unincorporated Arapahoe County, Colorado. Mr. Jim Cowart, P.E. is Sr. Project Manager.

BROWNFIELDS & VOLUNTARY CLEANUP REDEVELOPMENT, ELYSIAN PARK, JAMESTOWN, COLORADO
Mr. Cowart is Project Director for redevelopment of a public park resting on mine tailings in Jamestown, Colorado. A soil cover will be used at this 5 acre site to control stormwater runoff, minimize infiltration, and prevent dermal exposure to elevated levels of metals in the historic tailings. An Analysis of Brownfields Cleanup Alternatives (ABCA) has been prepared for EPA, and a Voluntary Cleanup (VCUP) application for the State of Colorado, to fulfill grant requirements. Construction plans and specifications will be prepared for implementation in 2009.

ARAPCO LANDFILL VOLUNTARY CLEANUP, SHERIDAN, COLORADO
Mr. Cowart is Project Manager for the Voluntary Cleanup (VCUP) of a 130 acre former landfill in Sheridan, Colorado. Vapor assessment and mitigation are being performed for 800,000 square feet of commercial buildings, as well as parking lots and utilities, in order to protect public health and safety from explosive levels of methane and other toxic gases. In addition, the project includes a Phase 1 site assessment of 50 properties, asbestos and lead-based paint assessment and abatement design for 150,000 square feet of existing buildings, preparation of a wetlands assessment and riparian and in stream improvements, and a Materials Management Plan for excavation of more than 1 million cubic yards of solid waste. All activities are performed under supervision of the Colorado Department of Public Health and Environment.

BURLINGTON MINE VOLUNTARY CLEANUP, JAMESTOWN, COLORADO
At the former Burlington Fluorspar Mine Site near Jamestown, Colorado, Mr. Cowart was project manager for the reclamation design and construction oversight for this Voluntary Cleanup (VCUP). This 13-acre facility contained over 10,000 feet of underground tunnels, adits and shafts. Acid rock drainage was generated from approximately 35,000 cubic yards of waste rock, and acid mine drainage from underground workings was discharging to a nearby creek. The reclamation included: diversion of a 220 cfs surface water stream; consolidation of waste rock in a neutralized and capped repository; closure of subsidence pits, shafts and adits, and grading/drainage; and revegetation of the site. This project won the Colorado Mined Land Reclamation Board (MLRB) Hard Rock Reclamation Award for 2005.

ENVIRONMENTAL AUDIT OF THIOKOL OPERATIONS, UTAH, MARYLAND, AND NEW JERSEY
For a company recently acquiring the operations of Thiokol Corporation, Mr. Cowart led a team that evaluated environmental contamination issues at operational facilities in 3 states. All were propellant manufacturing plants, including the site where the Space Shuttle Boosters are fabricated. The plants in Utah and Maryland were large, totaling 500 and 150 buildings, respectively. The environmental assessment noted where existing or potential contamination of ground and surface water would lead to environmental liabilities. In addition, a Screening Level
Ecological Assessment was conducted at the Thiokol Promontory, Utah facility to address potential on- and off-site impacts.

**ASSESSMENTS, PERMITTING, AND WASTE REMOVAL, SCHERING PHARMACEUTICAL LABORATORIES, MIAMI, FLORIDA**

Mr. Cowart performed services in the following areas: a wastewater treatability study which ensured that batch wastes from the Nitro-Dur heart pacing product met pre-treatment standards for the Dade County Water and Sewer Authority; volatile organic contaminant air permits for the use of solvents in the Nitro-Dur process; the characterization and removal of RCRA wastes; and soil and groundwater impact assessment for the preparation of a property transfer.

**PERMITTING FOR MUNICIPAL COMPOSTING FACILITY, DADE COUNTY, FLORIDA.**

For Agripost, Mr. Cowart served as project manager for permitting of Florida's largest municipal solid waste composting facility, including odor control, stormwater, ground water, and product leachate.

**ASSESSMENTS OF CHROMIUM CONTAMINATION, ROYAL PALM ICE COMPANY, PENNSYLVANIA**

At this ice manufacturer, Mr. Cowart directed assessments of chromium contamination in soils and groundwater, using surface geophysical tools (electromagnetics) to correlate metals concentration and conductivity.

**UNDERGROUND STORAGE TANK ASSESSMENTS, REMEDIATIONS, INSTALLATIONS, FLORIDA**

Mr. Cowart served as project director or manager for more than 40 petroleum contamination assessments, remediations, and UST installations at service stations and maintenance facilities in South Florida. Systems that were designed included groundwater pump-and-treat, soil vapor extraction, product removal, and dig and haul.

**METHANE GAS ASSESSMENTS AND VENTING DESIGNS, MUNICIPAL AND INDUSTRIAL LANDFILLS, FLORIDA AND COLORADO.**

Mr. Cowart conducted assessments of subsurface methane gas and prepared designs for both active and passive venting at the following municipal and industrial landfills in Florida: West Dade - 580 acres; North Dade - 125 acres; North Miami Beach - 80 acres; Key Biscayne - 40 acres; Broward County - 600 acres; and Crudele Industries - 5 acres, and in Colorado: Ralston Industrial Park-3 acres; Voyager Trucking -3 acres; Aztlan Community Center-2 acres; and River Point at Sheridan-130 acres.

**REMEDIATION OF FREE PRODUCT & GROUNDWATER, FT. LUPTON, COLORADO**

Mr. Cowart served as senior design reviewer for a remedial design to remove approximately 2 feet of free product and dissolved hydrocarbons in groundwater which had been released from a natural gas gathering and compression station. The design included product recovery trenches, horizontal air sparging and vapor extraction wells. The system was installed and is in operation.

**NOISE PROJECTS**

**NOISE SURVEY AND ABATEMENT, SEWAGE TREATMENT PLANT, JACKSONVILLE, FLORIDA**

For the USEPA, Region 4, Mr. Cowart managed an Environmental Impact Statement which focused on potential noise impacts from expansion of a sewage treatment plant. It was determined that the major high decibel noise source was compressors powering the high pressure sludge treatment unit. A conceptual design was prepared which provided for a separate insulated enclosure for the compressors, in order to reduce noise levels to acceptable levels at the property boundary.
EXPERT TESTIMONY, DEPOSITION AND LITIGATION SUPPORT

EXPERT DEPOSITION FOR MANUFACTURING OPERATIONS AT A PERCHLORATE-CONTAMINATED GROUNDWATER PLUME, MORGAN HILLS, CALIFORNIA.
On behalf of the defendant, Standard Fusee, Mr. Cowart was deposed as an expert for flare manufacturing operations at a perchlorate-contaminated groundwater plume in Morgan Hills, California. Mr. Cowart was deposed March 9, 2005 re: In the United States District Court for the Northern District of California San Jose Division, Jayne Palmisano and Richard Palmisano, individuals, Plaintiff(s), vs. Olin Corporation, a corporation, Standard Fusee Corporation, doing business as Orion Safety Products, a Delaware corporation. No. C 03-01607 RMW.

EXPERT DEPOSITION AND TESTIMONY FOR VAPOR INTRUSION AT A DIESEL SPILL IN MANDAN, NORTH DAKOTA
Mr. Cowart directed sampling of groundwater, soil vapor, soil, indoor air, and outdoor air in order to assess the potential human health impacts in indoor air located over this 3 million gallon diesel spill in the City of Mandan. On behalf of selected residents, Mr. Cowart was deposed twice and testified in court as an expert concerning the potential for diesel-related contaminants in groundwater to have migrated through soil vapor into indoor air.

Mr. Cowart was deposed January 22, 2004 in North Dakota Department of Health, et. al., Plaintiffs, and Schleicher Land Co., et. al., Deb Knudsen, et. al., and City of Mandan, Intervenors, vs. The Burlington Northern and Santa Fe Railway Company, Defendant, in District Court, County of Morgan, State of North Dakota South Central Judicial District, Civil Action No. 02-C-1174.

Mr. Cowart was deposed September 14, 2004 in Schleicher Land Co., et. al., Deb Knudsen, et. al., and City of Mandan, Plaintiffs, vs. The Burlington Northern and Santa Fe Railway Company, Defendant, in District Court, County of Grand Forks, State of North Dakota Northeast Central Judicial District, Civil Action No. 04-C-157.

Mr. Cowart testified September 23-24, 2004 in Schleicher Land Co., et. al., Deb Knudsen, et. al., and City of Mandan, Plaintiffs, vs. The Burlington Northern and Santa Fe Railway Company, Defendant, in District Court, County of Grand Forks, State of North Dakota Northeast Central Judicial District.

EXPERT DEPOSITION FOR VAPOR INTRUSION AT A PCE-CONTAMINATED GROUNDWATER PLUME, SECURITY, COLORADO.
On behalf of the plaintiffs, a group of residents living over a perchloroethylene (PCE) groundwater plume, Mr. Cowart has been deposed three times concerning the potential of PCE in groundwater to migrate through soil vapor and into indoor air.

Mr. Cowart was deposed on February 26, 2003 in The United States District Court for the District of Colorado, Civil Action No. 02-RB-1188(OES), Susan Stalcup, Craig Lewis And Sharon Lewis, Plaintiffs, vs. Schlage Lock Company, Ingersoll-Rand Company And Eagle-Picher Industries, Inc. Defendant.

Mr. Cowart was deposed January 7, 2004 in The United States District Court for the District of Colorado, Jim Stulb, Trustee, Fountain Valley Environmental Remediation Trust, Plaintiff, vs. Schlage Lock Company, Ingersoll-Rand Company, Eagle Picher Incorporated And Eagle-Picher Industries LLC, Defendants, Civil Action No. 03-RB-0002.

Mr. Cowart was deposed March 27, 2006 in The United States District Court for the District of Colorado, Susan Stalcup, Craig Lewis and Sharon Lewis, Defendants, vs. Schlage Lock Company and Ingersoll-Rand Company, Defendants, Civil Action No. 1:02-CV-01188-REB-MEH. A Judgment in this case was issued January 8, 2007.

EXPERT TESTIMONY, COAL BED METHANE IMPACTS, LA PLATA COUNTY, COLORADO
Mr. Cowart testified on behalf of La Plata County, Colorado, before the Oil and Gas Conservation Commission of the State of Colorado, regarding effects of methane seepage on the subsurface, groundwater and land surface, in Cause No. 112, Docket No. 11-1, November, 1997.
EXPERT TESTIMONY, MINING RECLAMATION
In Bettale vs. Hartley, Mr. Cowart testified for the plaintiff in District Court, Clear Creek County, Colorado, concerning the time and cost for cleanup of acid mine drainage at the Lincoln Lode and Donna Julia Gold Mining Claims.

EXPERT DEPOSITION AND TESTIMONY REGARDING PETROLEUM CONTAMINATION AND WASTEWATER TREATMENT.
In Environmental Recycling Systems vs. Nesbitt, Mr. Cowart was deposed and provided expert testimony for the plaintiff concerning petroleum contamination of soils and ground water, and wastewater treatment via ozonation/ultraviolet/photolysis systems, in El Paso County Court, Colorado.

EXPERT DEPOSITION, PESTICIDE FORMULATION, PACKAGING, AND WASTE MANAGEMENT PRACTICES
At the Thompson Hayward Agriculture and Nutrition CERCLA Facility in Fresno County, California for litigation filed in Wilmington, Delaware in North American Phillips Corp. vs. Aetna, Mr. Cowart was deposed for eight days as an expert for the plaintiff in pesticide formulation and packaging industry operations and waste management practices. The case was settled out of court.

EXPERT DEPOSITION AND TESTIMONY, ENVIRONMENTAL PRACTICES FOR ELECTROPLATING OPERATIONS
In City Bumper vs. Goettinger, Mr. Cowart was deposed and provided expert testimony for the defense in the area of assessment, treatment, and remediation of RCRA hazardous chromium wastes at an electroplating facility in Broward County, Florida.

EXPERT DEPOSITION AND TESTIMONY REGARDING ASSESSMENT AND REMEDIATION OF PETROLEUM CONTAMINATION FROM USTS
In Florida National Properties vs. Mobil Oil Corporation, Mr. Cowart was deposed and provided expert testimony in Broward County Court for the plaintiff in the area of petroleum contamination assessment and remediation from an UST facility in Coral Springs, Florida, which was settled out of court.

EXPERT DEPOSITION AND TESTIMONY FOR ENVIRONMENTAL MANAGEMENT PRACTICES AT AUTO SALVAGE FACILITY
In State of Florida Department of Environmental Regulation vs. Alex Rodriguez and Safe Harbor Enterprises, he was deposed and provided expert testimony for the defense in the areas of solid waste, petroleum contamination of soil and ground water, asbestos contamination, and assessment and remediation, resulting in allowance of continued operation at an auto salvage facility in Key West, Florida.

EXPERT DEPOSITION AND TESTIMONY REGARDING ASSESSMENT AND REMEDIATION COSTS
In Safe Harbor Enterprises vs. U.S. Fidelity and Guarantee, Mr. Cowart was deposed and testified as an expert for the plaintiff, related to assessment and remediation costs, in Monroe County, Florida.

EXPERT DEPOSITION, MUNICIPAL SOLID WASTE
In Adler vs. L.A. Davis Stock Farms, Mr. Cowart was deposed as an expert witness for the defense in the area of municipal solid waste, which was settled out of court, in Miami, Florida.

LITIGATION SUPPORT FOR MUNICIPAL WASTE COMPOSTING
In City of Miami Beach and Fisher Island vs. Florida Department of Environmental Regulation, Mr. Cowart provided litigation support for the plaintiff in the area of composting of municipal solid waste at Virginia Key, Florida.

LITIGATION SUPPORT FOR AIRLINE OPERATIONS ENVIRONMENTAL PRACTICES
In Metropolitan Dade County vs. Eastern Air Lines and Pan American Airlines, Mr. Cowart provided litigation support for the plaintiffs in the areas of hazardous waste, industrial wastewater, petroleum contamination, soil/ground-water contamination, and assessment and remediation at Miami International Airport, resulting in an award of more than $50 million in damages to Dade County. An expedited investigation of 150 buildings was conducted, and conceptual designs were prepared for dig and haul, pump-and-treat, product recovery, and vapor extraction systems.
LITIGATION SUPPORT TO US EPA FOR POTW AND NPDES EFFLUENT LIMITATION GUIDELINES
In BASF Wyandotte, et. al. vs. Costle, Mr. Cowart provided litigation support to the U.S. Environmental Protection Agency (EPA) in the area of industrial wastewater treatment for the pesticide manufacturing and formulation industry, resulting in approval of POTW and NPDES Effluent Limitation Guidelines by the First Circuit Court of Appeals, Boston, Massachusetts.

LITIGATION SUPPORT FOR ALLEGED DAMAGES FROM PESTICIDE CONTAMINATION
In Kawamata Farms, Inc. and Stanley T. Tomono, et. al., vs. E.I. Du Pont De Nemours and Company, Inc., Mr. Cowart provided litigation support for the plaintiffs concerning remediation of the impacts in Hawaii on ornamental flowers and other crops due to alleged contamination from manufacturing and formulation of the pesticide Benlate. The case was settled out of court.

LITIGATION SUPPORT, RCRA LEAD SUBACETATE GENERATION AND DISPOSAL
In The Department of Justice vs. United States Sugar Corporation, Mr. Cowart provided litigation support to U.S. Sugar in the area of generation and disposal of lead subacetate hazardous wastes in defense of a $3.75 million penalty for violations of RCRA.

LITIGATION SUPPORT, FORMER PESTICIDE STORAGE FACILITY
Mr. Cowart provided litigation support to the lessee of a former pesticide storage facility in Greeley, Colorado. He provided affidavits in support of a lawsuit against a previous owner of the property, concerning pesticide residuals in the building and surrounding land.
PUBLICATIONS, PRESENTATIONS AND AWARDS


Cowart, James. 2005 Hard Rock Mine Reclamation Award, Burlington Mine, Jamestown, Colorado, presented by Colorado Department of Minerals and Geology and Mined Land Reclamation Board to Honeywell International and Walsh Environmental, James Cowart, Project Manager.


PROFESSIONAL AND CIVIC ASSOCIATIONS

- National Society of Professional Engineers
- Water Environment Federation
- National Groundwater Association
- Boulder Creek Watershed Initiative, Board of Directors
- Lefthand Watershed Oversight Group, Technical Advisor
- Preserve Unique Magnolia Road Association, Board of Managers
- Nederland Parks, Recreation, Trails and Open Space Advisory Board
- Nederland Historical Mining Association
- Nederland Caribou Wind Hockey Coach
Peer Reviewer Conflict of Interest Certification

Peer Review: “Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds”

A conflict of interest or lack of impartiality exists when the proposed peer reviewer personally (or the peer reviewer’s immediate family), or his or her employer, has financial interests that may be affected by the results of the peer review; or may provide an unfair competitive advantage to the peer reviewer (or employer); or if the peer reviewer’s objectivity in performing the peer review may be impaired due to other factors. When the Peer Reviewer knows that a reasonable person with knowledge of the facts may question the peer reviewer’s impartiality or financial involvement, an apparent lack of impartiality or conflict of interest exists.

The following questions, if answered affirmatively, represent potential or apparent lack of impartiality (any affirmative answers should be explained on the back of this form or in an attachment):

- Did you contribute to the development of the document under peer review, or were you consulted during its development, or did you offer comments or suggestions to any drafts or versions of the document during its development? X No  ☐ Yes
- Do you know of any reason that you might be unable to provide impartial advice on the matter under consideration in this peer review, or any reason that your impartiality in the matter might be questioned? X No  ☐ Yes
- Have you had any previous involvement with the review document(s) under consideration? X No  ☐ Yes
- Have you served on previous advisory panels, committees, or subcommittees that have addressed the topic under consideration? X No  ☐ Yes
- Have you made any public statements (written or oral) on the issue? X No  ☐ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? X No  ☐ Yes
- Do you, your family, or your employer have any financial interest(s) in the matter or topic under peer review, or could someone with access to relevant facts reasonably conclude that you (or your family or employer) stand to benefit from a particular outcome of this peer review? X No  ☐ Yes

With regard to real or apparent conflicts of interest or questions of impartiality, the following provisions shall apply for the duration of this peer review:

(a) Peer Reviewer warrants, to the best of his/her knowledge and belief, that there are no relevant facts or circumstances that could give rise to an actual, apparent, or potential organizational or personal conflict of interest, or that Peer Reviewer has disclosed all such relevant information to EMS or to EPA.
(b) Peer Reviewer agrees that if an actual, apparent, or potential personal or organizational conflict of interest is identified during performance of this peer review, he/she immediately will make a full disclosure in writing to EMS. This disclosure shall include a description of actions that Peer Reviewer (or his/her employer) has taken or proposes to take after consultation with EMS to avoid, mitigate, or neutralize the actual, apparent, or potential organizational conflict of interest. Peer Reviewer shall continue performance until notified by EMS of any contrary action to be taken.

☐ Check here if any explanation is attached

Signature            Date

Printed Name

Affiliation/Organization

Digitally signed by James B. Cowart
DN: cn=James B. Cowart,
o=EnviroGroup Limited, ou,
email=jcowart@envirogroup.com,
c=US
Date: 2012.04.18 14:01:42 -06'00'
AREAS OF EXPERTISE

Areas of expertise include but are not limited to:

- **Vapor intrusion investigation and mitigation**, including screening methods, soil vapor migration pathway evaluation, Johnson & Ettinger modeling, indoor air testing, background source evaluation, building mitigation, indoor air monitoring, and standard of practice.

- **Groundwater contamination investigation and remediation**, including investigation of the nature and extent of contamination, contaminant fate and transport evaluation, source identification and allocation, evaluation of remedial alternatives, remediation and costs.

- **Soil contamination investigation and remediation**, including investigation of the nature and extent of contamination, vertical transport, forensic evaluation of contaminant sources, background sources of metals, evaluation of remedial alternatives, remediation and costs.

VAPOR INTRUSION QUALIFICATIONS

Mr. Folkes is an expert in vapor intrusion investigation and mitigation, a recent focus of the US Environmental Protection Agency (EPA) and many state agencies across the US. His qualifications and experience include but are not limited to:

- Project manager of one of the largest vapor intrusion sites in the US, including investigation of over 700 buildings, and mitigation of over 375 buildings.

- Consultant on over 90 vapor intrusion projects across the US and overseas.

- Testifying and consulting expert for several vapor intrusion cases, including class actions lawsuits;

- Reviewer of vapor intrusion proposals and projects for the Department of Defense SERDP and ESCTP programs, under contract to HydroGeoLogic.

- ASTM⁠¹ committee co-chair, development of ASTM E2600 Standard Practice for Assessment of Vapor Intrusion into Structures on Property Involved in Real Estate Transactions;

- Member, Interstate Technology and Regulatory Council (ITRC)² vapor intrusion team, co-author of the 2007 vapor intrusion guidance document and classroom instructor;

- Member, ITRC Petroleum Vapor Intrusion Team, assisting with development of PVI guidance and training program.

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¹ ASTM International, formerly known as the American Society of Testing and Materials, is one of the largest voluntary standards development organizations in the world and a source for technical standards for materials, products, systems, and services.

² The Interstate Technology and Regulatory Council is an association of 43 states, the District of Columbia, multiple federal partners including EPA, industry participants, and other stakeholders, developing guidance documents and training courses to meet the needs of both regulators and environmental consultants.
Co-recipient, award for outstanding contributions to the ITRC vapor intrusion team, 2005;


Invited to help educate EPA and state regulators on vapor intrusion issues at the 2000 and 2002 National RCRA Meetings;

Invited by EPA to help train EPA and state regulators at the EPA Subsurface Vapor Intrusion Guidance training seminars in San Francisco (2002), Dallas (2003), and Atlanta (2003);

Invited by numerous state agencies to speak at vapor intrusion training seminars, including New Jersey DEP, Northeast Waste Management Officials’ Association, Colorado DPHE, Wyoming DEQ, Minnesota PCA, North Carolina DNER, Illinois EPA;

Technical advisor to the Colorado DPHE and Wyoming DEP on vapor intrusion matters at several major environmental sites; and

Author of numerous papers and presentations on vapor intrusion issues, including screening and evaluation methods, background sources of indoor air compounds, and mitigation.

EDUCATION

B.A.Sc. Geological Engineering, University of Toronto
Toronto, Ontario, Canada, 1977

M.A.Sc. Civil (Geotechnical) Engineering, University of Toronto
Toronto, Ontario, Canada, 1980

In addition to his formal education, Mr. Folkes has attended and participated in numerous conferences, seminars, training programs, and workshops over the past 30 years.

REGISTRATIONS

1985 Professional Engineer, Colorado, No. 23229
1980 Professional Engineer, Alberta (not current)

ASSOCIATION MEMBERSHIPS

- ASTM International
- National Ground Water Association
- American Chemical Society
- Colorado Hazardous Waste Management Society

TECHNICAL WORK GROUP MEMBERSHIPS

- ASTM Vapor Intrusion Task Group, 2006 – present
- ITRC Vapor Intrusion Team member and instructor, 2004 - present
- EPA ad-hoc expert work group on Vapor Intrusion Guidance, 2000 - present
- Wyoming DEQ Voluntary Remediation Program (VRP) Remedy Work Group 2003 - 2004
- Denver Dept. of Environmental Health Residential Arsenic Technical Advisory Group c.2001
ADVISORY BOARD MEMBERSHIPS

- Trust for Land Restoration Advisory Board

AWARDS, INVITATIONS AND APPOINTMENTS

2008-2011 Invited instructor, ITRC vapor intrusion classroom training program, being held at various locations across the US (to date, Portland, OR; Oklahoma City, OK; Sacramento CA; Long Beach CA; upcoming July 2010, Boston MA and Atlanta GA).


2010 Invited speaker, on new developments in vapor intrusion evaluation and mitigation, Illinois EPA, including review of draft guidance, February 24, 2010.

2009 Invited speaker, American Industrial Hygiene Conference and Exhibition, on new developments in vapor intrusion mitigation, Toronto, Ontario, June 1, 2009.


2008 CLE Faculty member, Colorado Bar Association, on the new ASTM vapor intrusion standard for real estate transactions (E2600), Denver, CO, October 2008.


2008 Invited speaker, American Industrial Hygiene Conference and Expo, on vapor intrusion mitigation, Minneapolis, MN, June 2008.


2008 Invited reviewer, Minnesota *Risk Based Guidance for the Vapor Intrusion Pathway*, February 2008 draft, Minnesota Pollution Control Agency Remediation Division.

2008 Invited speaker, Environmental Bankers Association meeting, on Tier 3 and 4 of the *ASTM Standard Practice for Assessment of Vapor Intrusion into Structures on Property Involved in Real Estate Transactions*, San Antonio, TX, January 2008.


2007 Invited speaker, ACI 2nd Annual Conference on Chemical Products Liability Litigation, on evaluation of vapor intrusion claims, Chicago, IL, November 2007.


2006 Invited faculty member, Mealey’s Teleconference on Vapor Intrusion, August 15, 2006.

2006 Invited speaker, Minnesota Pollution Control Agency vapor intrusion training seminar, St. Paul MN, June 2006


2006 Invited speaker, Wyoming DEQ vapor intrusion training seminar, Cheyenne, WY, March 2006

2006 Invited speaker, Colorado DPHE vapor intrusion training seminar, Denver, CO, March 2006


2005 ITRC award for outstanding service on the Vapor Intrusion Team

2004 invited speaker, vapor intrusion training session, Colorado Department of Public Health and Environment, Rocky Mountain Arsenal team, February 2004

2003 invited speaker, ABA CLE Seminar on Environmental Litigation, Snowmass Village, Colorado.

2003 invited speaker, CDPHE panel on arsenic, AEHS Conference on Soil, Sediment, and water, University of Amherst, Amherst, MA, October 2003.

2002 invited speaker, EPA National RCRA meeting, special session on Vapor Intrusion, Washington D.C.

2002 invited speaker, Colorado Hazardous Waste Management Society, Vapor Intrusion and Indoor Air Quality Workshop, Denver, CO


2000 invited speaker, Impacts of Groundwater Solvent Contamination on Indoor Air Quality, Colorado Hazardous Waste Management Society, Denver, CO

2000 guest lecturer, groundwater and soil contamination, University of Colorado at Denver.

2000 invited speaker, EPA National RCRA national forum on Environmental Indicators, special session on Vapor Intrusion, Washington D.C.


1996 invited speaker, Round Table Forum on arsenic migration and attenuation behavior, for U.S. EPA Region VIII, State of Utah, ASARCO Incorporated, Salt Lake City, Utah

1991 invited speaker, Rocky Mountain Mineral Law Foundation Institute on Ground Water Contamination, Salt Lake City, Utah

1991 invited speaker, National Western Mining Conference, on Technical Strategies for Reducing CERCLA Risks, Denver, Colorado


1990 instructor, environmental assessments for property transactions, Red Rocks Community College, Denver, Colorado

1988 invited speaker, Rocky Mountain Mineral Law Foundation Institute on Environmental Considerations in Natural Resource and Real Property Transactions, Denver, Colorado

1986 invited speaker, University of Colorado at Boulder, Department of Civil Engineering, on "Remedial Engineering"


1985 asked to provide expert testimony for the Colorado Association of Commerce and Industry on proposed groundwater regulations before the Colorado Water Quality Control Commission

1985 member, Colorado Department of Health ad hoc technical committee on proposed groundwater regulations

1983 invited speaker, Western Canada Water and Sewerage Conference (co-sponsored by the American Water Well Association), Edmonton, Alberta, on "Lagoon Liner Construction Considerations"

1982 member, National Research Council of Canada Task Force on the Geotechnical Aspects of Waste Disposal

1981 selected by the National Research Council of Canada to prepare 5th Canadian Geotechnical Colloquium on "Control of Contaminant Migration by the Use of Liners", presented at the 34th Canadian Geotechnical Conference, Frederickton, New Brunswick

1979 selected to co-author State-of-the-Art report on "Mechanical Properties of Soft Soils" for the 32nd Canadian Geotechnical Conference, Quebec City

1977 W.S.Wilson Medal, first place standing in graduating class

EMPLOYMENT HISTORY
2001 - present  Principal and President, EnviroGroup Limited
Denver, Colorado

1991 - 2001  Principal and Vice-President, EnviroGroup Limited
Denver, Colorado

1986 - 1991  Manager, Remedial Engineering Division, TRC Environmental Consultants, Inc.
Denver, Colorado

1985 - 1986  Senior Geotechnical Engineer, Hydro-Search, Inc.
Denver, Colorado

Denver, Colorado

1980 - 1983  Senior Geotechnical Engineer, Komex Consultants Ltd.
Calgary, Alberta

1977 - 1980  Geotechnical Engineer, Golder Associates Ltd.
Toronto, Ontario, Canada

PROJECT EXPERIENCE

Representative projects are summarized below, organized by the following categories: vapor intrusion, groundwater investigation and remediation, impoundment and liner design, and mining and metals.

Vapor Intrusion Projects

Project Manager, investigation and remediation of chlorinated solvent vapors in houses and other buildings at the Redfield Site, Denver, Colorado, resulting from groundwater contamination. Work includes groundwater contaminant plume delineation, soil and soil vapor testing, indoor air testing of over 700 buildings, design and installation of sub-slab depressurization (ventilation) systems in over 350 homes and apartments, monitoring of ventilation system performance, modeling of vapor migration into construction trenches, design and installation of a ventilation system for a manufacturing building, design and installation of a groundwater containment system, DNAPL source characterization, and design and installation of an in-situ bioremediation system. Included deposition, hearing, and courtroom testimony in class action and cost recovery litigation.

Project Manager, review of mitigation conceptual designs and evaluation for a proposed new development in Italy over highly contaminated soils, including the use of aerated floor systems and liners, and use of Johnson and Ettinger model to evaluate the potential for passive venting to achieve mitigation goals. Work conducted through prime consultant on project.

Project Manager, multi-media investigations of a light industrial facility in Denver, Colorado, including groundwater, soil vapor, sub-slab vapor, and indoor air investigations. Line of evidence evaluations determined that the source of elevated TCE concentrations in indoor air was an operating unit inside the building and not vapor intrusion. Forensic evaluation of compound
ratios and other lines of evidence indicated that fortuitous biodegradation of solvents due to co-
mingling with a petroleum plume had controlled off-site migration.

Project Director, vapor intrusion investigations in a neighborhood downgradient of a former chemical facility in Mount Holly, New Jersey, including soil vapor and indoor air testing. The results of tests and lines of evidence evaluation indicated that indoor air concentrations due to vapor intrusion, if any, were below action levels.

Project Director, vapor intrusion investigations in a neighborhood downgradient of the North Penn 12 Superfund site Pennsylvania, including development of a vapor intrusion site conceptual model and vapor intrusion investigation work plan, which was approved by EPA Region 3. Efforts are currently underway to gain access for indoor testing in a number of residential and commercial buildings.

Project Manager, investigation and evaluation of vapor intrusion potential in an active commercial building, East Rutherford, New Jersey, where chlorinated solvents are present in shallow groundwater (within 2 feet of the building slab) adjacent to and under the building. The evaluation was conducted in a phased manner to limit any unnecessary indoor testing, by comparing groundwater and then sub-slab soil gas data according to NJDEP screening levels. Indoor air testing was ultimately required because concentrations exceeded screening levels, but was limited to compounds not being used by the manufacturing operation, as agreed by DEP. A line of evidence evaluation demonstrated that elevated indoor air concentrations of chloroform and PCE were due to municipal water line leaks and ambient sources, respectively, leading to a no further action recommendation.

Project Director, oversight of vapor intrusion mitigation of the east wing of the Inman Grove Shopping Center, Edison, New Jersey, to mitigate vapors entering the building due to historic releases of PCE from a dry cleaner in the strip mall. We performed diagnostic tests to design a sub-slab depressurization system, including determining location and number of suction points and size of fans.

Reviewer of vapor intrusion research proposals and progress reports for the Department of Defense SERDP and ESTCP programs, as subcontractor to HydroGeoLogic. Work has included review of proposals and reports related to real time measurement of VOCs in indoor at part per billion levels; development of procedures to screen buildings for vapor intrusion under with low permeability, high moisture content soils; and evaluation of the vapor intrusion pathway at a dedicated research home.

Project Manager, evaluation of vapor intrusion potential and mitigation alternatives at the sites of former manufacturing facilities in Sao Paulo and Rio de Janeiro, Brazil. This included site visits and meetings with local environmental agencies, who agreed to a phased approach and lines of evidence evaluation process consistent with the approaches advocated by ITRC 2007 and EPA. Ongoing work includes review of groundwater and soil vapor data and recommendations for site specific screening levels.

Project Director, evaluation of vapor intrusion at a former manufacturing building in Asbury Park, New Jersey, including indoor air and sub-slab testing, and a line of evidence evaluation consistent with NJDEP guidance. Indoor air benzene concentrations in all samples were below the NJDEP Screening Value and within the range of typical indoor air background levels for
commercial buildings. In addition, first floor concentrations were typically higher than basement concentrations, opposite to the expected behavior for vapor intrusion. Further, indoor air concentrations of benzene were higher than predicted based on benzene to xylene ratios in the groundwater. Therefore, no further action was recommended for vapor intrusion at this facility.

Project Director, evaluation of the nature and extent of PCE orphan plumes in Casper and Cheyenne, Wyoming, for the Wyoming Department of Environmental Quality, including soil vapor testing using mobile lab facilities to evaluate the extent of impacts, indoor air and sub-slab testing in homes above the DEQ soil vapor action level (and adjacent buffer zone homes); and mitigation of residential and commercial structures.

Project Manager, evaluation of vapor intrusion potential based on sub-slab vapor and indoor air tests conducted by prime consultant (as advised by EnviroGroup) in Sanford, North Carolina, including line of evidence evaluation of the likely sources of detected VOCs, and development of mitigation alternatives.

Project Manager, vapor intrusion investigation and mitigation services at voluntary cleanup site in Long Island City, New York, including soil vapor, indoor air, and sub-slab vapor testing; evaluation of vapor intrusion impacts at a YMCA and other commercial buildings; technical support to community relations team; and design of vapor intrusion mitigation systems. EnviroGroup is providing vapor intrusion support to the prime consultant on this project.

Project Manager, vapor intrusion investigation and mitigation services for a major industrial complex in western New York, including soil vapor investigations in residential and commercial areas around the complex (including use of mobile laboratory for real time decision making), indoor air and sub-slab vapor testing in residences, and evaluation of potential vapor intrusion impacts to on-site commercial buildings based on groundwater data. The results of testing in three off-site residential areas led to no further action determinations by the state agencies.

Project Manager, vapor intrusion investigations and mitigation designs for a commercial building in Puerto Rico, including indoor air and sub-slab vapor testing, evaluation of HVAC system impacts on air flows and differential pressures, and design of passive mitigation system with option of converting to an active system if necessary.

Expert Witness, for defendants at site in Lake Charles, Louisiana, where a PCE leak from a rail car in 1983 is alleged to be causing ongoing ambient air and vapor intrusion impacts to residents in the surrounding area. Work has included evaluation of historic data and reports, calculation of potential ambient air levels due to diffusion through the vadose zone, preparation of an expert report, and a deposition.

Project Manager, oversight of soil vapor investigations and evaluation of vapor intrusion mitigation options for various buildings in Aarschott, Belgium, including review of previous investigation reports, development of a conceptual site model for the vapor intrusion pathway, and preparation of a mitigation decision tool. EnviroGroup recently provided on-site supervision of a soil vapor testing pilot program, and is helping develop scopes of work for soil vapor testing, indoor air testing, and potential mitigation of residential homes.

Project Manager, vapor intrusion evaluation at a Legacy site near Albany, New York, for an
industrial client, including evaluation of groundwater data and soil vapor investigations.

Project Director, vapor intrusion investigation at a former manufacturing facility in Cheektowaga, New York. Work includes evaluation of historic groundwater and geologic data for development of a vapor intrusion work plan, including subsurface investigations and indoor air testing in residences. Expert review of soil vapor testing plan, for industrial client with a facility in Victoria, Australia. Included review of existing data, proposed testing procedures, and recommendations to improve the testing program.

Expert Witness, for the owner of a commercial office building in Nassau County, New York. Work included review or previous indoor air and sub-slab testing procedures and results; groundwater, soil vapor and sub slab vapor investigations; and evaluation and expert report on the source and cause of the elevated soil vapors.

Project Manager, indoor air testing in two fast-food restaurants located at a former gasoline station site in Denver, Colorado, with free product observed in nearby wells. A comparison of results with ambient air, typical background levels, and state indoor air target levels indicated no further action was necessary.

Project Director, vapor intrusion investigations at an industrial facility in Chicago, Illinois, including indoor air testing and evaluation of potential background sources of compounds detected in the indoor air.

Project Manager, vapor intrusion investigations at a 225,000 square foot commercial office building in Memphis, Tennessee, including sub-slab vapor, indoor air, and ambient air testing for building owner. Work included evaluation of the potential sources of compounds detected in the indoor air, and comparison to appropriate standards and guidelines.

Project Manager, vapor intrusion evaluations and mitigation in residential areas surrounding a manufacturing facility in southern California, including evaluation of contributions of ambient air and background (indoor) sources to VOCs detected in school buildings and residences, and mitigation of a residence. EnviroGroup is providing vapor intrusion support services to the prime consultant on this project.

Responsible Principal, evaluation of the potential for vapor intrusion at a Brownfields site in Indiana, including comparison of groundwater data to IDEM screening levels, recommendations for soil vapor testing, and recommendations for development strategies to minimize the potential for vapor intrusion impacts.

Project Manager, vapor intrusion investigations and evaluation for a commercial office building in Long Island, New York. Work included evaluation of indoor air and sub-slab vapor data collected by others, identification of background sources of volatile compounds found in the indoor air, and soil vapor and groundwater investigations.

Project Manager, evaluation of the performance of existing vapor intrusion mitigation systems at a large warehouse complex near Seneca Falls, New York, including evaluation of indoor air and sub-slab vapor data, and recommendations for modifications to existing mitigation systems. EnviroGroup was providing vapor intrusion support services to the prime consultant on this
Expert witness for defendant, class action lawsuit regarding potential for vapor intrusion due to PCE in groundwater in residential areas downdrift of the Schlage Lock facility near Colorado Springs, Colorado. Included expert report on application of EPA screening levels and guidance. Follow on work included project director of indoor air testing and mitigation program offered to class as part of settlement.

Expert Witness, for defendant, class action lawsuit related to alleged vapor intrusion impacts resulting from chlorinated solvent plume in groundwater, Hamilton Sundstrand Site, Denver, Colorado. Included deposition and class certification hearing testimony.

Project Director, indoor air testing program in the vicinity of a PCE plume due to historic releases from a former dry cleaning facility in Denver, Colorado.

Project Manager, evaluation of the potential for vapor intrusion impacts to on-site and off-site structures at a manufacturing facility in Ohio under a voluntary cleanup program, including development of site-specific screening levels; evaluation of soil vapor test data; and Johnson & Ettinger modeling. EnviroGroup is providing vapor intrusion support to the prime consultant on this project.

Project Manager, evaluation of the potential for vapor intrusion into homes on at a Brownfield site in Georgia, due to historic releases of PCE from the base laundry. Included evaluation of existing groundwater data and Johnson & Ettinger modeling.

Expert Witness for industrial company in Dallas, Texas, evaluation of potential for vapor intrusion in nearby residential community due to historic releases of solvents. Included evaluation of groundwater, soil vapor, and indoor air data, and the potential for vapor intrusion and/or background sources to have contributed to detected levels.

Project Manager, review of vapor intrusion investigations and mitigations for a school in Littleton, Colorado overlying contamination soil and groundwater due to releases from an adjacent service station. Included review of indoor air, sub-slab vapor, and soil vapor data; evaluation of sources of VOCs found in indoor air; evaluation of sub-slab depressurization system performance; and collection of confirmatory indoor air samples.

Expert witness for defendant, multi-party lawsuit related to alleged vapor intrusion impacts in several residential homes resulting from TCE plume in groundwater downdrift of a manufacturing facility in Indiana. Potential issues include the lateral extent of vapors beyond groundwater plume boundaries and potential for indoor sources.

Expert witness for defendants, potential class action lawsuit in Chicago, Illinois, regarding the potential for vapor intrusion due to historic releases of solvents from former industrial facilities. Included review of groundwater data and Johnson & Ettinger modeling.

Technical expert, assisted other EnviroGroup staff with the design and evaluation of an indoor air testing program in residential areas near the former Gates Rubber facility in Denver, Colorado. Met with EPA, Colorado DPHE, and City of Denver officials to discuss and reach consensus on
the study findings, and presented the results of the study at a public meeting.

Project Manager, developing vapor intrusion guidance for the Wyoming DEQ voluntary remediation program, including standard procedures for conducting Johnson & Ettinger modeling.

Project Manager, review of soil vapor testing work plans and results at a former Texaco oil refinery property in Casper, Wyoming, on behalf of the Wyoming DEQ. Made recommendations for state-of-the-art soil vapor sampling techniques. Reviewed results for evidence of biodegradation of petroleum constituents in the vadose zone.

Project Director, indoor air testing program at industrial facility in Kansas, evaluating the potential for solvents in groundwater to have impacted indoor air.

Expert Witness, for defendant, potential class action lawsuit related to alleged vapor intrusion impacts resulting from chlorinated solvent plume in groundwater at an industrial facility in New York.

Expert Witness for Occidental Chemical and other defendants in a multi-party lawsuit filed by the City of Modesto, California against the manufacturers and distributors of PCE, dry cleaning equipment manufacturers, and numerous dry cleaners in the City of Modesto. Work has included evaluation of potential vapor intrusion impacts in buildings and modeling of vapor migration into construction trenches. Included deposition testimony.

Project Manager, vapor intrusion (Johnson-Ettinger) modeling for prospective new developments and evaluation of vapor intrusion modeling conducted by the USEPA at the Rocky Mountain Arsenal site, for the Colorado Department of Public Health and Environment.

Project Manager, evaluation of vapor intrusion potential at large industrial complex in New York, including on-site and off-site areas of concern and industrial and residential land use, as required to complete Environmental Indicator assessments at the site. Included review of approximately 400,000 groundwater records, development and application of screening criteria, development of investigation work plans.

Project Manager, evaluation of vapor intrusion issues at former industrial site near Paris, France, including evaluating the consistency of groundwater, soil vapor, and indoor air, and the potential merits of vapor intrusion (Johnson-Ettinger) modeling.

Consulting Expert, evaluation of potential vapor intrusion issues at large industrial site in Minnesota, including evaluation of vadose zone soils, floating product, and dissolved groundwater plumes containing combinations of petroleum hydrocarbons and chlorinated solvents in a complex hydrogeologic setting.

Project Manager, assisting Wyoming Department of Environmental Quality (WDEQ) with oversight of investigations and cleanup of a former oil refinery in Casper, Wyoming. Work included review of RFI, RA, CMS and design documents, participation in collaborative work groups on various technical issues, presentations to the public. Issues include NAPL recovery; air sparging, in situ biodegradation, MNA, and phytoremediation of groundwater; vapor intrusion
evaluation and mitigation; sediment and soil cleanup. Work includes evaluation of vapor intrusion screening levels and mitigation designs for new commercial buildings on site.

Expert Witness for Public Service Company of Colorado, including review of historic soil vapor monitoring data and the potential for methane to have migrated from a coal mine in **Leyden, Colorado** used for storage of methane. Included testimony before the Colorado Oil and Gas Conservation Commission and development of soil vapor monitoring plan.

Consulting Expert, for plaintiffs in class-action lawsuit in **Indiana**, related to the potential for vapor intrusion issues due to petroleum releases to groundwater. Includes evaluation of the use of soil vapor data and Johnson-Ettinger model.

Project Manager, evaluation of designs to mitigate intrusion of PCE vapors into former dry cleaner building in **Boulder, Colorado**.

Project Manager, indoor air testing of chlorinated solvents to evaluate vapor intrusion potential in commercial building, **Dallas, Texas**. Designated as potential expert witness. Case settled.

Project Manager, training Hill Air Force, Utah base personnel and contractors on vapor intrusion testing and mitigation procedures.

Expert Witness for defendant in two cases in **Colorado**, evaluation of the potential for methane intrusion into commercial buildings, including potential costs of mitigation and monitoring. Cases settled.

Project Manager, evaluation of seasonal effects on vapor intrusion for confidential client in **Ontario, Canada**.

**Groundwater Investigation and Remediation Projects**

Project Manager, investigation and remediation of chlorinated solvent vapors in houses and other buildings in Denver, Colorado, resulting from groundwater contamination. Work includes groundwater contaminant plume delineation, soil and soil vapor testing, indoor air testing of over 700 homes, design and installation of sub-slab depressurization (ventilation) systems in approximately 370 homes, monitoring of ventilation system performance, design and installation of a ventilation system for a manufacturing building, evaluation of on-site and off-site groundwater and soil remediation alternatives, design and installation of a groundwater containment system, DNAPL source characterization, and design and installation of an in-situ bioremediation system. Included evaluation of contributions of other sources, including PCE from a neighboring dry cleaner. Has included expert and consulting witness roles in class action and cost recovery lawsuits.

Project Manager of an RI/FS at a metals refinery and former smelter site in Denver. Over the past 20 years, responsibilities have included direction of multi-media remedial investigations; multi-media feasibility studies and alternative evaluations; and selected remedy designs for groundwater, soil, surface water, sediment, and air emission issues. Supervised preparation of construction plans and specifications for groundwater interception drain, and implemented several interim remedial actions including pipe repairs, groundwater interception, and temporary
capping of tailings material.

Project Manager, assisting Wyoming Department of Environmental Quality (WDEQ) with oversight of investigations and cleanup of former oil refineries and/or operating gas plants in Casper, Glenrock, Sinclair, Evansville, Patrick Draw, and Greybull, Wyoming. Work includes review of RFI, RA, CMS and design documents, participation in collaborative work groups on various technical issues, presentations to the public. Issues include NAPL recovery; groundwater containment; groundwater flushing and pump and treat remedies; air sparging, in situ biodegradation, MNA, and phytoremediation of groundwater; vapor intrusion evaluation and mitigation; sediment and soil cleanup.

Project Manager for evaluation of chlorinated solvent contamination of groundwater near grain elevators in Kansas, including identification of sources, fate and transport issues, and evaluation of potential off-site impacts.

Project Manager for evaluation of soil, groundwater, and vapor impacts at a former landfill in Wamsutter, Wyoming, under the Targeted Brownfields Assessment program. Work includes groundwater, soil, and vapor investigations, development of a hydrogeological conceptual site model, evaluation of the extent of impacts, and development and evaluation of remedial alternatives.

Project Manager for investigations of soil and groundwater impacts at a closed grain silo in northern Colorado, including evaluation of barium impacts to road base materials, pesticides in soil and within the building, and asbestos and lead paint. Work included development and evaluation of remedial alternatives to address TCLP levels of barium in soil.

Consulting expert, for defendant and former co-owner of a dry cleaner in Frisco, Colorado, where historic releases of PCE have impacted soil and groundwater.

Consulting expert, assisting the Colorado Department of Public Health and Environment (CDPHE) and the Colorado Attorney General’s Office with technical evaluation of contamination and remediation of solvents, metals, and other compounds at the Rocky Mountain Arsenal in Denver.

Expert Witness, review of the relative contributions of two former dry cleaners to PCE in groundwater, including allocation of investigation and remediation costs.

Consulting expert, evaluation of cleanup costs and procedures at the Lowry Landfill for Coors Brewing Company, a party to the cleanup, on an annual basis. Includes evaluation of cap, groundwater containment, groundwater treatment, soil vapor recovery, and thermal technologies.

Technical consultant, evaluation of groundwater contamination and remedial alternatives at a municipal landfill in Sheridan, Wyoming, including nature and extent of solvent, petroleum, metal, and nutrient impacts.

Project Manager, technical oversight of groundwater investigations and evaluation of remedial alternatives at an operating gas plant near Rock Springs, Wyoming, for the Wyoming DEQ.
Issues include the nature and extent of NAPL migration in weathered and unweathered, fractured sedimentary bedrock; evaluation of the nature and extent of dissolved BETX impacts; and evaluation of removal, treatment, containment, and MNA remedies at the site.

Expert witness for industrial client in Denver, being sued for cost recovery under CERCLA by the U.S. Army for alleged contributions to groundwater contamination at the Rocky Mountain Arsenal. Work included evaluation of geologic conditions, groundwater hydrology, contaminant migration rates, and potential sources of chlorinated solvent plume. Case settled 1996.

Project Manager for investigations and designs related to cleanup of a diesel oil plume at a former industrial site in Los Angeles. Up to 10 feet of free product were detected on the groundwater table. Principal role involved evaluation of cleanup and closure alternatives, including demonstration of intrinsic bioremediation processes, and overseeing the work of a local hydrogeological firm on behalf of the client.

Assisting prime consultant on evaluation of existing hydraulic containment system and source control/removal options for chlorinated solvent plume at industrial facility in Colorado. Evaluating soil vapor extraction, dual phase extraction, in-situ bioremediation, and zero-valence iron wall alternatives.

Project Director for investigation and remedial designs to address TCA contamination in groundwater at an industrial facility in Denver. The approved Corrective Action Plan includes an array of groundwater recovery and vapor extraction wells, designs and contingencies for water treatment and scrubbing of air emissions, and appropriate discharge permits. Computer modeling was used to optimize the well spacing and pumping rates. Role included Consent Order negotiation. The design was implemented and closure was achieved.

Project Manager for investigations and remedial designs to address MEK and toluene contamination in soil and groundwater at a manufacturing facility in North Carolina. Role includes Consent Order negotiation, interfacing with counsel on regulatory matters, overseeing investigations by a local consultant, and design and permitting of a groundwater and soil vapor recovery/treatment system.

Expert review of data and testimony related to groundwater contamination at a municipal landfill in Colorado, involving preparation of an affidavit. This review was conducted on behalf of an insurance company representing a former owner/operator of the landfill. The case was dismissed.

Review of data and reports related to petroleum contamination in soils and groundwater at a former gasoline station and bulk fuel storage facility in northern Colorado, on behalf of a former owner and defendant in a civil lawsuit.

Review of environmental assessments and investigations conducted by others at a manufacturing facility in southern Colorado, on behalf of the buyer. Included additional investigations to assess the potential for soil and/or groundwater contamination due to four solid waste disposal sites, a leachfield, solvent storage area, and leaking underground fuel storage tanks.

Project Manager and technical advisor for a PRP committee. This former waste oil and hazardous waste storage facility was subject to removal action pursuant to a CERCLA Consent
Order with EPA. Responsibilities included regulatory negotiations, preparation of work plans, site security and storm water control, prior to removal actions.

Project Director of remedial investigation/feasibility study at a former petroleum refinery in Montana, under state "Mini-Superfund" program. The remedial investigation has been completed and the feasibility study is in progress.

Expert review of the Operable Unit No. 1 Feasibility Study of the Sand Creek NPL site for one of the PRP's. Preparation of a Removal Action Plan involving temporary site capping and drainage control, which was approved by EPA and implemented by TRC.

Expert review of hydrogeological issues surrounding the Hazard Ranking System scoring of a pipeline facility, including client representation at a meeting with EPA. Specific issues included evaluation of the existence of an aquifer discontinuity as defined by the NCP.

Provided expert advice to legal counsel for a property owner potentially impacted by migration of organics from an adjacent manufacturing facility.

Provided expert advice to legal counsel for a small chemicals firm facing civil and criminal indictments under RCRA for illegal disposal of hazardous wastes.

Supervised contaminant investigations and provided conceptual remedial alternatives for an abandoned petroleum refinery and fuel blending facility in Colorado. Concerns included a large pit containing tank bottom residues and sludges, fuel leaks and spills, and potential tetraethyl lead releases.

Supervised emergency response investigations and design and implementation of a groundwater cleanup system for a large fuel oil release in Colorado. Role included negotiations with EPA on behalf of the PRP to allow the client to take over investigation and clean-up responsibilities, and extensive permitting negotiations with the city and state for discharge of treated groundwater (this case has set regulatory precedence in both the city and state). Served as expert witness in subsequent litigation, which was settled out of court in favor of the client.

**Impoundment and Liner Design Projects**

Principal Investigator, leaking double-lined (HDPE) impoundments in Colorado Springs. Investigation included pump test on interstitial drain system and back calculation of permeabilities of and seepage rates through the upper and lower liners of two impoundments. Successfully repaired by laying bituminous panels over top liner.

Supervised hydrogeological investigation of a major sanitary landfill in Milwaukee, Wisconsin, with the purpose of demonstrating to state officials that natural geologic conditions prevented significant migration of contaminants.

Supervised final design and installation of a leachate dewatering system in a sanitary landfill in Denver. The purpose of the dewatering system was to remove leachate perched in the waste material and permit closure of the landfill. Successfully installed and operating.
Supervised remedial investigations at a sanitary landfill in Northern Colorado to determine the extent and potential impacts of groundwater and surface water contamination.

Provided geotechnical designs and assisted in the permitting of a new sanitary landfill in Colorado.

Investigated seepage from a bentonite clay lined brine pond in Colorado under notice of violation from the county. Provided regulatory liaison with county and prepared remedial designs, construction plans and specifications for upgrading and relining the facility. Inspected lined wastewater impoundments at a metals refinery in Oklahoma and provided recommendations to address problems with liner flotation and damage.

Investigated the cause of berm slumping and liner damage at two industrial wastewater lagoons in Colorado; prepared remedial designs; implemented interim repairs to slopes and liners.

Investigated the failure of a oil spill retention pond outlet structure for a manufacturing site in Colorado and prepared remedial designs (successfully completed).

Prepared detailed manual on the design and construction of wastewater treatment lagoons and various types of liners for the Government of Alberta. Published in 1985 as a guidance document for municipalities and consulting firms.

Conducted assessment of current lagoon liner practices in the Province of Alberta for the Alberta Research Council.

Supervised investigations, remedial designs, and implementation of remedial designs for stabilizing and re-lining 2 large brine storage reservoirs with leaking clay liners and slumping berm slopes. Fort Saskatchewan, Alberta.

Supervised investigations and designs and provided construction oversight for a new brine storage reservoir. Redwater, Alberta.

Provided designs and remedial recommendations for numerous impoundments in western Canada, including a gold tailings pond, gas plant run-off ponds, arsenic ponds at a mine site, and run-off ponds at a sanitary landfill.

Supervised three years of investigations and geotechnical analyses for 6 large artificial drilling islands constructed in the Mackenzie River, Northwest Territories, including specifications for liners below the work pads to control oil spills.

**Mining and Metals Projects**

Project Manager, implementation of Remedial Design/Remedial Action of a $38 million Natural Resource Damages (CERCLA) cleanup at a former smelter and operating metals refinery site in Denver, Colorado. Principal metals of concern were lead, arsenic, cadmium, and zinc. Operable Units include cleanup of surface soils at over 500 residential and commercial properties in the surrounding community; interception and treatment of groundwater; removal and disposal of contaminated ditch sediments; construction of a slurry wall and RCRA cap to contain a 7 acres
pile of calcium sulfate precipitates; stabilization of contaminated sediments; and air emission controls.

Expert Witness for defendant, class action lawsuit related to alleged contamination of soil in residential areas near a former metals processing facility in the northeast.

Expert witness for one of the defendants in a class action suit in the Silver Valley and Bunker Hill region of northern Idaho.

Project Manager, remedial investigation and feasibility study of the former Omaha Grant lead smelter in Denver, Colorado. Principal metals of concern include lead and arsenic. Media being evaluated include groundwater, surface water, sediments, and soils.

Expert witness for the defendant in class action lawsuit (Escamilla), concerning alleged contamination of surface soils in the neighborhoods surrounding a metals refinery and former smelter site. Testimony principally addressed the cleanup plans and background levels of metals in soils. Case was settled.

Expert witness for the defendant in class action lawsuit (C. DeBaca), concerning alleged contamination of surface soils in additional neighborhoods near a metals refinery and former smelter site. Testimony principally addressed class certification issues. Case was settled.

Project Manager, evaluation of surface soil impacts due to historic point source and fugitive air emissions of lead and arsenic from a 110 year old smelter and refinery. Included researching historic emission rates and metals contents of feedstocks and by-products, air dispersion and deposition modeling of emissions over the history of the facility, simulation of vertical transport of lead and arsenic in soils, and comparison to measured concentrations in soils. The work demonstrated that airborne impacts were limited to defined areas and that other impacts were due to background sources.

Project Manager, evaluation of vertical transport of cadmium, arsenic, and lead in soils due to leaching. Included testing to determine partitioning coefficients and other factors controlling migration and modeling of vertical transport. Results showed that concentrations substantially higher than typical soil screening levels could be left in place without risk to groundwater, and that inexpensive methods such as vegetation, sloping, and pH modification could treat soils with high concentrations of metals.

Expert witness for multinational mining and metals refining company in insurance cost recovery litigation. Testimony related to technological and regulatory conditions prior to the 1980's and the ability of the client to predict the nature and extent of soils and groundwater contamination, as well as predict the ultimate cleanup requirements and costs under CERCLA.

Project Manager, evaluation of the source of high arsenic and lead concentrations in soil over a widespread area in Denver, including geostatistical modeling and analyses, scanning electron microscope analyses, and review of historic aerial photographs and construction date records. Work to date has shown that fugitive emissions from client's metals refining site were not responsible for the high arsenic concentrations, possibly reducing cleanup obligations by several million dollars, and that application of arsenic and lead bearing herbicides and insecticides during
the 1950's and 1960's is the most probable cause. EPA and CDPHE ultimately agreed with these findings, issuing a ROD that identified pesticides as the source of the arsenic and some of the lead.

Project Manager, evaluation of the sources of lead contamination of soil in Omaha, currently attributed to historic lead refinery emissions. Evaluations to data indicate lead paint is the primary cause of elevated lead levels.

Expert witness in cost recovery action (U.S. district court) and review of remedial investigations/feasibility studies being conducted at seven log-sort yards and a landfill site in Tacoma, Washington, for one of the PRP's. Principal contaminants included arsenic, copper, and zinc in surface runoff and groundwater. Included collation and review of all pertinent data, assessment of technical quality and consistency with the National Contingency Plan, investigation of technical issues, and expert testimony in federal court.

Project Manager, evaluation of potential impacts of historic mining adits, shafts, waste rock and tailings on surface and groundwater quality, and preparation of waste rock and tailings management plan to allow residential and commercial site development, Colorado.

Project Manager, evaluation of potential impacts of placer mining operations and upgradient sources of acid mine drainage on site development, Colorado.

Project Manager, evaluation of source and extent of tailings on undeveloped land near Creede, Colorado, including recommendations for cleanup to allow site development.

Principal Investigator for evaluation of leaching and migration potential of metals in soils at former mine and mill site in New Mexico.

Principal Investigator for evaluation of migration and attenuation potential for metals in tailings water at proposed tailings impoundment site in Arizona.

Contributor to State of Arizona draft guidance on soil cleanup standards (prepared section on statistical methods for determining background concentrations).

Principal Investigator, evaluation of potential Hazard Ranking System score of metals refining site under CERCLA, including recommended actions to improve environmental conditions and reduce potential score, prioritized according to cost and benefit.

Evaluation of acid mine drainage and tailings impoundment stability and closure at a former lead mine and mill site in Missouri.

Prepared engineering cost estimates for the selected remedy at the Smuggler Mountain NPL site in Aspen, Colorado, for the PRP committee. Included evaluation of alternative sites for high level waste disposal.

Project Director for RI/FS at a former metals plating facility. Assisted legal counsel in negotiating a consent decree with state officials, which met the satisfaction of EPA overseers.
Remedial designs included excavation and disposal of metals contaminated soil. Remediation was successfully completed.

Prepared remedial designs for lining of a gold mine tailings pond and dump area near Idaho Springs, Colorado. Represented client before the Colorado Mined Land Reclamation Board and succeeded in having fine for failure of client to meet previous compliance schedule waived on the basis that previously approved designs were technically unfeasible.

Performed geotechnical investigations and designs for a 100 foot high sedimentation pond dam in British Columbia, including design of compacted clay and synthetic membrane liners and underdrain system.

Investigated a major landslide at an operating coal mine in British Columbia. Assessed options for stabilizing the slide, which was threatening the integrity of a principal haul road and culvert.

Conducted investigations and computer analyses of ground subsidence over an abandoned coal mine near Hanna, Wyoming. Provided recommendations for remediation, protection of surface facilities, and monitoring.

**PUBLICATIONS, PAPERS, & PRESENTATIONS**


Considerations in Natural Resource and Real Property Transactions, Denver, Colorado.


J.P. Kurtz, D.J. Folkes, and T.E. Kuehster, 2004. Approaches to Quantification of Background VOCs in

J.P. Kurtz and D.J. Folkes, 2005. Discerning Background Sources of VOCs from Vapor Intrusion Sources using Multiple Lines of Evidence. Presented at the 8th International Conference on In-Situ and On-Site Bioremediation Symposium, Baltimore, MD, June 2005.


D.J. Folkes, E.J. Wannamaker, and J.P. Kurtz, 2006. Vapor Intrusion Attenuation Factors Based on Long Term Indoor Air Data, 22nd International Conference on Soils, Sediments and Water – University of Massachusetts, Amherst, October 19, 2006


Peer Reviewer Conflict of Interest Certification

Peer Review: 

“Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds”

A conflict of interest or lack of impartiality exists when the proposed peer reviewer personally (or the peer reviewer’s immediate family), or his or her employer, has financial interests that may be affected by the results of the peer review; or may provide an unfair competitive advantage to the peer reviewer (or employer); or if the peer reviewer’s objectivity in performing the peer review may be impaired due to other factors. When the Peer Reviewer knows that a reasonable person with knowledge of the facts may question the peer reviewer’s impartiality or financial involvement, an apparent lack of impartiality or conflict of interest exists.

The following questions, if answered affirmatively, represent potential or apparent lack of impartiality (any affirmative answers should be explained on the back of this form or in an attachment):

- Did you contribute to the development of the document under peer review, or were you consulted during its development, or did you offer comments or suggestions to any drafts or versions of the document during its development? ☒ No ☐ Yes
- Do you know of any reason that you might be unable to provide impartial advice on the matter under consideration in this peer review, or any reason that your impartiality in the matter might be questioned? ☒ No ☐ Yes
- Have you had any previous involvement with the review document(s) under consideration? ☒ No ☐ Yes
- Have you served on previous advisory panels, committees, or subcommittees that have addressed the topic under consideration? ☐ No ☒ Yes
- Have you made any public statements (written or oral) on the issue? ☒ No ☐ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? ☒ No ☐ Yes
- Do you, your family, or your employer have any financial interests in the matter or topic under peer review, or could someone with access to relevant facts reasonably conclude that you (or your family or employer) stand to benefit from a particular outcome of this peer review? ☒ No ☐ Yes

With regard to real or apparent conflicts of interest or questions of impartiality, the following provisions shall apply for the duration of this peer review:

(a) Peer Reviewer warrants, to the best of his/her knowledge and belief, that there are no relevant facts or circumstances that could give rise to an actual, apparent, or potential organizational or personal conflict of interest, or that Peer Reviewer has disclosed all such relevant information to EMS or to EPA.

(b) Peer Reviewer agrees that if an actual, apparent, or potential personal or organizational conflict of interest is identified during performance of this peer review, he/she immediately will make a full disclosure in writing to EMS. This disclosure shall include a description of actions that Peer Reviewer (or his/her employer) has taken or proposes to take after consultation with EMS to avoid, mitigate, or neutralize the actual, apparent, or potential organizational conflict of interest. Peer Reviewer shall continue performance until notified by EMS of any contrary action to be taken.

Signature 4/18/12

[Signature] Date

☐ Check here if any explanation is attached

See reverse

Printed Name

DAVID FOLKES

Affiliation/Organization

ENVIRON GROUP LIMITED
I am a member of the recently formed ITRC petroleum vapor intrusion team and have attended one group meeting so far. I was previously a member of the ITRC vapor intrusion team (not focused on petroleum). I have expressed the opinion that petroleum biodegrades in the vadose zone, reducing its potential for vapor intrusion impacts, based on the literature and presentations I have heard, but have not conducted any research of my own on this topic. I have not endorsed any specific exclusion criteria or distance, nor do I know what this particular draft document advocates in that regard.

[Signature]
JEFFREY P. KURTZ, PH.D.
SENIOR SCIENTIST

EXPERTISE

- Vapor Intrusion Evaluations, including Indoor/Background Sources of VOCs
- Geochemistry and Geostatistics
- Investigation and Remediation of Soils and Groundwater
- Mine, Mill and Smelter Site Investigation
- Natural Resource Damage Assessments

SUMMARY OF EXPERIENCE

Dr. Kurtz, a Senior Scientist at EnviroGroup, has over twenty years experience as a consulting Geologist/Geochemist. He has extensive geochemistry, statistics and data management experience in water resources, Superfund litigation, site investigations, and environmental forensics, with emphasis on vapor intrusion and metals issues.

Dr. Kurtz is the indoor air testing Task Manager for one of the largest vapor intrusion sites in the country, with responsibilities that include evaluating the extent of vapor intrusion impacts and the performance of vapor intrusion controls, and evaluating the contributions of indoor sources and background to indoor air levels of VOCs. He has worked on a number of other vapor intrusion sites in Colorado, California, Kansas, New Jersey, New York, Utah and Wyoming, and is well known for his research and publications on indoor sources of VOCs, including the use of COC ratios in groundwater and indoor air to separate vapor intrusion from background sources. Dr. Kurtz has worked closely with Dr. Paul Johnson and Robbie Ettinger to publish the first study providing validation of the JE Model from empirical data.

Dr. Kurtz has acted as statistician and sampling advisor on chlorinated solvent contaminated indoor air and groundwater for the Colorado Department of Transportation MTL site and for the Alliant Techsystems (ATK) Dry Creek Road site in metropolitan Denver. He was responsible for: method development for indoor air COC selection; development of detailed data quality objectives for sampling plans to define background air concentrations and the spatial extent of the indoor air contamination; geostatistical mapping of indoor air contamination; defining groundwater to indoor air correlations for determination of preliminary remediation goals for groundwater; developing methods for identification of non-groundwater derived chlorinated solvents in indoor air; developing statistically based monitoring plans using surrogates; uncertainty characterization in risk assessment; writing significant portions of the indoor air corrective measures plan, and; presentations to the Colorado Department of Public Health and Environment and to the U.S. EPA.

Dr. Kurtz is currently serving as a consulting expert for the defense in a toxic tort case involving a chlorinated solvent groundwater plume and potential residential indoor air impacts. He was an Assistant Professor of Geology at the University of Colorado, where he was responsible for graduate and undergraduate student instruction in the areas of: mineralogy, aqueous geochemistry, ore deposits and field geology. Dr. Kurtz has prepared numerous papers and given presentations on a variety of topics, including mine site investigations, hydrothermal alteration related “background” acidity and geochemistry, and background sources of indoor air chemicals at vapor intrusion sites.

EDUCATION

1983  Ph.D., Geology, University of North Carolina - Chapel Hill
1979  M.S., Geochemistry, University of North Carolina - Chapel Hill

1975  B.S., Chemistry (minor in Geology from Scripps Institute of Oceanography)
      University of California, San Diego

PROFESSIONAL MEMBERSHIPS

   Society of Economic Geologists
   Geochemical Society

SELECTED PUBLICATIONS

Kurtz, J., Wolfe, E., Foster, S., and Woodland, A., 2010, Evidence for increasing indoor sources of 1,2-
dichloroethane since 2004 at two Colorado residential vapor intrusion sites, Ground Water

Gas from the Lowry AFB Site, Denver, Colorado, in Proceedings Air & Waste Management

Folkes, D., Wertz, W., Kurtz, J., and Kuehster, T., 2009, Observed Spatial and Temporal Distributions of
CVOCs at Colorado and New York Vapor Intrusion Sites, Ground Water Monitoring &
Remediation, V. 29, No. 1, p. 70-80.

Ground Water-to-Indoor Air Attenuation Factors for the CDOT-MTL Denver Site, Ground Water

Plume, abst. and presentation at AEHS 17th Annual West Coast Conference on Soils, Sediments

Folkes, D. J., Kurtz, J.P., and Sanpawanitchakit, C., 2007, Vapor Intrusion as a Function of Lateral
Distance from a Groundwater Plume Boundary, in Proceeding of Air And Waste Management

Folkes, D. J., Kurtz, J.P., and Wannamaker, E.J., 2006, Vapor Intrusion Attenuation Factors Based on
Long-term Data, abst. and presentation at 22nd Annual Conference on Soils, Sediments and

Kurtz, J.P., and Folkes, D., 2005, Discerning Background Sources from Vapor Intrusion, presentation to
the Environmental Section of the Colorado Bar Association, October 26, 2005.

Kurtz, J.P., and Folkes, D., 2005, Discerning Background Sources of VOCs from Vapor Intrusion
Sources using Multiple Lines of Evidence, in Proceedings of the 8th International In Situ and On-
Site Bioremediation Symposium, Baltimore, MD, June 6-9, 2005, 8p.

at the CDOT MTL Site, Denver, CO, abst. and presentation at 20th Annual Conference on Soils,


Walsh Environmental, 2002, Active Soil Vapor and Groundwater Report, Phase I First and Second Quarter Results Alliant Techsystems (ATK) Dry Creek Road Facility, report to U.S.EPA, March 27, 2002.


A conflict of interest or lack of impartiality exists when the proposed peer reviewer personally (or the peer reviewer’s immediate family), or his or her employer, has financial interests that may be affected by the results of the peer review; or may provide an unfair competitive advantage to the peer reviewer (or employer); or if the peer reviewer’s objectivity in performing the peer review may be impaired due to other factors. When the Peer Reviewer knows that a reasonable person with knowledge of the facts may question the peer reviewer’s impartiality or financial involvement, an apparent lack of impartiality or conflict of interest exists.

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- Have you had any previous involvement with the review document(s) under consideration? ☒ No ☐ Yes
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- Have you made any public statements (written or oral) on the issue? ☐ No ☑ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? ☒ No ☑ Yes
- Do you, your family, or your employer have any financial interest(s) in the matter or topic under peer review, or could someone with access to relevant facts reasonably conclude that you (or your family or employer) stand to benefit from a particular outcome of this peer review? ☒ No ☑ Yes

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Signature: __________________________ Date: 4/8/12

[Signature]

Printed Name: Jeffrey P. Kurner

Affiliation/Organization: Enviro Group Limited

☐ Check here if any explanation is attached
GENERAL COMMENTS
Of May 3, 2012

Having reviewed the subject draft report and provided editorial comments on almost every page, the following general comments may help prioritize the revisions:

1) if the data used in the analysis are all high quality and if the uncertainty in the calculated exclusion distances are negligible (neither of which have been demonstrated), the bottom line is that dissolved phase source can be neglected unless there is a very shallow water table and NAPL sources can be neglected if the building is more than about 30 feet away (which is already a fairly typical exclusion distance). This could be summarized in a much, much shorter document. There is far too much redundancy, and at the same time, far too many vague statements. What is needed is to get to the point, do so in comprehensive detail, and clearly state the uncertainties in the outcome.

2) It is not enough to simply focus on exclusion distances. The report refers to “screening criteria” in the title, and “screening methods” in the text, as if these are interchangeable and the exclusion distance is the only component. This is not true. If petroleum hydrocarbons behave significantly differently than chlorinated solvents, then it is fair to treat them differently during a PVI assessment; however, this has many implications for the scope and methods of assessment, which have been noted throughout the edited document. For example, I find a landfill gas meter is invaluable for assessing soil vapor conditions at a hydrocarbon site and seldom informative at chlorinated solvent sites. If hydrocarbons degrade and therefore do not travel far, then the sample spacing required to minimize the risk of failing to identify a hot-spot would have to be much closer than for persistent chlorinated solvent vapors. The list goes on and on. The draft OUST Guidance does not address all of the implications raised in this document, and it is not clear whether the two are intended to be complimentary or not. Either way, one of the documents needs to provide guidance on the site characterization that is sufficiently detailed to distinguish the extent of NAPL, and for buildings that are not excluded, the scope and methods of data collection needed to make a determination whether PVI poses a risk or not. At present, this is a major gap.

3) There are certain conditions that have been excluded (preferential pathways, fractured rock, large buildings, etc.). It is important to incorporate methods of dealing with these circumstances in the screening process. If any of these occur, is indoor air sampling needed? Or would it be necessary to collect vertical profiles of soil vapor concentrations through the floor of each building? If no guidance is provided to inform the regulators, practitioners and owners how to proceed, then the document really hasn’t advanced the status quo.
4) There are far too many instances in the report where a topic is discussed in a sentence or two that really needs a couple of paragraphs or pages to be sufficiently detailed for the average regulator or consultant. Methanogenesis is not limited to ethanol-enriched fuels, and methane can be a dominant contribution to oxygen demand, so it needs much more extensively discussed and incorporated in the screening process. Oxygen is the reason hydrocarbons can be degraded, yet the correlation between O2 and TPH in the database is not consistent with theoretical expectations, and that indicates either a poor conceptualization or poor data quality. Lots of the sites in the database don’t even have oxygen or methane data, which I would consider to be essential for verifying data quality. There is no discussion at all regarding whether samples were collected from temporary probes or properly sealed soil vapor implants, which in my experience is a critical determinant to data quality in all soil types except uniform medium to coarse sand.

Considering the extent of the comments and the significance of the omissions, this reviewer recommends a major revision.

Furthermore, the following charge questions were specifically asked and my responses follow each in italics, below:

As a peer reviewer, you are being asked to review the Golder/RTI Report and provide opinion and perspective regarding:

- the scientific appropriateness of the database for OUST’s purposes;

**I consider the database to be dubious at best. While lots of sites are included, the distribution is very skewed so a small number of sites contribute the majority of the data. Practitioners have over the period that this data was collected used a wide range of sampling and analytical methods, and standards of QA/QC and care, so without knowing who collected and analyzed the samples, I can’t have a lot of confidence in the results. Temporary probes are common, but in my experience, they leak a lot and especially should not be used in low permeability materials, but there is not enough information to be able to tell whether or to what extent this occurred. There are indications of questionable data quality (soil gas samples with high TPH and O2, which is not expected in nature, and is expected if a sample with high TPH and low O2 concentrations was subject to addition of atmospheric air from a leaking fitting or seal). Furthermore, there is a huge amount of scatter (i.e., poor correlations) in the data, so any values calculated must also consider the associated error bars, which would be huge.**

- whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST’s purposes; and
The analysis essentially concludes that dissolved hydrocarbons only pose a risk if the source/building separation is very small and NAPL can pose a risk to about 30 feet, with the caveat that sites with preferential pathways, fractured rock, large buildings, etc. are not included. If that is all that the report will be used for, the analyses are appropriate.

- whether the reported conclusions are adequately supported by the data and analyses.

The data is not highly reliable, as stated above.

Specific questions to which answers are requested are:

1. Is the report written in a manner that is clear, robust, and transparent for its intended purpose?

No, it is repetitive and vague and much, much longer than it needs to be to support the outcome. The database is missing several key components that are essential to verifying the integrity of the data.

2. Does the report meet its stated objectives (listed above) for which it was conducted? If not, please indicate any identified gaps.

No, the report does not address the final objective: “Identify methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.” In my opinion, there needs to be a PVI site characterization protocol that addresses all the items in my comments where I noted that the statements have “implications” for PVI site assessment. If the objective was to identify methods for including or excluding sites, I interpret that to mean that there needs to be a robust and consistent method for site assessment that forms the foundation for that selection. If a site is poorly characterized, it doesn’t matter how good the decision criteria or exclusion distances are. Far too many people take it for granted that site assessment is true, accurate and complete, and in my experience, it is far more complicated than that. It would be acceptable to refer to another guidance document if one existed that meets this need, but the OUST draft guidance also does not address all of the implications raised in this draft document.

3. Are there any additional scientific issues relating to the stated objectives that are not addressed in the report?

Yes, the assessment implications, described above.
4. Are the criteria for data acquisition during the underlying studies (i.e., Davis, Eremita, Peargin and Kolhatkar) and into the assembled database adequately described? Do these criteria ensure that the estimated attenuation in vapor concentrations in the vadose zone at each site:
   - can be reasonably attributed to aerobic biodegradation (versus other explanations); and
   - is an appropriate value for predicting potential indoor air concentrations in nearby buildings?

No, please add details of whether probes were temporary, PRT, or implants, whether purging was monitored to assure steady readings, whether a shut-in test was performed and whether a helium test was performed.

If you don’t know how many soil gas samples had atmospheric air leaks, you don’t really know what caused the attenuation. A mass balance on O2 and CO2 might help.

Not clear why the last bullet is part of the Charge Questions. If exclusion criteria are adopted as concluded in this draft report, will attenuation factors still be needed? I would expect the only sites remaining would be wet-basements with dissolved hydrocarbons and buildings with a foundation within 30 ft of NAPL, and it seems preemptive mitigation would be appropriate in either case. That’s not specifically stated anywhere, which is another reason why this document is incomplete.

5. Is the assembled database adequately large and sufficiently representative of subsurface conditions and indoor air concentrations for purposes of reliably determining presumptive criteria for each of the following scenarios:
   - petroleum releases from USTs; and
   - petroleum releases from other sites (e.g., refineries, terminals, transmission pipelines)?

There are enough sites, but the data is skewed to a small number of sites with a large number of samples, and the data quality has not been adequately defended, so I would say no.

6. Are the statistical methods applied to the data appropriate for the data set and for the comparison being made?

No. Considering the uncertainties, the outcomes (exclusion distances) should be expressed with a range of possible error (i.e., $X +/- Y$), not as a single value.
7. Are the findings of the report of adequate scientific integrity to support establishment of a vertical distance between a source of petroleum vapor contamination and an overlying receptor in determining whether an UST site could pose a significant health risk to building occupants? Have all the factors that influence, or potentially influence, biodegradation (e.g., soil moisture, seasonal and climatological effects, preferential transport pathways, type of petroleum fuel, surface cover) been adequately considered?

No, but it may not matter much. Most guidance uses an exclusion distance of 30 feet anyway, and that’s pretty much the same value as determined in this draft report.

8. Does the Golder/RTI Report provide a sound basis for applying the proposed vertical separation distances for aromatic and aliphatic petroleum hydrocarbons (e.g., benzene) to other common fuel constituents (e.g., naphthalene) and fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide)?

No.

9. Are you aware of additional references or other resources that could be added to the report, or would be useful in meeting the stated objectives of the report? Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?

I provided two additional papers with carefully collected data that would add to the existing database. John Wilson of EPA Lab in Oklahoma is also interested in this subject and may have other resources.

10. Do you have any additional comments on the report itself or its intended use that have not been explicitly solicited? Please cite line number(s) in the report pertaining to specific comments.

It’s not really clear to me why this report is needed. How is it different than the OUST Guidance, and why isn’t it simply combined with the OUST guidance? In my review of Table 3 of the current draft OUST Guidance, I’m not sure anything further is an improvement, and this draft raises far more questions than it answers.
This is good but not enough. There should also be recommendations for what kind of data is needed to support the initial characterization and what spacing and frequency is acceptable. Also add recommendations for follow-up actions (further characterization or mitigation) when exclusion is not supported.
8. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Only detectable benzene vapor concentrations shown.  

9. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Data points shown are where both TPH vapor and oxygen concentrations were above detection limits. Shaded ellipse encompasses data that generally support the aerobic mineralization paradigm.  

10. Relation between Benzene and Ethylbenzene and Benzene and Xylenes Vapor Concentrations. Data points shown are where both compounds were above detection limits.  

11. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for Dissolved Sites (KM = Kaplan-Meier).  

12. Vertical Distance Method–PHC Fraction and Hexane Data for Dissolved Sites.  

13. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (UST only) Sites (KM = Kaplan-Meier).  

14. Vertical Distance Method–PHC Fraction and Hexane Data for LNAPL (UST only) Sites.  

15. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (all sites) Sites (KM = Kaplan-Meier).  

16. Vertical Distance Method–2,2,4-Trimethylpentane Data for LNAPL Sites (all sites).  

17. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (all sites). Below detection limit concentrations replaced with half the detection limit for analysis.  

18. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (UST sites). Below detection limit concentrations replaced with half the detection limit for analysis.  

19. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold for Different Soil Types (coarse and fine grained). Below detection limit concentrations replaced with half the detection limit for analysis.  

20. Results of Clean Soil (Davis) Method for Dissolved-Source Sites 47 sites, N = 170.  

21. Results of Clean Soil (Davis) Method for LNAPL Source Sites (UST-only), 53 sites, N = 172.  

22. Results of Clean Soil (Davis) Method for LNAPL Source Sites (all), 60 sites, N = 216.
1. Introduction

This study is an evaluation of empirical data and select modeling studies of the behavior of petroleum hydrocarbon (PHC) vapors in subsurface soils and how they can affect subsurface-to-indoor air vapor intrusion (VI), henceforth referred to as petroleum vapor intrusion or “PVI” for short. The purpose of this study is to support the development of a soil vapor screening methodology for PHC compounds for the U.S. Environmental Protection Agency’s Office of Underground Storage Tanks (U.S. EPA OUST); consequently, the focus is primarily on characterizing PVI at Subtitle I underground storage tank (UST) sites with petroleum fuel releases. However, PVI data from other types of sites (fuel terminals, petroleum refineries) are also presented and discussed.

1.1 Background

In support of its general guidance development effort for the VI exposure pathway, U.S. EPA has compiled an empirical database of paired measurements of subsurface media (groundwater, soil gas) and indoor air concentrations, which consists primarily of data for chlorinated solvent chemicals, with very limited data for PHC compounds (approximately 3 percent of the database) (U.S. EPA, 2012a). The study discussed in this document is exclusively directed at PHCs and only analyzes subsurface media (soil gas, soil, and groundwater) concentrations and other supporting data for PHCs. The rationale for this focus on subsurface PHC measurements is that PHC vapors can rapidly biodegrade in the presence of oxygen and attenuate to much lower concentrations in soil gas (U.S. EPA, 2011).

Because the bioattenuation process is well documented and widespread (U.S. EPA, 2011), the analysis of subsurface soil gas data from sites provides an opportunity for developing improved and more realistic screening evaluation methods for PHC compounds based on the observed attenuation. These data can be used to identify “an exclusion distance,” defined in this report as the contamination source-separation distance at which the potential for PVI is deemed negligible. This exclusion distance, and much of the underlying data on which it is based, primarily stems from the work of Robin Davis, a regulator with the Utah Department of Environment’s UST program (see Davis, 2009, 2010, 2011a, and 2011b).

As part of a group of interested parties organized by U.S. EPA OUST to develop guidance and methods specific to PVI, Ms. Davis began to gather soil gas and groundwater data from UST sites across the United States where PVI investigations had been conducted. Through collaboration with the work group and other PVI practitioners, Ms. Davis’ effort led to the “exclusion criteria” concept and an expanded PVI database (Davis, 2009) the May 2011 version of her database was used as the basis for the effort described in this report, although data from other sources were also incorporated into the database used in this report.

In addition, several similar parallel efforts are in progress in this country (Lahvis et al., In prep.; Peargin and Kolhatkar, 2011), and Australia (Wright, 2011, 2012) using somewhat different data sets than the one used in this document. Regarding these complementary database evaluations, the benzene data from sites in the United States and Canada are identical for this
database study and the Lahvis et al. (In prep.) effort. The main differences between Lahvis et al. (In prep.) and this U.S. EPA study are that:

1. The Lahvis et al. (In prep.) study includes data from sites in Wright’s (2011) Australian database, whereas the U.S. EPA database does not¹.

2. The U.S. EPA database includes a more extensive evaluation of a range of chemicals, including aromatic and aliphatic hydrocarbon fractions, whereas the focus of Lahvis et al. (In prep.) is benzene vapor attenuation.

Section 9 of this report compares and contrasts these parallel studies and their results with the results of this study.

1.2 Goals and Objectives

The goal of this study was to provide information on the behavior of PHCs with respect to vapor intrusion that would support establishing an assessment framework and set of criteria for evaluating potential petroleum vapor migration from subsurface to indoor air. The study included three general scenarios:

1. Sites with a relatively high potential for a complete PVI pathway² and possible unacceptable risks.

2. Sites with a relatively high potential for an incomplete PVI pathway.

3. Sites with an unknown potential for a complete PVI pathway and risk, thus requiring further assessment.

The main intent of the evaluation was to determine if the vapor migration pathway is complete (or incomplete) to indoor air. Risk in this context is the potential to exceed human health-based concentration criteria in indoor air due to VI.

This report addresses a key part of this framework: the identification and justification of exclusion distances between contamination and receptors that can be used to quickly assess whether the PVI pathway is complete. However, the scope of this study did not include development of the framework and criteria that will be needed to apply these exclusion distances as part of the developing PVI guidance.

To develop and support the exclusion distances, the objectives of this study were to:

- Assemble an empirical database from petroleum release sites where the PVI pathway has been evaluated via primarily soil gas and groundwater measurements;

- Consolidate and independently check existing databases and enter and check newly available data;

¹ The U.S. EPA database does include one site in Perth, Australia, from Patterson and Davis (2009).
² For the purposes of this report, a complete PVI pathway is defined as measurable indoor petroleum hydrocarbon vapor concentrations that come from a subsurface contamination source.

The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
• Analyze the database and available case studies to determine when and under what conditions there is the potential for a complete PVI pathway at a site;
• Review published modeling studies on PHC vapor transport and intrusion as a supporting line-of-evidence; and
• Identify methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.

1.3 Document Organization

This report is organized as follows:
• Section 2 describes the conceptual site model (CSM) for aerobic biodegradation of PHC vapors and select case studies where PVI has been documented.
• Section 3 provides a review of select modeling studies of the biodegradation of PHCs in the subsurface.
• Section 4 provides a review of empirical database studies of PHC vapor attenuation.
• Section 5 provides a review of exclusion distances for PVI in existing state VI guidance.
• Section 6 describes the PVI database development, structure, and content.
• Section 7 describes the PVI database analysis approach and methods.
• Section 8 describes the PVI database analysis results.
• Section 9 provides a discussion of the results and comparisons with other studies.
• Section 10 provides conclusions drawn based on this study.

2. Conceptual Site Model and Select Case Studies

The CSM for PVI described below builds on the CSM described in U.S. EPA (2011), with additional emphasis on the difference in PHC vapor concentrations for light nonaqueous phase liquid (LNAPL) and dissolved groundwater contamination sources. In addition, select case studies indicating a confirmed or likely complete transport pathway for PVI are described.

2.1 Aerobic Biodegradation Processes

Petroleum liquids (e.g., gasoline, diesel) are moderately soluble in water and often form separate phase liquids commonly referred to as LNAPLs when released into the environment. When LNAPL reaches the water table, it tends to accumulate and spread laterally and vertically (as the water table rises and falls) to form a smear zone where residual LNAPL occupies soil pore spaces across the water table. A dissolved hydrocarbon groundwater plume that extends beyond the LNAPL source zone is formed as PHC compounds dissolve from the LNAPL into groundwater or as water percolates through residual LNAPL in the vadose zone. Light, nonaqueous phase liquids or partially volatilization of PHEs will occur from both LNAPL and dissolved (groundwater) hydrocarbon sources. Methane and carbon dioxide gas may be generated through microbial...
breakdown of PHC compounds in anaerobic source zones. Fuel oxygenates, such as ethanol and methyl tert-butyl ether (MTBE), can also be present in the vapor phase in the unsaturated zone proximate to LNAPL source zones.

The biodegradation of PHC vapors is relatively rapid when oxygen is present; therefore, aerobic biodegradation can typically limit the concentration and subsurface migration of PHC vapors in unsaturated soils and in groundwater. Modeling studies (Abreu and Johnson, 2006; DeVaull, 2007a; Abreu et al., 2009) and field studies (Riric et al., 2002; Hers et al., 2000; Roggemans et al., 2001; Fitzpatrick and Fitzgerald, 2002) indicate that the potential for PVI is greatly reduced when aerobic biodegradation processes occur in soils between the hydrocarbon source and receptor (building foundation).

The aerobic biodegradation process between the hydrocarbon source and receptor may be conceptualized with respect to fluxes where the oxygen availability must exceed microbial metabolically driven oxygen demand associated with the hydrocarbon source (Lahvis et al., In prep.). Hydrocarbon biodegradation rates are rapid (e.g., half-lives on the order of hours to days; DeVaull, 2007b, 2011) and typically are much faster than the rate of hydrocarbon transport by diffusion and advection within the unsaturated zone. For this reason, there are typically sharp reaction fronts where the PHC vapor concentrations attenuate by orders of magnitude over short distances (e.g., 1 to 5 ft [0.3 to 1.5 m]) and where there is a corresponding decrease in the oxygen concentrations, as observed in several field studies (Lahvis and Baehr, 1999; Hers et al., 2000; Sanders and Hers, 2006; Davis et al., 2009; Luo et al., 2009). The lower threshold oxygen concentrations required to support aerobic biodegradation of PHC vapors are reported to be in the range of 1 to 4 percent (DeVaull, 2007b).

2.2 Factors Influencing Aerobic Biodegradation

Biodegradation of petroleum hydrocarbons has been reported in more than 70 years of publications (ZoBell, 1946; Atlas, 1981; Leahy and Colwell, 1990), including PHC liquids and gases; straight, branched, and ring-structure PHC compounds with single and multiple carbon bonds; by many microbial species, including 30+ genera of bacteria, 25+ genera of fungi, and several algae (although not every chemical is degraded by every microbial species); in marine, freshwater, sediment, and soil environments; and in direct metabolism and co-metabolism (co-

oxidation). Microbial degradation of petroleum produces biomass, intermediate products (alcohols, aldehydes, organic acids), and the ultimate mineralization products carbon dioxide (CO$_2$) and water (H$_2$O). In general, relatively fast acclimation times are observed, absent other limits, by population enrichment (fast biomass growth) and/or plasmid transfer. Acclimation times tend to be shorter with prior chemical exposure. Environmental conditions under which petroleum biodegradation has been observed range from 0° to 70°C, salinity up to 25 parts per thousand sodium chloride (NaCl), and pH from 6 to 10, although optimum conditions can be narrower. Aerobic biodegradation is the primary mechanism in the unsaturated zone, but anaerobic biodegradation near source zones may also occur through other electron acceptors present (nitrate, sulfate, etc.) (strict or facultative), or under fermentative or methanogenic conditions (DeVaull et al., 1997; Madigan et al., 2010). There have been extensive compilations of rates of aerobic degradation specific to vadose zone aerobic soils (e.g., DeVaull et al., 1997; Hers et al., 2000; Riric et al., 2002; Davis et al., 2009; DeVaull, 2011).
The U.S. Air Force Bioventing Initiative study of 125 sites indicated that environmental factors, such as soil moisture, nutrients, and pH, did not significantly influence biodegradation activity and respiration rates, except for one site located in the Mohave Desert with very dry soils (moisture content of 2 percent), although some biological activity did still occur at this moisture content (Leeson and Hinchee, 1996). Biological activity is limited when the moisture content is at or below the permanent wilting point (Zwick et al., 1995; Holden et al., 1997), which is expected to be rare in most geological and climatic environments (note that the empirical database for this project includes sites in dry areas).

Aerobic biodegradation of PHCs is a robust process that has been demonstrated under a wide range of environmental conditions. Important factors influencing aerobic biodegradation of PHC vapors include the:

- Vapor source hydrocarbon concentration, flux, and composition (including methane);
- Oxygen demand (i.e., the oxygen required to biodegrade the available hydrocarbons and any other organic matter that is present);
- Distance between the vapor source and the building;
- Soil type and properties;
- Size and characteristics of the building and adjacent land surface.

### 2.3 Dissolved versus LNAPL Vapor Sources

The PHC vapor source concentration is highly dependent on whether partitioning occurs from compounds present as a dissolved phase in groundwater or directly from LNAPLs present above the capillary fringe. The vapor mass flux from LNAPLs present in the unsaturated zone will be higher than for a dissolved source because for a dissolved source, chemicals must diffuse through water in the capillary zone before reaching continuous gas-filled soil pores, and hydrocarbons may also be attenuated through biodegradation and sorption within the capillary zone. The vapor mass flux for LNAPL source zones will also tend to be sustained for longer periods of time given the larger contaminant mass and lower biodegradation rates compared with dissolved sources. In addition, the vapor composition will be different depending on whether the vapor source is LNAPL or the dissolved phase. For LNAPL sources, there will tend to be a higher proportion of relatively insoluble PHC compounds, including aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), such as naphthalene. For dissolved sources, there will tend to be higher concentrations of the more soluble chemicals, including single-ring aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (Lahvis et al., In prep.).

The differences in the PHC vapor concentrations and fluxes for LNAPL and dissolved vapor sources are an important distinction for defining exclusion distances (Figure 1). Conceptually, the source type (dissolved or LNAPL) will affect the position of the aerobic reaction front in the unsaturated zone relative to the oxygen source. For dissolved sources, the reaction front will be located close to the hydrocarbon source (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009), while for LNAPL sources, the reaction front position is more variable, but typically is located at greater distances from the source compared with dissolved sources (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009). For
dissolved vapor sources, case study meta-analyses, and database evaluations reported in the literature indicate no confirmed cases of PVI for a wide range of site conditions (Davis, 2009; McHugh et al., 2010).

2.4 Conditions for Increased Potential for Petroleum Vapor Intrusion

As described in U.S. EPA (2011), certain site conditions, such as the following, may result in increased potential for PVI:

- **Direct contact between contamination (either dissolved or LNAPL) and a building foundation.** Most documented cases of PVI are for this condition (McHugh et al., 2010).

- **Insufficient separation distance.** For biodegradation to limit the potential for PVI, a sufficiently thick layer of "clean," oxygenated soil is needed between the building foundation and the contamination (the required thickness will depend on source type). Clean soil is defined as un-impacted by residual LNAPL.

- **Preferential transport pathways.** If a preferential pathway connects a contamination source to a building, the chemical transport can be faster and extend farther than transport through the surrounding soils.

- **Anaerobic (low oxygen) conditions.** Building foundations and adjacent land surfaces with low effective diffusivity and soil-air permeability can reduce oxygen transfer to the subsurface by serving as a surface cap. Natural conditions can also limit oxygen availability, as evidenced by low oxygen concentrations found in the presence of some highly organic soils (e.g., peat) or areas where methane is naturally high. The relative importance of a potential capping effect is not well understood, although significant diffusive oxygen transport through intact concrete can occur, as indicated by measured rates reported in the literature (Branco and de Brito, 2004; Kobayashi and Shuttih, 1991; Tittarelli, 2009). Adveotive transport of atmospheric air to the subsurface also can occur through openings (e.g., cracks, drains, sumps) in the building foundation during time periods when the building is positively pressurized. These mechanisms can limit the potential for low oxygen conditions beneath a building.

- **Production of methane gas.** Methane may be produced through microbial breakdown of PHC compounds in anaerobic source zones, and the presence of ethanol in a source zone may increase the generation rate of methane compared with a gasoline LNAPL-only source zone (Nelson et al., 2010; Spalding et al., 2011; Jourabchi et al., 2012). Note that releases of fuel containing 10% ethanol (E10) are most likely included in the reviewed database (this document, see Section 6.3) and in Lahvish et al. (in prep.). Evaluation of methane generation from ethanol fuel blends is an area of active research (Jewell and Wilson, 2011). Methane production can result in soil gas pressures and flow toward receptors and may deplete oxygen that otherwise could be used for biodegradation of the PHC vapors. Elevated methane therefore could increase the potential for PVI at a PHC release site. However, to our knowledge, there are no published data from UST sites where significant source zone advection has

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2.5 Case Studies Indicating Confirmed or Likely Complete Transport Pathway for Petroleum Vapor Intrusion

Confirmed occurrences of subsurface vapor intrusion to indoor air or elevated subslab hydrocarbon vapor concentrations at petroleum sites are rare in the literature, but are important to understand for defining the inclusion criteria—that is, sites where PVI is likely to be found and evaluation of PVI is warranted.

Eight case study sites were identified in the literature where PVI was confirmed or likely (Table 1). Five sites were refinery or petrochemical sites, and three were UST sites. Common site conditions involved the following: large fuel releases, extensive LNAPL contamination at the water table, and shallow depth to LNAPL contamination, although at two sites the separation distances between the building and LNAPL source were approximately 25 to 30 ft (7.6 to 9.1 m). Factors that appeared to contribute to PVI at sites with somewhat deeper contamination were a possible capping effect at a former refinery site (unknown location) and heavy rain and/or a sharp water table rise at a site with a very large petroleum fuel release (Hartford, Illinois).

2.5.1 Refinery Site, Perth, Australia (Patterson and Davis, 2009)

Monitoring at a former refinery site near Perth, Australia, with a kerosene LNAPL source indicated elevated (up to 20 mg/L) PHC vapor concentrations and depleted oxygen (<1 percent) below the interior of a building, but much lower hydrocarbon and near-atmospheric oxygen concentrations near the edge and beside the building. The slab-on-grade building footprint area is 2,700 ft² (251 m²) with a 30-ft (9.1-m) wide concrete apron on three sides of the building, and uncovered open ground on one side of the building. The building is underlain by sand with a LNAPL zone across the water table at approximately 10 ft (3.0 m) below ground surface (bgs).
The effective diffusion coefficient for chemical transport through concrete was measured at the site and was found to be relatively low compared with published data, indicating the concrete slab was not overly porous. The relatively low diffusivity of the concrete may have reduced oxygen transport to the subsurface under the building. In addition, because of the wide concrete aprons, the effective area of the building with respect to oxygen transport restrictions may be larger than its footprint.

2.5.2 Chatterton Petrochemical Site, Vancouver, B.C., Site (Hers et al., 2000; Hers et al., 2002)

At the former Chatterton petrochemical site near Vancouver, B.C., a building (greenhouse) was constructed above a residual LNAPL source comprising benzene, toluene, and xylenes. Monitoring indicated depletion of oxygen (<1 percent) and a complete PVI pathway when the building was continually depressurized (to approximately 10 Pa), but only partial oxygen depletion and no complete pathway under natural (near-neutral) pressure conditions. The slab-on-grade building footprint area was 610 ft² (57 m²), the building was underlain by sand, and the depth to the LNAPL smears zone was 5 ft (1.5 m) below the building foundation slab.

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2.5.3 Refinery Site, Casper, Wyoming (Luo et al., 2009)

Monitoring at a site in Casper, Wyoming, indicated a complete PVI pathway at a refinery site with a light distillate (gasoline-range) LNAPL source. LNAPL contamination was present in the unsaturated zone at depths between about 1 and 5 ft (0.3 and 1.5 m) below a small warehouse-type building with a slab-on-grade foundation. Monitoring of subslab soil gas indicated oxygen was depleted (<1 percent) below the interior regions of the building, but not below the edges of the building.

2.5.4 Former Refinery Site (Unknown location) (Luo et al., 2010)

Monitoring at a former refinery site (unknown location) with a building overlying a light distillate (gasoline-range) LNAPL source indicated relatively uniform and elevated (60 to 160 mg/L) PHC vapor concentrations and depleted oxygen beneath and around the building foundation. The building footprint area is 2,100 ft² (195 m²) with a basement depth of 5 ft (1.5 m) bgs. The ground surface is predominantly grass covered, except on one side of the building where there is an asphalt/concrete parking lot. Soils with LNAPLs were first encountered at about 30 to 35 ft (9.1 to 10.7 m) bgs; therefore, the separation distance between the building foundation and contamination (LNAPL) is approximately 25 to 30 ft (7.6 to 9.1 m). Detailed soil respiration and soil-air permeability test results suggest two possible reasons for the observed behavior: 1) significant background oxygen uptake in surface soils and/or 2) physically limited oxygen transport from the atmosphere. Soil oxygen uptake rates in shallow soil ranged from 2 to 25 mg-oxygen/kg-soil/day. There were silt and clay layers between 2 to 5 ft (0.7 to 1.5 m) and 7 to 8 ft (2.1 to 2.4 m) bgs, both with soil-air permeabilities of less than 1 × 10⁻¹⁴ m². The results from Luo et al. (2010) suggest both of these reasons are plausible.

2.5.5 Refinery Site, Hartford, Illinois (Illinois Department of Public Health, 2010)

Monitoring at a refinery site in Hartford, Illinois, with a very large petroleum fuel spill (several million gallons) indicated episodic PVI occurred when there were heavy rain events or a sharp rise in the water table. The vadose zone soils consisted of coarse sand overlain by fine sediments, and the depth to groundwater ranged from 7 to 10 m (23 to 33 ft) bgs.

2.5.6 UST Site, Stafford, New Jersey (Sanders and Hers, 2006)

Monitoring of a house above a residual gasoline LNAPL source at a site with sandy soils indicated PVI of MTBE, 2,2,4-trimethylpentane (TMP), and cyclohexane, but not benzene, toluene, and xylene compounds. The depth to the LNAPL source was 10.75 ft (3.27 m), which was 5.25 ft (1.60 m) below the basement foundation. The source soil vapor concentrations of benzene, 2,2,4-TMP, and MTBE were 0.66 mg/L, 2.1 mg/L, and 5.9 mg/L, respectively. It was inferred that MTBE and 2,2,4-TMP were attenuated to a lesser degree than benzene because of their greater solubility. No PVI was detected at several nearby buildings that were either above the residual LNAPL or dissolved hydrocarbon source.
2.5.7 UST Site, Ogden, Utah, Mini-Mart Release (McHugh et al., 2010)

A large release at a UST site in Ogden, Utah, resulted in free product gasoline floating on shallow groundwater less than 1 m (3.3 ft) below the bottom of the slab. Petroleum odors were reported in a building, which were mitigated by installing a positive pressure HVAC system.

2.5.8 UST Site, Gunnison, Utah, Top Stop Release (McHugh et al., 2010)

A large, sudden gasoline release (20,000 gallons [75,708 L]) occurred at a UST site in Gunnison, Utah. The vadose zone soils consisted of silty sand and gravel overlain by sandy silt, and the depth to groundwater was 4 to 5 m (13 to 16 ft) deep. The soil headspace photoionization detector (PID) readings in the LNAPL source zone were in the range of 100's to 1,000's ppmv. In the first several months after the release occurred, people complained of gasoline odors, and elevated PID readings were reported in several buildings up to 500 m (1,640 ft) from the release site in the direction of groundwater flow.

3. Review of Modeling Studies

Numerous modeling studies of aerobic biodegradation have been conducted to evaluate biodegradation processes, identify factors influencing biodegradation, compare modeled to predicted hydrocarbon vapor attenuation, and estimate first-order biodegradation rates (e.g., Jury et al., 1983; Lahvis and Baehe, 1999; Hers et al., 2000; Ririe et al., 2002; Grauthwol and Maier, 2002; Robinson and Tursczynowicz, 2005; Abreu and Johnson, 2005; Abreu and Johnson, 2006; DeVauil, 2007b; Abreu et al., 2009; Davis et al., 2009; DeVuall, 2011; Hers et al., 2012; U.S. EPA, 2012b).

Modeling studies using representative first-order decay rates indicate that aerobic biodegradation is a rapid, and in some cases, essentially instantaneous process and that attenuation of benzene, toluene, and xylenes vapor concentrations occurs over relatively short distances of a few feet, which is consistent with the observed field data (e.g., Hers et al., 2000; Davis et al., 2009). The biodegradation of aliphatic hydrocarbon compounds is less well studied, but available data suggest bioattenuation distances may be greater for aliphatic hydrocarbons compared with aromatic hydrocarbon compounds (Hers et al., 2012). An important input to modeling studies is the first-order decay rate; a comprehensive compilation of such rates is provided in DeVauil (2011).

The modeling studies reviewed below were selected to provide insight on the vertical and lateral attenuation of PHC vapors and, where possible, the influence of factors such as vapor concentration source strength and layered soil deposits on PHC vapor migration and attenuation.

This review represents a line of evidence that can help inform the development process for exclusion distances.

3.1 Abreu Three-Dimensional Model Simulations

Abreu and Johnson (2005) present the theoretical basis for a three-dimensional model for predicting soil vapor-to-indoor air attenuation factors incorporating subsurface processes of diffusion, gas-phase advection through building depressurization, oxygen-limited first-order
biodecay, and uniform mixing of vapors entering a building. Subsequent three-dimensional
modeling studies of interest are summarized below.

3.1.1 Three-Dimensional Model Simulations—Below-Building Contamination Source and
Homogeneous Soil Conditions

Abreu et al. (2009) presents model simulation results for oxygen-limited aerobic
biodegradation for a scenario where building parameters representative of a residential house and
an unsaturated zone comprising a homogenous sand unit were assumed. The “hydrocarbon”
modeled in this study was assumed to have the same fate and transport properties as benzene.
Oxygen-limited decay was simulated in the aerobic portion of the unsaturated zone (i.e., when
oxygen concentrations exceeded 1 percent). A first-order decay rate of 0.79 h\(^{-1}\) was assumed for
the hydrocarbon (benzene), which is consistent with published rates (e.g., DeVaull, 2011).

Potentially conservative attributes of the Abreu et al. (2009) model simulations include
the following: 1) oxygen transport occurs only through cracks in the foundation and not through
intact concrete; 2) the building is continuously depressurized; thus, no atmospheric air moves
downward into the soil at times when the building is pressurized, for cases where pressure
cycling is a relevant condition, and 3) there is no oxygen recharge through pressure effects
caused by wind and/or atmospheric pressure changes. Potentially non-conservative attributes of
the modeling are primarily that spatially variable soil properties (e.g., moisture, porosity,
permeability) were not considered. Conceptually, there are scenarios where layered systems
consisting of a fine-grained, wet surface soil layer underlain by a coarser-grained, drier soil layer
could increase the potential for oxygen limitations below buildings.

The Abreu et al. (2009) model results are summarized in Figure 2. For context, the
database compiled for this study indicates representative total hydrocarbon vapor concentrations
between 100 and 200 mg/L above gasoline LNAPL distributed above the capillary fringe, and
the approximate lower end of this range likely indicates weathered gasoline sources. For a
dissolved vapor source, the database indicates that the maximum total petroleum hydrocarbon
(THP) vapor concentration measured in vapor was 10 mg/L with >99 percent of the data
indicating THP vapor concentrations less than 1 mg/L.

The model-predicted vapor attenuation factors presented in Figure 2 are highly sensitive
to source hydrocarbon concentrations above 10 mg/L. Below 10 mg/L, the attenuation factors are
relatively constant for a given separation distance. For a source vapor hydrocarbon concentration
representative of weathered gasoline (100 mg/L), the model predictions shown in Figure 3
indicate that a vertical separation distance of 23 ft (7.0 m) or more is required for aerobic
reaction front development within the unsaturated zone; however, the model predictions may be
conservative, as previously discussed.

Abreu et al. (2009) also present a chart that provides representative attenuation factors
that apply to all source hydrocarbon vapor concentrations below 10 mg/L and for a range of
biodegradation rates (Figure 4). There are significant reductions in attenuation factors when
aerobic biodegradation is included, relative to the non-biodegradation case; for example, for a
separation distance of 5 ft (1.5 m), there is an approximate three orders-of-magnitude reduction
in the attenuation factor with biodegradation at a first-order decay rate of 0.79 h\(^{-1}\).

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and should not be construed to represent any Agency determination or policy.
3.1.2 Three-Dimensional Model Simulations—Lateral Migration Scenario and Homogeneous Soil Conditions

U.S. EPA (2012b) presents a modeling study of conceptual model scenarios for the VI pathway where the Abreu and Johnson (2005) model was used for a range of simulation scenarios, including oxygen-limited aerobic biodegradation of PHC compound vapors (using benzene as a surrogate for TPH). The building assumptions in U.S. EPA (2012b) are similar to those described in Abreu et al. (2009). One of the scenarios evaluated was the influence of PHC source and building lateral separation distance on the predicted vapor attenuation factor. The simulations were conducted for a TPH vapor concentration of 200 mg/L, a 2-m (6.6 ft) deep basement, two contamination source depths (3 m and 8 m [9.8 ft and 26 ft] bgs), and a range of first-order decay rates (0.018, 0.18, and 1.8 h\(^{-1}\)). The predicted vapor attenuation factors decrease rapidly as the lateral distance increases. For example, the vapor attenuation factor for a shallow LNAPL source that is offset approximately 15 ft (4.6 m) from the edge of the building is \(1 \times 10^6\) for a decay rate of 0.018 h\(^{-1}\) and less than \(1 \times 10^{-10}\) for a decay rate of 0.18 h\(^{-1}\). The vapor attenuation factor for a shallow below-building LNAPL source and same biodecay rate is approximately \(1 \times 10^3\). A key point is that there is greater attenuation, and hence lower vapor attenuation factors, for the lateral compared with vertical building-contamination source separation scenarios.

Another key point is that currently almost nobody collects vertical profiles of soil vapor concentrations below buildings. Should this be incorporated into the new PUI screening protocol? If not, why not?

3.1.3 Three-Dimensional Model Simulations—Surface Capping Scenario

U.S. EPA (2012b) also presents aerobic biodegradation modeling simulations of the influence of variable soil moisture and layered soil deposits, including a two-layer capping scenario with a 1-m (3.3-ft) thick surface soil layer with higher moisture content (60 percent saturation) underlain by a soil layer with a lower moisture content (20 percent saturation). The hydrocarbon source for these simulations was located at 8-m (26-ft) depth, below a house with a 2-m (6.6-ft) deep basement. For a high source hydrocarbon vapor concentration (200 mg/L), the attenuation factor predicted for the two-layer scenario was one order of magnitude greater than the single-layer scenario (Table 2). For a lower source vapor concentration (2 mg/L), the vapor attenuation factor for the two-layer scenario was \(7.1 \times 10^{-15}\). Although a single-layer simulation was not performed for the lower source strength, the two-layer scenario attenuation factor is very low and indicates essentially complete biodegradation, and the cap had no effect on the hydrocarbon vapor attenuation below the building.

3.1.4 Comparison of Modeled to Measured Soil Vapor Concentration Data

The three-dimensional model predictions of vertical profiles of hydrocarbon vapor and oxygen concentrations showed good agreement between measured and modeled data for three sites evaluated by Abreu and Johnson (2006). The estimated first-order biodegradation rate for these studies ranged between 0.18 and 0.4 h\(^{-1}\). The three-dimensional model was also applied to compare measured and modeled hydrocarbon vapor concentrations for the former refinery site (unknown location), described in Section 2 of this report (Luo et al., 2010). A good comparison was obtained when the model incorporated site-specific conditions (a surface soil layer of low diffusivity and low soil-air permeability), but when generic (homogeneous) soil conditions were assumed, the model was not conservative and under-predicted the measured concentrations by a
factor of approximately 100. The first-order rate incorporated in the Luo et al. (2010) model simulations was 0.18 h⁻¹.

3.2 DeVaull (2007b) Study (BioVapor Model Development)

DeVaull (2007b) presents the theory and model simulation results for a subsurface soil vapor-to-indoor air chemical PVI model that includes oxygen-limited biodegradation (the model described is the basis for the BioVapor model [American Petroleum Institute (API), 2012]). The processes simulated by the algebraic model are one-dimensional upward diffusion and aerobic biodegradation of chemicals in a homogeneous subsurface soil layer and mixing of vapors within a building enclosure. The soil is divided into a shallow aerobic layer where first-order decay is assumed to occur and a deeper anaerobic layer in which biodegradation does not occur because of oxygen limitations. The boundary between the aerobic and anaerobic zones is determined iteratively to match oxygen demand to oxygen supply.

The model results indicate that vapor intrusion of PHCs can be significantly less than indicated by estimates that neglect biodegradation. A model sensitivity analysis using specified ranges of scenario parameters showed a high degree of sensitivity to oxygen availability, soil properties, and biodegradation rates. The attenuation factor varied by more than nine orders of magnitude about a specified attenuation factor of 1 × 10⁻⁵; however, the corresponding variation in contamination source to foundation separation distance was within only a factor of approximately three. A conclusion drawn by Devaul (2007b) is that identifying a distance where PVI is unlikely to occur is a more robust screening tool than an attenuation factor for PHC compounds.

Favorable comparison of the one-dimensional model to the three-dimensional results of Abreu and Johnson (2005) is shown in Devaul (2007b). With matched model parameters, both models show similar estimates of indoor-to-subsurface source vapor concentrations and similar sensitivities of both attenuation factor and exclusion distance to changes in model parameters.

3.3 DeVaull (2010) Study of BioVapor Application

DeVaull (2010) presents BioVapor model simulations where the sensitivity of the model predictions was evaluated for a residential house scenario, dissolved gasoline source concentrations, and a hydrocarbon vapor source–building separation distance of 5 ft (1.5 m). The model simulations, in part, were designed to provide insight on the applicability of the dissolved-source exclusion distance of 5 ft (1.5 m) proposed by Davis et al. (2009). The source groundwater concentrations were 1 mg/L benzene and 3 mg/L each for toluene, ethylbenzene, and xylenes, for a total benzene, toluene, and xylene source concentration of 10 mg/L. The source vapor concentrations were estimated from the Henry’s Law constant and a groundwater-to-source vapor attenuation factor of 0.1, resulting in source benzene and total benzene, toluene, and xylene vapor concentrations of 12 mg/m³ and 120 mg/m³, respectively. The oxygen mass transfer to below the building, a key model input parameter for the BioVapor model, was estimated from 13 studies where the soil gas advection rate and/or diffusive oxygen mass transfer rate were measured for small buildings.

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Devauill (2010) presents model-predicted indoor air concentrations as a function of the effective foundation airflow rate, which is conceptually easier to understand than the oxygen mass transfer rate (Figure 5). For modeling purposes, the foundation airflow rate is converted to an oxygen mass transfer rate. The model predicts low indoor air benzene concentrations (less than 1 µg/m³) for the range of effective foundation airflow rates considered. It is also instructive to note that the model results for recalcitrant non-degrading chemicals show an opposite trend in that the indoor air benzene concentration increases as the effective foundation airflow rate increases.

3.4 Summary of Modeling Studies

The results of the modeling studies cannot be directly correlated to distances (or exclusion distances) where PV1 is unlikely to occur but for dissolved vapor sources they indicate very low attenuation factors and negligible potential for a complete PV1 pathway, including a modeling scenario where a surface capping effect was simulated.

For LNAPL vapor sources, the Abreu et al. (2009) three-dimensional model simulations for a residential house scenario and homogeneous soil conditions predict that a vertical separation distance of 23 ft (7.0 m) or more is required for aerobic reaction front development within the unsaturated zone. The modeling results for smaller separation distances and an LNAPL source indicated the attenuation factor calculated by the model is sensitive to a surface capping effect. I'm not aware of any field data to show the surface capping effect and the model input was not validated.

The modeling results indicate further evaluation of factors potentially influencing oxygen supply and demand, such as source vapor concentration strength, building size, surface foundation and soil layer properties, and natural soil oxygen demand, is warranted for the LNAPL source scenario.


Three published studies that analyze empirical data on PHC vapor attenuation are summarized below.

Davis (2009) obtained soil gas data from 53 geographical locations in the United States and Canada and from an analysis of 259 benzene and 210 TPH samples and then estimated that 5 ft and 30 ft (1.5 m and 9.1 m) of vertical thicknesses of clean soil are required to significantly attenuate benzene and TPH vapors emanating from the dissolved-phase and LNAPL sources, respectively. Dissolved-phase sites were defined on the basis of benzene concentrations in groundwater < 1,000 µg/L. The data obtained by Davis (2009) are incorporated in this study.

Peargin and Kolhatkar (2011) evaluated 218 pairs of benzene soil vapor and groundwater concentration data from 25 sites. Data were categorized in bins based on 10⁻² to 10⁶ excess cancer risk and assuming a soil vapor-to-indoor air attenuation factor of 0.01 (U.S. EPA, 2002). No benzene soil gas concentrations exceeding 300 µg/m³ (risk-based air concentration for 10⁻³ cancer risk multiplied by 0.01) were observed at vertical separation distances greater than 15 ft (4.6 m). Benzene soil vapor concentrations exceeding 300 µg/m³ were only observed above...
groundwater sources where benzene concentrations exceeded 1,000 μg/L. The authors concluded that the data support a CSM where benzene vapor transport at concentrations exceeding target screening values can only occur where groundwater source concentrations are high, defined for this study as a dissolved benzene concentration greater than 1,000 μg/L. Some of the data analyzed by Peargin and Kolhatkar (2011) that were provided to Davis (2009) are incorporated in this study. The remaining Peargin and Kolhatkar (2011) data were not readily accessible during the time frame of this study.

Wright (2011) presents data from 124 sites in Australia. There are 1,080 pairs of benzene soil vapor and groundwater concentration data; 41 percent of the data were obtained at sites with fractured rock aquifer systems and 12 percent represent data obtained below building foundations (i.e., subslab). The analysis resulted in vertical exclusion distances of 5 to 10 ft (1.5 to 3.0 m) for relatively “low-strength” dissolved-phase sources (benzene < 1 mg/L and TPH < 10 mg/L), and ~30 ft (~10 m) for LNAPL and poorly characterized dissolved-phase sources (including sites with large building slabs). The lower threshold benzene and TPH soil vapor concentration for estimating the exclusion distances was based on 5 percent of the lowest Australian Health Screening Levels (Friebel and Nadebaum, 2011). None of the Australian data analyzed by Wright (2011) were incorporated in this study but are analyzed by Lahlis et al. (in prep). A preliminary analysis of the Australian data suggested that the conclusions of the empirical analysis would not change if the Australian data were included; therefore, the data were not incorporated into this study.

5. Review of Exclusion Distances in Existing Vapor Intrusion Guidance

Most regulatory approaches identify distances for determining when a PVI assessment is not warranted—defined as “exclusion distances” in this report, although guidance on vertical and lateral exclusion distances for PHCs based on detailed evaluations of empirical data and/or modeling studies is a recent development.

Most states exclude sites from the need for VI assessments if they are more than a specified distance from the source of vapor contamination, which generally is the 100-ft (30-m) lateral distance, although guidance for New Hampshire, New Jersey, Connecticut, and Massachusetts includes a 15- to 30-ft (4.6- to 9.1-m) exclusion distance for aerobically biodegradable chemicals. The technical justification for the exclusion distance criteria is relatively limited or not provided in guidance by these jurisdictions.

Several states are in the process of developing or have recently developed guidance for PHCs based on a pathway exclusion distance approach. Guidance from New Jersey, California, and Wisconsin is summarized below. Specifically:

- The New Jersey Department of Environmental Protection (NJ DEP, 2012) recommends a PVI investigation based on a 30-ft (9.1-m) critical distance criterion for PHC-related groundwater contamination and a 100-ft (30-m) criterion for PHC-

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1 The U.S. EPA’s 2002 Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils specified vertical and lateral exclusion distances of 100 ft (30 m), based on empirical observations of the approximate distance from the interpolated edge of chlorinated solvent plumes where indoor vapor detections were observed; this guidance did not address vapor intrusion from petroleum releases.

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related free product contamination. As an alternative approach, NJ DEP (2012) allows for an exclusion distance approach based on benzene concentrations for gasoline contamination. A PVI investigation is not necessary if the vertical separation distance between the water table (all references to water table are for seasonal high conditions) and building slab is:

- At least 10 ft (3.0 m), for a benzene groundwater concentration \( \leq 1,000 \mu{g/L} \);
- At least 5 ft (1.5 m), for a benzene groundwater concentration \( \leq 100 \mu{g/L} \); or
- At least 5 ft (1.5 m), for oxygen \( \geq 2 \) percent (v/v) in the unsaturated zone, and a benzene groundwater concentration \( \leq 1,000 \mu{g/L} \).

The gasoline exclusion criteria apply only when all of the following four conditions exist: 1) the building is relatively small, 2) the area around the building is not extensively paved, 3) clean soil exists between the water table and the building, and 4) NAPL is not present within 30 ft (9.1 m) of the building (vertically and horizontally) (see NJ DEP [2012] for additional details).

- The California EPA (2011) presents an exclusion distance approach to managing retail petroleum sites, characterized as a “low-threat” closure scenario. The exclusion distances were based on a review of empirical data (primarily Lahvis [2011] and Davis [2009]) and modeling studies (primarily Abreu et al. [2009]). Four scenarios are defined each with benzene exclusion distance criteria as follows:

  - **Scenario 1—Unweathered LNAPL on groundwater:**
    - A 30-ft (9.1-m) vertical bioattenuation zone between an unweathered LNAPL (residual or free-phase) source and a building foundation.

  - **Scenario 2—Unweathered LNAPL in soil:**
    - A 30-ft (9.1 m) lateral and vertical separation distance between an unweathered LNAPL (residual or free-phase) source in soil and a building foundation.

  - **Scenario 3—Dissolved phase benzene concentrations in groundwater:**
    - With no oxygen measurements:

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- A 5-ft (1.5 m) vertical separation distance between a dissolved-phase benzene source < 100 µg/L and a building foundation.

- A 10-ft (3.0 m) vertical exclusion distance for a dissolved-phase benzene source < 1,000 µg/L and a building foundation.
  - With oxygen > 4 percent:
    - A 5-ft (1.5 m) vertical separation distance between a dissolved-phase benzene source < 1,000 µg/L and a building foundation.

- Scenario 4—Direct measurement of soil gas concentrations:
  - Application of a bioattenuation (additional attenuation) factor of 1,000 times to risk-based soil gas criteria (i.e., vapor sources) located within 5 ft (1.5 m) of a building foundation.

- Wisconsin's Department of Natural Resources (2010) in their guidance states that where no petroleum odors are detected, PVI can be ruled out at most petroleum release sites with low source concentrations where there is 5 ft (1.5 m) in the horizontal and vertical direction of clean, unsaturated soil with an oxygen content greater than or equal to 5 percent between the residual petroleum and the building. Larger exclusion distances are specified when free product is present (30 ft [9.1 m]) or benzene concentrations in groundwater exceed 1 mg/L (20 ft [6.1 m]). When the above distance thresholds and other criteria (e.g., no preferential pathways, no fractured bedrock) are met, a PVI assessment is not required.

6. Database Development, Structure, and Content

6.1 Database Development and Checking

The starting point for the PVI database developed for this study is a database compiled by Ms. Robin Davis of the State of Utah (the “Davis” database). Ms. Davis compiled data on PHC vapor behavior from over 50 sites starting in 2003; the May 2011 version of the Davis database
was imported and used for this analysis. The Davis database includes information on primarily groundwater and soil vapor chemistry, soil properties, and other site data.

The Davis database was imported into Microsoft Access and then exported into a working Microsoft Excel spreadsheet to enable data checking, addition, and analysis. The original Davis database was expanded by adding new data fields to describe the data types needed to meet the objectives of this study. The data were checked against the original data (e.g., reports, journal articles) when available, and all available references are included as electronic files linked to the database. Additional data were also added to the database, such as the comprehensive data on 11 Maine sites made available from Peter Eremita of the Maine Department of Environmental Protection (Maine DEP).

Once the checks and additions were complete, the Excel spreadsheets were re-imported into the Access database and checked and cleaned for consistency and accuracy of import using queries and manual checks. The final Access database is available as an attachment to this report, along with spreadsheet outputs of the basic data used in the data analysis.

6.2 Database Structure

The tables and fields in the PVI database and a comprehensive data dictionary and entity relations diagrams are provided in Appendices A and B, respectively. An Excel spreadsheet was designed to facilitate evaluation, analysis, and presentation of data relations in the PVI database and was used to perform the analyses described in this report. Filters were added for most data fields, enabling screening of data based on site conditions and other applicable attributes.

The different data types are summarized as follows:

- **Background data**: Site location, geologic setting, contamination type, and generic soil description.
- **Facility type**: UST, fuel terminal, petroleum refinery, and petrochemical plant.
- **Site conditions**: Soil type, water-filled and total porosity, and surface cover at soil vapor probe (bare ground, asphaltic pavement, building).
- **Sampling data**: For each probe, vertical depth from ground surface to water table, to top of contamination, and to media sampling locations. Lateral distance between soil gas probe and groundwater monitoring well and between soil gas probe and UST facility infrastructure (e.g., tanks, fuel dispensers) and buildings.
- **Analytical data**: Sampling date, analytical method, quality control data, and chemistry data for soil, groundwater, and soil vapor. Analytes in the database are fixed gases (oxygen, carbon dioxide, methane); benzene, toluene, and xylene; TPH; naphthalene; MTBE; 1,3-butadiene; hexane; heptane; and aromatic and hydrocarbon fractions according to methods prescribed by the State of Massachusetts.
- **Building data**: Building use (e.g., residential, commercial, institutional), foundation type, and building size, for example.

*Probe design, purging procedure, soil gas permeability and leak-check procedures

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As part of the data verification process, certain data quality indicators were reviewed to ensure data of known and acceptable quality. The database was processed to remove data of unacceptable quality or type, as follows: 1) analytical data obtained by unacceptable methods, or no reported methodology or evidence of quality assurance/quality control processes, to remove suspect quality data; 2) soil gas data from fractured rock systems due to the potential for preferential soil gas flow; 3) benzene concentrations in groundwater below detection level because it is not meaningful to conduct an analysis when no contamination source exists, and 4) lateral spacing between groundwater monitoring well and soil gas probe (for paired data) greater than about 30 ft (9.1 m) because of variability in sources (this information was not available for all data).

The following analytical methods for hydrocarbon compounds were considered acceptable: EPA Method TO-15, EPA Method TO-3, Modified EPA 8260, and Massachusetts Air Phase Hydrocarbons. The following analytical methods for fixed gases were considered acceptable: ASTM D1946 and EPA Method 3C. Note that because Ms. Davis performed these checks for the data imported from the Davis database, these checks were not repeated for this analysis, but some spot-checks were made.

As part of the database development process, it was considered whether data should be screened out based on the presence/absence of probe leak tracer test results. Given that a significant proportion of the data are older data for which no leak tracer was conducted, or leak tracer testing was not reported, this criterion was not adopted for data screening; however, it should be noted that much of the recent data include leak tracer test data.

### 6.3 Database Content

The number of sites and site locations in the PVI database are listed in Table 3. The contents of the database for key fields are summarized in Tables 4 and 5. The majority of the sites are UST release sites, although the database also includes data from fuel terminals and petroleum refineries. Most sites were affected by gasoline releases, although a small number of sites have other types of PHC contamination (e.g., diesel, kerosene). The gasoline composition was unknown and assumed to be variable with respect to fuel oxygenate composition, given the relatively broad time span for data collection (1995 to 2011). Gasoline containing ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large increase in use in 2006 (U.S. EPA, 2009), so some sites in the database where recent releases occurred likely have gasoline containing ethanol.

Subslab vapor samples were obtained at 38 sites with buildings. Almost all buildings in the database were residential houses or smaller commercial buildings (Table 3 includes the building footprint area when available). At a few sites, soil vapor samples were obtained from below and beside a building.

The database is populated to varying degrees depending on the data type. It contains data for most sites and records on facility type, vertical distances, surface cover, soil type, and benzene and TPH vapor concentrations. Groundwater benzene and TPH concentration data are also available for many sites, and the database also includes data on fixed gases for a majority of the sites. For the other analytes listed above (e.g., toluene, ethylbenzene, xylenes, naphthenes).
the database includes data for fewer sites, although the data set for aromatic and aliphatic
hydrocarbons is substantial because recent data from 11 Maine sites are included. Although
indoor air data are included for a limited number of sites, indoor air data were not used in the
analysis because of the limited number of data points and the known effect of background in
introducing bias in soil vapor-to-indoor air attenuation factors for PHC compounds.

Key statistics on the quantity of records in the database are:
- Number of benzene soil vapor records = 879
- Number of oxygen soil vapor records = 645
- Number of records with paired benzene soil vapor and groundwater data = 823

Additional information on each site in the database is provided in Tables 4 and 5 and in
the database itself. Many of the original sources of the data in the database (e.g., reports, journal
articles, figures, data tables) are referenced and linked in the database to a full set of electronic
document files organized by site.

7. Database Analysis Approach and Methods

The data analysis began with an evaluation of whether the soil gas data at the site were
obtained in an area of LNAPL or dissolved-phase groundwater contamination. Given the
importance of the contamination source type on soil vapor concentrations, the analyses were
conducted separately for the LNAPL and dissolved sources. The data analysis consisted of three
main parts:

1. Exploratory data plots, discussed in Section 7.1.1;
2. Estimation of vapor concentration attenuation distance using the “vertical distance
   method,” discussed in Section 7.1.2 developed for this analysis; and
3. Estimation of non-contaminated vertical soil thickness needed for concentration
   attenuation using the “clean soil method,” discussed in Section 7.1.3, developed by
   Davis for her database.

The source zone identification and three data analysis methods are described below.

7.1 Source Zone Identification Methods (LNAPL versus Dissolved Indicators)

Several indicators were adopted for identifying whether the soil gas probe was located in
an area of LNAPL or dissolved-phase contamination (Table 6).

The primary indicator is direct evidence of LNAPL, such as a sheen or product in a
nearby monitoring well, borehole logs indicating a sheen or significant hydrocarbon staining in
soil, or when the author of the site investigation report indicated the soil gas probe was installed
in an LNAPL source zone. This was the determining factor for approximately 80 percent of the
sites identified as having LNAPL contamination.

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The thresholds adopted for identifying LNAPL sites are a benzene soil concentration of 10 mg/kg and a TPH (gasoline) soil concentration of 250 mg/kg. The benzene concentration (10.7 mg/kg rounded down to 10 mg/kg) was estimated from the equation for soil saturation ("C_sat") and the default input parameters in Exhibit 9 of the U.S. EPA Soil Screening Guidance (U.S. EPA, 1996). A TPH soil concentration of 250 mg/kg was adopted to provide a slightly more conservative screening basis (i.e., more sites are included as dissolved sites with higher thresholds) than the ranges reported in the literature cited above. An LNAPL source site was identified on the basis of either the benzene or TPH soil concentration exceeding the threshold.

7.1.3 Proximity to Fuel Storage/Dispensing Facilities

Soil gas probes located near or within former UST fields or fuel dispenser areas are considered to have a higher probability of being within LNAPL zones, and, therefore, were categorized as within LNAPL source zones. A threshold distance of 20 ft (6.1 m) was selected to approximately correspond to the exclusion criteria distance that was estimated for LNAPL sites, as described in Section 8 of this report (i.e., a screening distance greater than the exclusion distance would not be appropriate).

For soil gas probes located near USTs or dispensers there is also greater potential for soil contamination within the vadose zone, which confounds the estimation of clean soil thicknesses for exclusion distances. When available, borehole logs and other information were reviewed to determine the depth to contamination to improve the accuracy of the estimation process. Fifteen sites included data for soil gas probes that were within 20 ft (6.1 m) of USTs or dispensers. A data flag identifying such probes was included so these data could be filtered, if desired.

7.2 Data Analysis Methods

The data analysis consisted of three main parts:

1. Exploratory data analyses to evaluate data trends and relations between different media (e.g., groundwater versus soil gas) and analytes (e.g., hydrocarbon versus oxygen),

2. Plots of benzene and other hydrocarbon soil vapor concentrations versus the vertical separation distance of the vapor probe above the contamination source ("vertical distance method"), and

3. Estimated thickness of un-impacted soil for benzene vapors to attenuate to below a threshold ("clean soil method"). This technique required establishing rules for data interpolation.

The analysis focused on benzene given its importance for risk evaluations; however, it was also performed for select other compounds, including those analyzed at the Maine sites where full-spectrum hydrocarbon analyses are available (e.g., hexane, aliphatic and aromatic fractions).
Given that the database was set up to allow for filtering, the influence of site type (UST, fuel terminal, petroleum refinery), soil properties, presence or absence of buildings, and other factors was evaluated.

### 7.2.1 Exploratory Data Analysis

The exploratory data analysis involved evaluating the relations between groundwater and soil vapor concentrations, and oxygen and hydrocarbon concentrations to assess whether there were thresholds for minimum concentrations where aerobic biodegradation readily occurs (Davis et al., 2009; Sweeney, 2012). The rationale for this analysis is described in Section 8.1.

### 7.2.2 Vertical Distance Method

The vertical distance method involved plotting soil vapor concentration versus distance above a source and estimating either statistically the soil vapor concentrations or the probability for the soil vapor concentration to be less than a concentration threshold for variable distances above the contamination source. The conditional probabilities were estimated as follows:

\[ P \left(C_v \leq C_{\text{threshold}} | z > d, \text{Contamination (}z = 0) = \text{LNAPL or dissolved}\right) \]

where \(C_v\) is the soil vapor concentration, \(C_{\text{threshold}}\) is the soil vapor concentration threshold, \(z\) is the vertical direction, \(d\) is the vertical distance from the top of the contamination to the soil gas probe, and source contamination is characterized as either an LNAPL or dissolved source.

The data were sorted in a cumulative distribution of specified vertical separation distances from the source (e.g., \(\geq 0\), \(\geq 2\), \(\geq n\) ft). The conditional probabilities were calculated for two different benzene vapor concentration thresholds (50 or 100 \(\mu\)g/m\(^3\) for benzene) using two different methods:

1. Probability \(P = N \left[ C_v < C_{\text{threshold}} \right] / N \left[ \text{total} \right] \) where \(N \left[ C_v < C_{\text{threshold}} \right] \) is the number of benzene vapor concentrations less than the threshold and \(N \left[ \text{total} \right] \) is the total number of concentration measurements; for this analysis, concentrations below the reporting limits were replaced with half the reporting limit, a common first approximation for non-detect measurements.

2. Probability was estimated from the concentration distribution calculated by the non-parametric Kaplan-Meier method (Kaplan and Meier, 1958).

Approximately 31 percent and 57 percent of benzene soil vapor concentrations associated with LNAPL and dissolved-phase sources, respectively, were non-detects, i.e., below specified reporting limits. The Kaplan-Meier method is a robust, non-parametric method for considering data below reporting limits, particularly when there are multiple reporting limits (Helsel, 2005; 2006).

The next step was to estimate the depth to contamination, which is important for an accurate estimation of the thickness of un-impacted soil needed for attenuation of soil vapor concentrations. For LNAPL sites, this depth was estimated from boring logs and indications of LNAPL zones (e.g., observations of product, high headspace organic vapor concentrations above...
500 to 1,000 parts per million (ppm), and soil chemistry data); in the absence of data, the depth to contamination was assumed to be the seasonal high water table. For dissolved sites, the depth to contamination was the depth to the water table closest to the time the soil gas data were obtained.

7.2.3 Clean Soil (Davis) Method

The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of unimpacted clean soil required for soil vapor benzene concentrations to attenuate to below a defined threshold, which for this analysis is 100 µg/m². The purpose of conducting this analysis was to enable comparison to published exclusion distances based on this method previously reported by Davis (2009; 2010). A clean soil thickness was calculated except when the vertical distance between soil gas probes was greater than 10 ft (3.0 m), because there is insufficient resolution (i.e., spacing between probes) for meaningful estimation of the thickness when the vertical distance between probes is greater than about 10 ft (3.0 m). Two methods were used to estimate the clean soil thickness:

- **Method A:** Distance to first soil gas probe with benzene C<sub>vapor</sub> < 100 µg/m<sup>2</sup> where:
  - Lower depth = D<sub>L</sub> = Depth to top of contamination
  - Upper depth = D<sub>U</sub> = Depth to first probe with benzene C<sub>vapor</sub> ≤ 100 µg/m<sup>3</sup>
  - Distance = D<sub>L</sub> - D<sub>U</sub>

- **Method B:** Interpolated distance to between a soil gas probe with benzene C<sub>vapor</sub> > 100 µg/m<sup>3</sup> and a soil gas probe with C<sub>vapor</sub> < 100 µg/m<sup>2</sup> where:
  - Lower depth = D<sub>L</sub> = Depth to top of contamination
  - Upper depth = D<sub>U</sub> = Interpolated as halfway between the depths to a probe with benzene C<sub>vapor</sub> ≤ 40 µg/m<sup>3</sup> and C<sub>vapor</sub> > 100 µg/m<sup>3</sup>; however, if the lower concentration is greater than 40 µg/m<sup>3</sup>, then D<sub>U</sub> = depth to first probe with benzene C<sub>vapor</sub> ≤ 100 µg/m<sup>3</sup>
  - Distance = D<sub>L</sub> - D<sub>U</sub>, subject to minimum thickness of 0.5 ft (0.2 m) because the semi-log plot of benzene vs. distance fitted a straight line for the scope of the data collection.

For both Methods A and B, benzene concentrations below reporting limits were replaced with half the reporting limit. A lower concentration threshold was considered warranted for Method B because of the potential for the halfway distance interpolation to be non-conservative when the lower concentration is much greater than 100 µg/m<sup>3</sup> (which is often the case) and the upper concentration is just less than 100 µg/m<sup>3</sup>. The 40 µg/m<sup>3</sup> threshold is subjective, but when the upper benzene vapor concentration is less than this threshold, the halfway interpolation method is more accurate. Although more complicated and possibly more accurate interpolation rules could have been developed, Method B was intended as a simple, approximate method.

For locations where the measured soil vapor benzene concentration does not attenuate to less than < 100 µg/m<sup>3</sup>, a clean soil thickness cannot be calculated, but a minimum clean soil...
thickness (i.e., greater than) is reported as the distance between the shallowest soil gas probe and the top of contamination.

An example calculation of clean soil thicknesses and exclusion distances is presented in Figure 6. For the Area 1A soil gas probe profile, the Method A and B distances are 11 ft (3.4 m) and 9 ft (2.7 m), respectively. For Site D, the benzene concentration in the shallowest probe is greater than 100 µg/m³ in the shallowest probe; therefore, the clean soil thickness is identified as greater than 11 ft (3.4 m) in the database.

7.3 Soil Vapor Concentration Thresholds

An important part of the analysis was defining a soil vapor concentration threshold when soil PVIs would typically not be of potential concern. The concentration threshold was based on the expected attenuation in vapor concentrations between shallow soil vapor and indoor air, and the toxicity of the chemical under consideration.

The processes that affect the vapor concentration in indoor air for a shallow soil vapor source are primarily soil gas advection and ventilation and mixing of the chemical within the enclosed space (Hers et al., 2003; Johnson, 2005), although some additional biodegradation and sorption could also occur between a shallow vapor source and an indoor environment. Several modeling studies provide insight on the attenuation factor for a typical residential house. Yao et al. (2011) reported attenuation factors between \(2 \times 10^{-4}\) and \(7 \times 10^{-3}\) for a numerical modeling study. Johnson (2005) in a modeling study using the Johnson and Ettinger (1991) model calculated attenuation factors between \(4.4 \times 10^{-3}\) and \(7.3 \times 10^{-3}\) for a shallow soil vapor source and representative input parameters for a residential house. A similar study by Hers et al. (2003) included a sensitivity analysis where the maximum attenuation factor for a range of conditions was \(9 \times 10^{-3}\) and a relatively good comparison (within an order of magnitude) was obtained between Johnson and Ettinger model predictions and measured attenuation factors for chlorinated solvent chemicals. Although this comparison is for chlorinated solvent chemicals, it is relevant here because it identifies typical attenuation factors between shallow or subslab vapor and indoor air, irrespective of possible biodegradation processes.

The U.S. EPA database of empirical vapor attenuation factors (U.S. EPA, 2012a) is another information source, although selection of a representative attenuation factor was challenging. This is because the empirical attenuation factors vary over several orders of magnitude, due to the variability in both indoor air and subslab vapor concentrations, and background sources of chemicals in indoor air.

The U.S. EPA database 50th and 95th percentiles of the subslab attenuation factor are \(5.0 \times 10^{-3}\) and \(1.8 \times 10^{-1}\), respectively, for the data set limited to indoor air concentrations above the 90th percentile literature background concentration. For the data set filtered based on subslab vapor concentrations greater than 100 times the literature background, the 50th and 90th percentiles of the subslab attenuation factor are \(2.5 \times 10^{-3}\) and \(2.0 \times 10^{-2}\), respectively. Based on the above review, a shallow soil vapor-to-indoor air attenuation factor of 0.01 was considered a reasonably conservative factor for the analysis.

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Risk-based indoor air concentrations for a residential scenario are provided in Table 7 for the chemicals of potential concern considered in this analysis. The risk-based indoor air concentrations assume a residential scenario, continuous life-time exposure to vapors, and no exposure amortization. For chemicals other than benzene, a risk-based soil vapor concentration (RBC,) was calculated as 100 times the risk-based air concentration. The thresholds adopted for benzene, 50 and 100 \( \mu \text{g/m}^3 \), were based primarily on practical considerations relating to the detection limit (i.e., the frequency of non-detects increases as the benzene concentration decreases). For comparison, assuming an attenuation factor of 0.01, the calculated benzene threshold is 29 \( \mu \text{g/m}^3 \) for an incremental lifetime cancer risk (ILCR) of \( 1 \times 10^{-6} \), and 290 \( \mu \text{g/m}^3 \) for an ILCR of \( 1 \times 10^{-7} \).

8. Database Analysis Results

8.1 Exploratory Data Analysis

The cumulative distributions of benzene concentrations in groundwater are plotted in Figure 7 for hydrocarbon sources classified as dissolved phase and LNAPL. The groundwater benzene concentrations for LNAPL sites are higher than for dissolved sites, but for a proportion of the LNAPL site data, there are relatively low benzene groundwater concentrations. This may be due to spatial variability in groundwater concentrations, highly weathered residual-phase LNAPL that is relatively depleted of benzene, variable well screen intervals relative to the water table, and vadose zone LNAPL sources.

The relations between benzene concentrations in groundwater and deep soil vapor probes (within 3 ft [0.9 m] of the contamination source) for dissolved and LNAPL sources are shown in Figure 8. There is no apparent correlation for dissolved-source data, but a weak proportional relation exists between groundwater and soil vapor concentrations for LNAPL source data.

For dissolved-source data, the measured deep benzene vapor concentrations are, in almost all cases, at least an order of magnitude (10 times) and, in many cases 2 orders of magnitude (100 times), less than the predicted soil vapor concentration based on Henry’s Law partitioning. A dimensionless Henry’s Law constant of 0.14 was used for benzene, which is based on a groundwater temperature of 15°C, considered a representative value based on the groundwater temperature map in U.S. EPA (2004).

For the LNAPL source data, the measured benzene vapor concentrations are significantly less than predicted for benzene groundwater concentrations less than approximately 1 mg/L. For concentrations greater than 1 mg/L, the benzene vapor concentrations for some data points are close to the predicted concentrations by Henry’s Law (which is consistent with an LNAPL source and limited attenuation between the source and deep soil vapor sample).

The poor correlation between groundwater and soil vapor concentrations is likely due to 1) variable well screen intervals relative to the water table, 2) variable biodegradation between the groundwater and lowest soil gas sampling location, and 3) spatial variability and differences in dissolved-phase concentrations at groundwater and soil gas sampling locations.

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The relation between co-located oxygen and PHC vapor concentrations has been hypothesized as potentially providing insight on biodegradation processes and a possible lower oxygen limit for occurrence of aerobic biodegradation. The expectation is low oxygen at high hydrocarbon vapor concentrations and high oxygen (near atmospheric) at low hydrocarbon vapor concentrations, excluding sites where there is high natural oxygen demand. The oxygen versus TPH vapor concentration data indicate general trends consistent with expected behavior and notably no data indicating depleted oxygen for dissolved sources, but considerable scatter in the data (Figure 9). For LNAPL sources, the low oxygen concentrations (less than 2 percent) occur when TPH vapor concentrations exceed approximately 1 mg/L. Some data points where oxygen and TPH vapor concentrations are both elevated may be due to the introduction of oxygen during sampling or analysis. Although the data suggest that aerobic biodegradation can occur at low oxygen concentrations (on the order of 1 to 2 percent), of greater relevance for the aerobic depth is the oxygen flux into the soil from the atmosphere and not the lowest oxygen concentration measured in soil.

The database includes methane data for 23 sites. Methane concentrations exceeded 5 percent (lower explosive limit in air) at four sites (three UST sites and one petroleum refinery site), but were less than 1 percent at the remaining 19 sites. There was no apparent correlation between methane and benzene vapor concentrations in this limited data set. Three of the four sites with elevated methane concentrations were investigated prior to 2000, so the methane at these sites was not associated with ethanol in the gasoline leaked into the subsurface.

The relations between benzene and ethylbenzene and benzene and xylenes soil vapor concentrations are shown in Figure 10. As shown, qualitatively there is a relatively good correlation between these two analyte pairs, although for the benzene-xylenes comparison, the xylenes' vapor concentrations for low concentrations are generally up to two orders of magnitude higher than the benzene concentrations.

### 8.2 Vertical Distance Method

For the vertical distance method, soil vapor concentrations (of the PHC compounds listed below) are compared with risk-based vapor concentrations, RBC, (risk-based indoor air concentrations multiplied by 100), and for benzene, the probability that the soil vapor concentration is less than a defined threshold (50 and 100 μg/m³) for varying source-separation distances was estimated. For definition of exclusion distances, a probability greater than 95 percent was considered a reasonable threshold.

#### 8.2.1 All Data

The data analysis was conducted for 1) dissolved sources; 2) LNAPL sources, incorporating data for just UST sites; and 3) LNAPL sources, incorporating data for all facility types (UST, fuel terminal, petroleum refinery, and petro-chemical) (Figures 11 through 15). There are only PHC fraction and hexane data for UST sites; hence, we do not include a figure for the all-LNAPL sites category for these compounds. The following compounds were evaluated:

- benzene, xylenes, hexane, 2,2,4-TMP, and Massachusetts Department of Environmental

It's not really clear why this paragraph is located here, it needs a better topic sentence and tie-in sentence to the findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any agency determination or policy.
Protection (MADEP) hydrocarbon fractions (C9-10 aromatics, C5-8 aliphatics, and C9-12 aliphatics).4

For the benzene analysis, nondetects were addressed both by the common practice of substituting half the detection limit for non-detects and by using the more statistically robust Kaplan-Meier non-parametric method. The Kaplan-Meier method resulted in similar or slightly higher (0 to 7 percent) probabilities than the substitution method. The probabilities the soil vapor concentration being less than a threshold was estimated for 5 and 30 mg/L groundwater concentration thresholds for benzene and TPH, respectively, which are part of the LNAPL hydrocarbon indicators (Table 6). A sensitivity analysis was conducted where the threshold for the benzene groundwater concentration was varied between 1 and 10 mg/L, and the TPH groundwater concentration was varied between 10 and 50 mg/L. The resulting variation in probability (estimated using the substitution method) for this range was less than 0.5 percent, indicating the results are not sensitive to the concentration thresholds (possibly because groundwater is a poor predictor of soil vapor concentrations).

The analysis results show distinct differences between the three scenarios considered (Table 8)5:

1. For dissolved sources, greater than 97 percent and 94 percent of the benzene soil vapor concentrations are less than the specified thresholds of 50 and 100 μg/m3, respectively, for source-separation distances as small as 0 ft (Table 8 and Figures 11 and 12). Comparisons for other compounds evaluated indicate that soil vapor concentrations above risk-based soil vapor concentrations occurred only for separation distances smaller than 3 ft (0.9 m). The analysis indicates there is a low probability of exceeded risk-based thresholds for small separation distances for dissolved sources.

2. For LNAPL sources, the PHC vapor concentrations were plotted against the separation distance between the soil gas probe and hydrocarbon source (Figures 13 through 15). The maximum concentrations of benzene and other hydrocarbon vapor concentrations were several orders of magnitude greater than for dissolved sources, but concentrations of benzene soil vapor concentrations decreased rapidly between 10 and 15 ft (3.0 and 4.6 m) separation distance and for other compounds at smaller separation distances, although it should be noted that the data sets for other compounds are relatively small. For LNAPL sources that are limited to UST sites, approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds (50 and 100 μg/m3) at a source-separation distance of approximately 15 ft (4.6 m), which increases to approximately 30 ft (9.1 m) when all LNAPL facility types are included.

Soil vapor data for 2,2,4-TMP for LNAPL sources (all facility types) were limited (Figure 16). There were elevated 2,2,4-TMP vapor concentrations (0.01 to 10 mg/L) representing data from two sites; at one site, concentrations remained elevated for separation

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4 Naphthalene was not analyzed because soil vapor concentrations are low and below levels of concern based on maximum soil vapor concentrations and expected attenuation between soil vapor and indoor air. The maximum detected naphthalene soil vapor concentrations at any separation distance are 100 μg/m3 for dissolved sources and 180 μg/m3 for LNAPL sources. Conducting an analysis was not meaningful because of the high proportion of nondetects (81 percent for dissolved sources, 86 percent for NAPL sources) and raised detection limits.

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distances as great as 50 ft (15 m). The U.S. EPA IRIS database does not contain toxicity
reference factors for 2,2,4-TMP. Therefore, the number of occurrences of exceedances of risk-based vapor concentrations for larger separation distances, when compared with the other compounds evaluated.

8.2.2 Influence of Surface Cover

The potential influence of a surface cover was evaluated through comparison of the probabilities of benzene soil vapor concentrations that are less than 100 μg/m² for varying soil-separation distances and through analysis of oxygen concentrations for three different surface covers: building concrete foundations, pavement, and bare-ground cover (Figures 17 and 18).
The data sets evaluated were limited to LNAPL sources because oxygen is not limiting for dissolved-source sites.

When all the facility types were considered (which yields the largest data set), the analysis of probabilities for varying soil-separation distances indicated different results depending on surface cover. The probabilities of benzene soil vapor concentrations less than 100 μg/m² were between 5 and 20 percent greater for the ground cover scenario, compared with the pavement and building scenarios, which yielded similar results (Figure 17). The oxygen concentration results were generally consistent with the above probabilities, with no oxygen concentrations below 2 percent for the ground cover scenario (excluding results for zero separation distance); however, several data points indicated oxygen concentrations less than 2 percent for separation distances up to 11 ft (3.4 m).

The above analysis was repeated for just LNAPL sources and UST sites. The results were different in that the probabilities for benzene concentrations less than 100 μg/m² were similar for the ground cover and building scenarios but were between 5 and 20 percent lower for the pavement scenario (Figure 18). The reason for this difference is not known, although it is noted that LNAPL sources and buildings will tend to be smaller at UST sites, compared with petroleum refinery or fuel terminal sites. There was a lower frequency of data points with low oxygen concentrations for UST sites, compared with the analysis where all facility types were considered.

These analyses suggest surface cover type can affect oxygen availability and PHC vapor transport. However, because the vertical distance method evaluation includes soil vapor concentration data from below buildings at 33 UST sites (Table 4), the results are considered sufficiently robust with respect to including the potential influence of surface cover.

8.2.3 Influence of Soil Type

The potential influence of soil type is evaluated through comparison of the probabilities of benzene soil vapor concentrations less than 100 μg/m² for varying soil-separation distances and for two general soil types: fine grained and coarse grained (Figure 19). The probabilities of benzene soil vapor concentrations less than 100 μg/m² were similar for dissolved-source sites for the two soil types. For LNAPL source sites, the probabilities are between 6 and 16 percent.
greater for coarse-grained soils than those for fine-grained soils for small separation distances, but at larger separation distances, there is a reversal in the trend. Based on the analysis, it is not possible to identify if soil type has an influence on benzene soil vapor concentrations and probabilities of exceedances.

If temporary probes were used in fine-grained soil, you'd need to do more to defend the data quality anyway.

8.3 Clean Soil (Davis) Method

The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-impacted clean soil required for soil vapor benzene concentrations to attenuate to below a defined threshold, which for this analysis is 100 µg/m³. As described in Section 7, two interpolation methods were used as part of the estimation process. The results of the analyses are shown in Figures 20 through 22 and can be summarized, as follows:

- For dissolved-source sites, there is no trend relative to dissolved benzene groundwater concentrations, and the 95th percentile clean soil thicknesses (calculated using Excel) for Methods 1 and 2 are 10 ft (3.0 m) and 5.4 ft (1.6 m), respectively.
- For LNAPL (UST-only) source sites, there is an increase in the clean soil thicknesses for benzene groundwater concentrations greater than approximately 5 mg/L. The 95th percentile clean soil thicknesses (incorporating all the data) for Methods 1 and 2 are 13.9 ft (4.2 m) and 13.5 ft (4.1 m), respectively. A small percentage of the data points represent vertical profile data where the shallowest benzene soil vapor concentration is greater than 100 µg/m³; therefore, an attenuation distance could not be calculated (green symbols on Figures 20 through 22).
- For LNAPL (all sites) source sites, there is a similar trend to UST-only sites with respect to clean soil thickness versus benzene groundwater concentrations. The 95th percentile clean soil thicknesses for Methods 1 and 2 are 20.0 ft (6.1 m) and 16.2 ft (4.9 m), respectively. A small percentage of the data points represent vertical profile data where the shallowest benzene soil vapor concentration was greater than 100 µg/m³.

9. Discussion

9.1 Conceptual Site Model and Mathematical Models

The CSM for PHC vapor behavior is the basis for the framework developed for identifying exclusion distances and inclusion criteria. At sites with dissolved PHC contamination in groundwater, aerobic biodegradation is expected to result in the attenuation of PHC vapors, such that there is limited potential for a complete PVI pathway, except for sites with very shallow contamination. For sites with shallow LNAPL contamination, there is greater potential for oxygen limitations below buildings and a complete PVI pathway depending on site conditions. Case studies reviewed suggest that the potential for a complete PVI pathway may exist at non-UST (i.e., petroleum refinery) sites with large-volume LNAPL releases, particularly where there are large buildings or a capping effect based on geologic conditions.

The mathematical modeling studies reviewed, in general, support the empirical analysis in that model simulations for dissolved PHC sources predict very low vapor attenuation factors.
except for small source-separation distances (i.e., less than about 5 ft [1.5 m]). For LNAPL
sources, the modeling simulations suggest hydrocarbon vapor attenuation behavior consistent
with the case studies and empirical data. Although the modeling studies are instructive, there has
been limited evaluation of the range of possible mechanisms for oxygen migration to below
buildings, including diffusive oxygen transport through concrete foundations and processes for
advective soil gas transport, which could be important at LNAPL source sites.

9.2 Methods and Characteristics of the Database

The results of the analysis may be used to derive exclusion distances based on the
probability of benzene vapor concentrations being less than defined thresholds for varying
contamination source-building separation distances and qualitative comparisons of soil vapor
concentrations to risk-based soil vapor concentrations for other compounds. The clean soil
method is an alternative method for defining exclusion distances, but requires interpolation to
avoid overly conservative results. This site-by-site interpolation process introduces uncertainty
particularly for sites where there is poor resolution with respect to vertical concentration
gradients (i.e., from soil gas probes that are too far apart).

The database is representative of a broad range of environmental site conditions, climatic
conditions (including dry areas), soil types, and land-surface covers that may be found at UST
sites. Although the data analysis indicates that the type of surface cover (e.g., building
foundation, pavement, open ground) can have an effect on the attenuation of benzene vapor and
oxygen concentrations, the database includes subslab or vapor data from deeper distances below
buildings for 38 sites with small- to medium-sized buildings. This is considered a sufficiently
large data set, such that exclusion distances derived from the analysis will include the potential
influence of surface cover.

The sites in the database were investigated between 1995 and 2011. Gasoline containing
ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large
increase in use in 2006 (U.S. EPA, 2009). Information on whether gasoline containing ethanol is
present at specific sites is not available in the current database, but some sites in the database
with recent releases likely have gasoline containing ethanol.

The sources of uncertainty associated with the analysis, and for which additional
validation studies should be considered, include the influence of ethanol content in gasoline on
methane generation rates and aerobic biodegradation of PHC vapors (particularly high ethanol
content fuels), sites with extensive high organic matter content soils (e.g., peat) with potentially
high natural oxygen demand, and large buildings where there may be increased potential for
oxygen limitations for certain foundation conditions. Although this analysis included an
evaluation of data for non-UST (e.g., petroleum refinery, fuel terminal) sites, uncertainty about
aerobic biodegradation of PHC vapors remains for larger volume NAPL releases than typically
encountered at UST sites.

Subsurface utilities are commonplace in urban areas, but their presence does not
necessarily equate to a preferential pathway of significance for PVI. However, a utility corridor
that directly connects an LNAPL source and the interior of a building may represent a significant
preferential pathway and is considered an inclusionary factor for PVI assessment. This analysis

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also does not include results for fractured rock unsaturated zone systems between the PHC source and building receptor.

9.3 Data Analysis Results

For dissolved sources, the vertical distance method indicates that the probability of benzene vapor concentrations being less than the defined concentration thresholds (50 and 100 µg/m³) is 94 to 97 percent (Kaplan-Meier statistics) for small source-separation distances (as little as 0 ft), meaning that PVI is unlikely to occur unless a dissolved source is very close to a building foundation. For development of exclusion distances for dissolved sites, allowance should be made for uncertainty in water table elevations due to seasonal variability. For LNAPL sources, the vertical distance method indicates that there is a very low probability of benzene vapor concentrations being less than the defined thresholds at distances less than about 15 ft (4.6 m) when just UST facilities are considered and about 30 ft (9.1 m) when all facility types evaluated are considered.

The data indicate a weak correlation between benzene concentrations in groundwater and deep soil vapor, but for the clean soil method, a trend was observed when the clean soil thicknesses needed for benzene vapor attenuation increased. Dissolved benzene concentrations were above approximately 5 mg/L (i.e., indicative of LNAPL source zones).

9.4 Exclusion Distance Assessment Framework

The assessment framework for vertical exclusion distances requires identification of the PHC source type (dissolved phase or LNAPL) based on a multiple lines of evidence approach similar to that described earlier in this report (see Table 6). This framework could include groundwater concentration thresholds for benzene (and potentially other chemicals) parameters), but given the uncertainty in the relation between groundwater and soil vapor concentrations, this should not be the primary factor for screening sites. Thresholds for soil vapor concentrations (e.g., minimum oxygen thresholds) could also be considered; however, this is not considered mandatory as long as there is sufficient rigor in the site characterization approach to delineate PHC sources and define clean soil zones along with robust methods for identifying LNAPL versus dissolved sites. For sites with dissolved-phase contamination, it will also be important to characterize water table fluctuations in relation to building structures.

An exclusion distance approach for LNAPL sources should also include inclusionary criteria designed to capture sites that fall outside of the findings of the above analysis, including non-UST facilities (related to size of petroleum release), high organic-rich soils (e.g., peat), large building foundations (e.g., associated with apartment complexes or commercial/industrial buildings), and significant subsurface preferential pathways. Future research may indicate certain ethanol contents in gasoline may also warrant inclusion and PVI assessments because of their tendency to generate methane that can interfere with the biodegradation of PHCs.

9.5 Lateral Exclusion Distances

Greater attenuation of PHC vapors is expected when hydrocarbon sources are offset laterally from buildings compared with sources that are directly below buildings. Although the

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modelling studies reviewed for this effort suggest that conceptually similar lateral exclusion
distances could be applied as the vertical distances addressed in this document, from a practical
standpoint, the uncertainty associated with delineating a PHC source near existing or future
buildings warrants larger lateral distances than those suggested based on the analysis for the
dissolved and LNAPL UST-only cases.

9.6 Comparison with Other Studies

Five different PHC data analysis efforts conducted in roughly the same time frame (this
one, Davis [2009], Lahvis et al. [in prep.], Wright [2011], and Peargin and Kolhatkar [2011])
support essentially the same exclusion distances for PHC UST sites, in spite of differences in the
base data analyzed and each study’s approach to the analysis. This suggests an underlying
consistency in mechanisms for PHC biodegradation in the subsurface and supports the
protectiveness of the use of these distances as exclusion criteria for UST petroleum release sites.

10. Conclusions

Approaches for assessing PVI that do not account for aerobic biodegradation processes
are typically highly conservative. The statistical analysis of soil gas data from 70 sites presented
in this study, along with four other similar but distinct efforts, provided an opportunity for
developing improved and more efficient screening evaluation methods for PHC compounds
based on the observed attenuation and an exclusion distance approach, defined as the
contamination source-separation distance at which there is limited potential for a complete PVI
pathway. The focus of this analysis was primarily on characterizing PVI at UST sites with
petroleum fuel releases, although data from other types of sites (fuel terminals, petroleum
refineries) were also considered. Important findings of this study include the following.

1. Knowledge of the PHC source type (dissolved versus LNAPL) and the vertical
   separation distance between the source and receptor (building foundation) is a critical
   factor affecting PVI and is an important metric for site screening.

2. For dissolved sources:
   a. For the vertical distance method, greater than 97 percent and 94 percent of the
      benzene soil vapor concentrations (based on Kaplan-Meier statistics) are less than
      the specified concentration thresholds (50 and 100 μg/m³, respectively) for
      contamination source-building separation distances as small as 0 ft. For other
      compounds evaluated, soil vapor concentrations above risk-based soil vapor
      concentrations only occurred for separation distances smaller than 3 ft (0.9 m).
   b. For the clean soil method (Method B), the 95th percentile vertical clean soil
      thickness for benzene vapor attenuation is approximately 5.4 ft (1.6 m).
   c. The analysis indicates for dissolved sources there is a low probability of
      exceeding risk-based concentrations, for small separation distances.

3. For LNAPL sources and UST sites:

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Therefore, you must also provide guidance on
what methods and scope and QA/QC and criteria are necessary
and sufficient to accomplish this
a. For the vertical distance method, approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds for a source-building separation distance of approximately 15 ft (4.6 m). For other compounds evaluated, soil vapor concentrations above risk-based soil vapor concentrations occurred at smaller separation distances.

b. For the clean soil method, the 95th percentile vertical clean soil thickness for benzene vapor attenuation is approximately 13.5 ft (4.1 m).

4. For LNAPL sources and all facility types considered (UST, petroleum refinery, fuel terminal, and petro-chemical sites), the findings are:

a. For the vertical distance method, over 95 percent of the benzene soil vapor concentrations are less than the thresholds for a source-building separation distance of approximately 30 ft (9.1 m). For other compounds evaluated, soil vapor concentrations above risk-based soil vapor concentrations occurred at smaller separation distances.

b. For the clean soil method, the 95th percentile vertical clean soil thickness for benzene vapor attenuation is approximately 16.4 ft (5.0 m).

5. The data indicate benzene is the risk driver with greater occurrences of exceedances of risk-based vapor concentrations for larger contamination source-building separation distances compared with other compounds evaluated.

6. The data indicate a weak correlation between benzene concentrations in groundwater and soil vapor from deeper distances, but for the clean soil method, a trend was observed where clean soil thicknesses for benzene vapor attenuation increased when the dissolved benzene concentrations were above approximately 5 mg/L.

7. Surface cover type appears to have a weak effect on oxygen availability and PHC vapor transport, and depending on the data set used, either sites with pavement or building surface covers had lower probabilities of benzene concentrations less than 100 μg/m³ for a given source-separation building separation, although these findings are uncertain given the size of the data set and variable results.

Because the vertical distance method evaluation includes soil vapor concentration data from below buildings at 33 UST sites, the results are considered sufficiently robust with respect to including the potential influence of surface cover.

The findings of this study have important implications for improved and more efficient screening methods for PHC compounds based on the observed attenuation in PHC vapor concentrations and an exclusion distance approach. Inclusion criteria or conditions not analyzed in this database, and where more detailed PVI assessment is considered warranted, include non-UST facilities, high organic-rich soils (e.g., peat), large building foundations (e.g., associated with apartment complexes or commercial/industrial buildings), and significant subsurface preferential pathways. Future research may indicate that certain ethanol contents in...
gasoline may also warrant inclusion and PVI assessments because of their tendency to generate methane that can interfere with the biodegradation of PHCs.

11. References


## Table 1. Summary of Case Study Sites with Confirmed or Likely Occurrences of Petroleum Vapor Intrusion

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance LNAPL-Building</th>
<th>Building Size</th>
<th>Source Vapor Concentrations</th>
<th>Facility</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casper, Wyoming (Luo et al., 2009)</td>
<td>1–5 ft (0.3-1.5 m)</td>
<td>2,300 ft²</td>
<td>TPH = 100 mg/L</td>
<td>Refinery</td>
<td>Shallow LNAPL source</td>
</tr>
<tr>
<td>Chatterton (Hers et al., 2000)</td>
<td>5 ft (1.5 m)</td>
<td>610 ft²</td>
<td>TPH = 40 mg/L</td>
<td>Petro-chemical</td>
<td>VI only when DP ~ 10 Pa</td>
</tr>
<tr>
<td>Perth (Patterson and Davis, 2009)</td>
<td>10 ft (3.0 m)</td>
<td>2,700 ft²</td>
<td>TPH = 20 mg/L</td>
<td>Refinery</td>
<td>30-ft (9.1 m) building apron on 3 sides of building</td>
</tr>
<tr>
<td>Unknown (Luo et al., 2010)</td>
<td>25–30 ft (7.6–9.1 m)</td>
<td>2,100 ft²</td>
<td>TPH ~ 60-160 mg/L</td>
<td>Refinery</td>
<td>Capping effect from geology observed</td>
</tr>
<tr>
<td>Hartford, Illinois (Illinois DPH, 2010)</td>
<td>Depth to groundwater ~ 23–33 ft (~7–10 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>Refinery</td>
<td>Very large spill, episodic PVI events when heavy rain or sharp rise in water table</td>
</tr>
<tr>
<td>Stafford, New Jersey (Sanders and Hers, 2006)</td>
<td>5.25 ft (1.6 m)</td>
<td>700 ft²</td>
<td>Benzene = 0.66 mg/L; 2,2,4-TMP = 2.1 mg/L; MTBE = 5.9 mg/L</td>
<td>UST</td>
<td>VI observed for MTBE, 2,2,4-TMP and cyclohexane but not for BTEX</td>
</tr>
<tr>
<td>Ogden, Utah Mini-Mart (McHugh et al., 2010)</td>
<td>3.3 ft (1.0 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>UST</td>
<td>Large release, odors detected in building</td>
</tr>
<tr>
<td>Gunnison, Utah Top-Stop (McHugh et al., 2010)</td>
<td>Depth to groundwater ~ 13–16 ft (~4–5 m)</td>
<td>N/A</td>
<td>N/A (gasoline source)</td>
<td>UST</td>
<td>Sudden 20,000-gallon (75,708 L) release, odors detected in buildings up to 500 ft (152 m) downgradient of source</td>
</tr>
</tbody>
</table>

**Notes:**

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Table 2. Select Three-Dimensional Abreu and Johnson (2005) Model Simulation Results from U.S. EPA (2012b)

<table>
<thead>
<tr>
<th>Source Hydrocarbon Vapor Concentration (mg/L)</th>
<th>Vapor Intrusion Attenuation Factor</th>
<th>Two Soil Layers (Capping Scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Soil Layer</td>
<td>N/A</td>
</tr>
<tr>
<td>200</td>
<td>$6.7 \times 10^{-5}$</td>
<td>$6.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>N/A</td>
<td>$7.1 \times 10^{-15}$</td>
</tr>
</tbody>
</table>

Notes: Depressurized building (~5 Pa), residential house with 2-m (6.6-ft) deep basement, depth to hydrocarbon vapor source = 8 m (25.3 ft), first-order decay constant equal to 0.18 h$^{-1}$.

Table 3. Number of Sites by Country and States in PVI Database (February 2012)

<table>
<thead>
<tr>
<th>Location</th>
<th>Sites</th>
<th>Location</th>
<th>Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>7</td>
<td>Ohio</td>
<td>4</td>
</tr>
<tr>
<td>Maine</td>
<td>13</td>
<td>South Carolina</td>
<td>1</td>
</tr>
<tr>
<td>Maryland</td>
<td>1</td>
<td>Utah</td>
<td>15</td>
</tr>
<tr>
<td>Minnesota</td>
<td>22</td>
<td>United States unknown</td>
<td>1</td>
</tr>
<tr>
<td>New Jersey</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>2</td>
<td>Australia</td>
<td>1</td>
</tr>
</tbody>
</table>

Total Sites = 70

The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.
<table>
<thead>
<tr>
<th>Site Name</th>
<th>City</th>
<th>Benzene</th>
<th>Toluene</th>
<th>Ethylbenzene</th>
<th>Xylenes</th>
<th>Naphthalene</th>
<th>2,4,5-Tri methyl / pentane</th>
<th>Hexane</th>
<th>Heptane</th>
<th>MTBE</th>
<th>1,2-Butadiene</th>
<th>TPH</th>
<th>TPH Method</th>
<th>MAEP-TPH Fractions</th>
<th>Oxygen</th>
<th>Carbon</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamedna Naval Air Station</td>
<td>Alameda</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Iso-pentane</td>
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<td>12</td>
<td>8</td>
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<tr>
<td>Coachella</td>
<td>Coachella</td>
<td>27</td>
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<td>0</td>
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<tr>
<td>Huntington Beach</td>
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<td>Mission Valley Terminal</td>
<td>San Diego</td>
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<td>TPHg 6260</td>
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<td>24</td>
<td>22</td>
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<td>Newport Beach</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>62</td>
<td>GC/FID</td>
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<td>55</td>
<td>47</td>
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<tr>
<td>Former Chevron Station #9-5669</td>
<td>South San Francisco</td>
<td>27</td>
<td>18</td>
<td>18</td>
<td>18</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>9</td>
<td>Modified TO-3 GC/FID</td>
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<td>18</td>
<td>18</td>
<td>9</td>
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<tr>
<td>Dave's Amoco</td>
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<td>TPH as Gas</td>
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</tr>
<tr>
<td>NYM</td>
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<td>0</td>
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<td>TPH as Gas</td>
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<td>Jacobsen Residence</td>
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<td>TPH as Gas</td>
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</tr>
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<td>D&amp;E Sales</td>
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<td>Johnsons Auto</td>
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<td>TPH as Gas</td>
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</tr>
<tr>
<td>John's Garage</td>
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<td>TPH as Gas</td>
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</tr>
<tr>
<td>Buchannon Nursing Home</td>
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<td>0</td>
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<td>TPH as Gas</td>
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</tr>
<tr>
<td>Red &amp; White Service</td>
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<td>0</td>
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<td>4</td>
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<td>TPH as Gas</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Side Lake Store</td>
<td>N/A</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>0</td>
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<td>TPH as Gas</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ossippe Store</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>TPH as Gas</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(continued)
Table 6. Potential LNAPL Hydrocarbon Indicators

<table>
<thead>
<tr>
<th>Type</th>
<th>Indicator</th>
<th>Measures and Screening Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adopted for this study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct</td>
<td>Current or historic presence of LNAPL in groundwater or soil</td>
<td>Laboratory and/or field observations, sheens, results of paint filter, dye and shake tests</td>
</tr>
</tbody>
</table>
| Indirect           | Individual PHC compound and/or TPH concentrations approaching (>0.2) effective solubilities or effective soil saturation concentrations ("Csat" concentration) | Groundwater  
- benzene > 5 mg/L  
- TPH > 30 mg/L (gasoline)  
Soil  
- benzene > 10 mg/kg  
- TPH > 250 mg/kg (gasoline) |                                                                                               |
| Indirect           | Proximity to source area likely to be impacted with LNAPL                | Soil gas probes located near (within 20 ft [6.1 m]) or within former underground storage tank (UST) fields or fuel dispenser areas |

Other potential indicators

| Indirect | Fluorescence response in LNAPL range | UV, LIF, or UVIF fluorescence above background levels (visual observation) |
| Indirect | Organic vapor analyzer (e.g., photoionization detector) | >500 ppmV |
| Indirect | PHC vapor, O<sub>2</sub> and CO<sub>2</sub> profiles | PHC vapor and CO<sub>2</sub> concentrations in soil gas that show no decrease (or O<sub>2</sub> concentrations that show no increase) or remain relatively constant with distance from contamination source |
| Indirect | Elevated aliphatic soil gas concentrations | For example, hexane soil gas concentrations > approximately 100,000 µg/m<sup>3</sup> suggest LNAPL because dissolved plumes are primarily composed of soluble aromatic hydrocarbons (Lahvis et al., In prep.) |

Note: For two sites, #6-046 and #102 Chevron, there were long dissolved plumes (several hundred feet long) with elevated benzene concentrations (up to 12 mg/L) in groundwater that exceeded the above criteria, but when there was no evidence of LNAPL (it was also considered unlikely that the LNAPL body would have migrated this far). For these sites, the above criteria were overridden (i.e., site was designated as a dissolved source).

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Table 7. Risk-Based Indoor Air Concentration for Primary Chemicals of Potential Concern

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Toxicity Endpoint</th>
<th>Risk-Based Indoor Air Concentration (µg/m³)¹</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>Carcinogenic</td>
<td>2.9 (1 x 10⁻³ ILCR); 0.29 (1 x 10⁻⁹ ILCR)</td>
<td>U.S. EPA IRIS²</td>
</tr>
<tr>
<td>Toluene</td>
<td>Non-carcinogenic</td>
<td>5.000 (RFC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>Non-carcinogenic</td>
<td>1.000 (RFC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Xylenes</td>
<td>Non-carcinogenic</td>
<td>100 (RFC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>Non-carcinogenic</td>
<td>3 (RFC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>Non-carcinogenic</td>
<td>700 (RFC)</td>
<td>U.S. EPA IRIS</td>
</tr>
<tr>
<td>MADEP Aliphatic C5-8</td>
<td>Non-carcinogenic</td>
<td>200</td>
<td>MADEP (2003)</td>
</tr>
</tbody>
</table>

¹ Assumes residential receptor, and continuous exposure over a lifetime.
² Midpoint of the range provided in U.S. EPA IRIS database.
³ ILCR = Incremental lifetime cancer risk; RFC = reference concentration.
⁴ IRIS database accessed February 2012.

Table 8. Summary of Results for Vertical Distance Method

<table>
<thead>
<tr>
<th>Dissolved Source</th>
<th>LNAPL Source—UST Sites</th>
<th>LNAPL—All Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most O₂ conc. &gt; 4%, and no O₂ &lt; 1%</td>
<td>Many data points with O₂ &lt; 4%, and O₂ &lt; 1% to 6 ft (1.8 m) separation</td>
<td>Many data points with O₂ &lt; 4%, and O₂ &lt; 1% to 11 ft (3.4-m) separation, greater O₂ depletion than UST only</td>
</tr>
<tr>
<td>Benzene (100 µg/m³ threshold)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pₚₐ₅ &gt; 97% for 0 ft separation increasing to 99% at 5 ft (1.5 m)</td>
<td>Pₚₐ₅ &gt; 61% for 0 ft separation increasing to ~ 95% for 15 ft (4.6-m) separation</td>
<td>Pₚₐ₅ &gt; 48% for 0-ft separation increasing to &gt; 90% at 15 ft (4.6 m) and ~95% at 30 ft (9.1 m)</td>
</tr>
<tr>
<td>Benzene (50 µg/m³ threshold)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pₚₐ₅ &gt; 94% to 95% for 0 ft to 5 ft (1.5 m)</td>
<td>Pₚₐ₅ &gt; 57% for 0 ft separation increasing to ~ 93% for 15 ft (4.6-m) separation</td>
<td>Pₚₐ₅ &gt; 46% for 0 ft separation increasing to &gt; 90% at 15 ft (4.6 m) and ~95% at 30 ft (9.1 m)</td>
</tr>
<tr>
<td>Xylenes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;10 vapor concentrations &gt; RBC, for separation distance of 3 ft (0.9 m)</td>
<td>Five vapor concentrations &gt; RBC, for separation distance up to 11 ft (3.4 m)</td>
<td>&gt;10 vapor concentrations &gt; RBC, for separation distance up to 12 ft (3.7 m)</td>
</tr>
<tr>
<td>Hexane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Five vapor concentrations &gt; RBC, for separation distance up to 4 ft (1.2 m)</td>
<td>N/A</td>
</tr>
<tr>
<td>C5-8 Aliphatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two vapor concentrations &gt; RBC, for separation distance up to 3 ft (0.9 m)</td>
<td>Five vapor concentrations &gt; RBC, for separation distance up to 3 ft (0.9 m)</td>
<td>N/A</td>
</tr>
<tr>
<td>C9-12 Aliphatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Eight vapor concentrations &gt; RBC, for separation distance up to 2 ft (0.6 m)</td>
<td>N/A</td>
</tr>
<tr>
<td>C9-10 Aromatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All vapor concentrations &lt; RBC, 0 ft</td>
<td>Four vapor concentrations &gt; RBC, for separation distance up to 2 ft (0.6 m)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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$P_{KM} = \text{Probability estimated using Kaplan-Meier method for exceeding threshold.}$

### Table 9. Summary of Results for Clean Soil (Davis) Method

<table>
<thead>
<tr>
<th>Source Scenario and Facility Type</th>
<th>Number Sites</th>
<th>Number Data Points</th>
<th>95th Percentile Clean Soil Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved</td>
<td>47</td>
<td>170</td>
<td>Method A: 10.0 ft (3.0 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Method B: 5.4 ft (1.6 m)</td>
</tr>
<tr>
<td>LNA PL (UST only)</td>
<td>53</td>
<td>172</td>
<td>Method A: 13.9 ft (4.2 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Method B: 13.5 ft (4.1 m)</td>
</tr>
<tr>
<td>LNA PL (all facilities)</td>
<td>60</td>
<td>216</td>
<td>Method A: 20.0 ft (6.1 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Method B: 16.2 ft (4.9 m)</td>
</tr>
</tbody>
</table>

Note: The above statistics include site data when no benzene groundwater concentration was available.

**Figure 1.** Conceptual Model Illustrating the Potential for Vapor Intrusion for a) Free-Phase LNA PL Source, b) Residual-Phase LNA PL Source, and c) Dissolved-Phase Source. (source Lahvis et al., In prep.; used with permission)

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Figure 6. Example Calculation of Clean Soil Distances.

Figure 7. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites).

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Figure 8. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Only detectable benzene vapor concentrations shown.

Values as a different symbol?

Figure 9. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Data points shown are where both TPH vapor and oxygen concentrations were above detection limits. Shaded ellipse encompasses data that generally support the aerobic mineralization paradigm.

What is the explanation for all the data? Is it a data quality issue? I even agree with this. The ellipse implies a linear relation or a semi-log plot, which implies a first-order relationship, but stoichiometrically it should be linear in even a negative slope. Is this the case?

How closely does the data agree with theoretical expectations? What does that your ability to use these data to build an argument?
Figure 10. Relation between Benzene and Ethylbenzene and Benzene and Xylenes Vapor Concentrations. Data points shown are where both compounds were above detection limits. It's not really clear why these are included or what they add to the analysis.

Figure 11. Vertical Distance Method--Benzene, Xylenes and Oxygen Data for Dissolved Sites (KM = Kaplan-Meier).

What is the uncertainty in the calculated values? Is the scatter in the data very high? What does it mean if the outcome is 50% ± 50%?
Figure 12. Vertical Distance Method—PHC Fraction and Hexane Data for Dissolved Sites.
Figure 13. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (UST only) Sites (KM = Kaplan-Meier).

Figure 14. Vertical Distance Method–PHC Fraction and Hexane Data for LNAPL (UST only) Sites.
Figure 15. Vertical Distance Method—Benzene, Xylenes and Oxygen Data for LNAPL (all sites) (KM = Kaplan-Meier).

Figure 16. Vertical Distance Method—2,2,4-Trimethylpentane Data for LNAPL Sites (all sites).
Figure 17. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (all sites). Below detection limit concentrations replaced with half the detection limit for analysis.
Figure 18. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (UST sites). Below detection limit concentrations replaced with half the detection limit for analysis.
Figure 19. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold for Different Soil Types (coarse and fine grained). Below detection limit concentrations replaced with half the detection limit for analysis.

Figure 20. Results of Clean Soil (Davis Method) for Dissolved-Source Sites. 47 sites, N = 170.
Figure 21. Results of Clean Soil (Davis) Method for LNAPL Source Sites (UST-only). 53 sites, N = 172.

Figure 22. Results of Clean Soil (Davis) Method for LNAPL Source Sites (all). 60 sites, N = 216.
A CASE STUDY ON THE INFLUENCE OF AEROBIC BIODEGRADATION ON VAPOR INTRUSION AT A FORMER REFINERY PROPERTY

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INTRODUCTION

Aerobic degradation of petroleum hydrocarbons in the unsaturated zone will often reduce the potential for subsurface vapor intrusion to indoor air. There is a need for improved understanding of the conditions under which aerobic degradation occurs and the extent to which it will cause attenuation of subsurface vapor concentrations. This chapter presents a case study of a soil vapor investigation conducted to evaluate the fate and transport of petroleum hydrocarbons present beneath an office building at a former refinery with fine-grained soils and strong seasonal variation in rainfall. The objectives of the investigation were to: 1) assess the distribution of petroleum hydrocarbons and biodegradation indicators in soil vapor around and under the office building; 2) assess spatial and temporal variability, and 3) compare the data to 1-D mathematical model simulations to assess the impact of biodegradation on vapor migration of petroleum hydrocarbons at the site.

BACKGROUND

The former refinery in Oklahoma operated for approximately seventy years until the early 1980s. It has since been decommissioned, and the infrastructure dismantled, with the exception of the office building (Figure 1), which is similar to a small residence (i.e., single-
story structure with slab-on-grade construction, 6 m wide by 12 m long, with an externally mounted heat pump heating and cooling system). A groundwater and free product extraction and treatment system, which removed about 36,000 barrels of hydrocarbons, was operated from 1984 to 1998 and decommissioned after it reached diminishing mass removal rates. Hydrocarbons currently exist as a light non-aqueous phase liquid (LNAPL) smear-zone in a sandy aquifer at an approximate depth range of 6 to 10.7 m below ground surface (m bgs). The water table varies from about 4.6 to 7.6 m bgs; therefore, the sandy aquifer is usually confined. The smear-zone is deeper than the current water table, because the groundwater extraction and treatment system caused a significant depression in the water table elevation while it was operating. Silty-clay soils are present from ground surface to about 6 m bgs.

Figure 1. Office Building at the Former Oklahoma Refinery.

**SCOPE OF WORK**

The scope of work consisted of many different investigative methods intended to characterize the subsurface vapor distribution around the office and provide inputs for mathematical modeling. The field activities included:

- Lithological characterization by continuous coring, laboratory analysis of soil physical properties and cone penetrometer testing (CPT);
- Mapping of the vertical distribution of petroleum hydrocarbons with laser-induced fluorescence (LIF) and soil headspace screening with photoionization detector (PID) and flame ionization detector (FID);
- Installation of nested external soil gas probes on each side of the building and sub-slab soil gas probes through the building foundation;
• Sampling and analysis to assess:
  o Spatial distribution of petroleum hydrocarbon vapors and biodegradation indicators (oxygen [O₂], carbon dioxide [CO₂] and methane [CH₄]);
  o Short-term (i.e., daily) temporal variability of soil gas concentrations, and
  o Seasonal variability of soil gas concentrations via sampling in October 2006 and June 2007. Sub-slab probes SSP-1, 2 and 3 and nested soil gas probes N11 and N12 were installed in October 2006 and the remaining probes were installed prior to the June 2007 sampling event;
• Supplemental testing to collect in-situ measurements of soil permeability; and
• Mathematical modeling to evaluate the soil gas concentration profiles and assess the degree of biodegradation.

Figure 2. Layout of Office Building and Sampling Locations (scale in metres).

Figure 3. Cross-Section of Office Building and Sampling Locations (schematic).
METHODS

This section describes the methods for evaluating the soil lithology, LNAPL distribution, installation and sampling of the soil gas and sub-slab probes. Figures 2 and 3 show the layout of the office building and sampling points in plan and cross section.

Lithological Characterization and LNAPL Distribution Assessment

Continuous core was retrieved from each of the 12 boreholes created for the soil gas probes. At each location (N-11, N-12, N-18, and N-19), three separate boreholes were advanced to depths of 1.8, 2.7 and 3.6 m bgs, and spaced less than 1 m apart. An additional borehole (N-21) was advanced to 6 m bgs (i.e., the top of the LNAPL smear zone). Continuous soil core was collected for visual inspection and logging in each soil gas probe location using the GeoProbe® 3.25-inch diameter Dual Tube (DT) system. From the 6 m borehole (N-21, Figure 2), core segments were sent to PTS Laboratories, Inc. of Houston, Texas for soil index testing (bulk density, specific gravity, moisture content, grain size distribution and fraction of organic carbon [foc]). Samples were also placed in wide-mouth Mason Jars, with foil covers and allowed to equilibrate over time for headspace screening using the FID and PID.

Cone penetrometer testing with laser-induced fluorescence (CPT-LIF) was conducted at two locations within about 3 m of the building (CPT-LIF-1 and CPT-LIF-2) to assess the vertical profile of soil texture and non-aqueous phase liquid hydrocarbon content. The CPT-LIF borings were advanced to depths of 12 m bgs by Fugro Geoservices, Inc. of Houston, Texas using their proprietary technology (both logs were similar, so only one is presented here).

Soil Gas Probe and Sub-Slab Soil Gas Probe Construction and Development

Twelve nested external soil gas probes were installed in separate boreholes on four sides of the building to 3 depths (1.8, 2.7 and 3.6 m bgs, or A, B and C, respectively) in four locations (N-11, N-12, N-18, and N-19). Soil gas probes consisted of a 6-inch stainless steel Geoprobe® screen with conical stainless steel tip attached via compression fittings to ¼-inch Nylaflow® tubing and completed with a compression-fit ball valve. An interval of about 46 cm in length surrounding the screen was backfilled with sand, followed by 7.6 cm of dry granular bentonite above the sand, and a thick slurry of bentonite and water throughout the remainder of the annulus to ensure the probe was sealed to prevent atmospheric air leakage down the borehole or gas exchange from different depth intervals.

Eleven sub-slab soil gas probes were installed through the building foundation. Sub-slab probes were constructed of 1/2-inch brass pipe with threaded fittings to a brass ball-valve, which was sealed using hydrating cement into a 5/8th-inch drilled hole in the floor slab, with the upper inch of the drilled hole reamed to a 1-inch diameter to provide sufficient annulus for placement of the seal.
Soil gas permeability testing was conducted on each sub-slab and soil gas probe by extracting gas at a measured flow rate and recording the corresponding vacuum, using the apparatus shown in Figure 4. Vacuum was monitored at flow rates of 100, 250 and 500 milliliters per min (mL/min). Vacuum readings at each flow rate typically stabilized within 1 minute. The total volume of gas extracted during the permeability testing was approximately 1 L, which is approximately equal to the void volume of the sand pack and tubing for each probe. Consequently, the soil gas permeability testing also served to remove the atmospheric air entrained during probe installation (referred to here as probe “development”). The flow and vacuum data were used to calculate soil gas permeability following methods described in Johnson et al. (1990). In some cases, the gas permeability was too low to yield sustainable flow, in which case, pneumatic testing was terminated when the applied vacuum reached 254 cm of water column (cm-H\textsubscript{2}O). After permeability testing and development, the probes were allowed to re-equilibrate at least overnight prior to purging and sampling.

Soil Gas Probe and Sub-Slab Soil Gas Probe Sampling and Analysis

Soil gas probes were purged prior to sample collection using the apparatus depicted in Figure 5. Helium (He) was used as a tracer to verify whether there was any leakage during purging and sample collection. Purging was conducted by partially filling a 1-L Tedlar\textsuperscript{TM} bag three times using a vacuum chamber (commonly called a lung box). The shroud was filled with helium at a concentration of about 10% to 30% throughout the purging process and the purged soil gas was field-screened using a MGD-2002 portable He detector to provide real-time leak check analysis. The purged gas was also screened using a miniRAE photoionization detector for total ionizable VOCs and a GEM2000 Multi-gas Meter for O\textsubscript{2}, CO\textsubscript{2} and CH\textsubscript{4}. These readings were used to assess the stability of soil vapor concentrations prior to sample collection, and assess adequacy of probe development after initial installation. Some soil gas
probes had very low flow rates, which required several attempts to purge the volume of gas in the sand pack and tubing prior to sample collection, and did not provide sufficient gas for field screening (N-11C, N-12B, N-12C, N-18A, N-18B, N-18C, N-19A, N-19B, N-19C), in which case, He concentrations were determined by laboratory analysis from the Summa canister samples.

![Image of Soil Gas Sample Collection Apparatus]

Figure 5. Soil Gas Sample Collection Apparatus.

Soil gas samples were collected immediately after field screening, by closing the valve between the Summa canister and the lung box, and opening the Summa canister valve. The He concentration in the shroud was maintained at approximately 10% to 30% by volume for the duration of sample collection. Where sustainable soil gas flow rates were greater than 100 mL/min, the vacuum in the Summa canister following sample collection was less than about 25.4 cm of mercury. This provided sufficient sample volume for the analytical laboratory to meet target reporting limits of about 1 part-per-billion by volume (ppb). However, sampling flow rates for several locations were too low to collect the required volume for field screening and sampling in a reasonable period of time. In these cases, best efforts were made to purge as much of the atmospheric air entrained during probe installation as practicable prior to sample collection. The very low flow probes were purged sequentially, withdrawing about 1/3 L at a time by applying a vacuum to remove the volume achievable via expansion of the gas in the sand-pack and probe tubing. After flow diminished to minimal levels, the probe valve was closed and time was allowed for the vacuum to dissipate as soil gas slowly entered the sand pack from the surrounding geologic materials. After which, additional aliquots of gas were extracted as needed to meet sample volume requirements. The stagnant gas in the probe tubing was purged to waste prior to collection of each aliquot in order to minimize potential negative bias via adsorption to the Nylaflow tubing, as described by McAlary et al. 2009.
Sub-slab and external soil gas samples were analyzed by Columbia Analytical Services of Simi Valley, California for hydrocarbon constituents via EPA Method TO-15 and He, O₂, CO₂ and CH₄ by Method TO-3. Field duplicate samples were collected at a rate of 1 for every 10 investigative samples.

Water level monitoring was conducted using Solinst Leveloggers between the first and second sampling events (October 2006 to June 2007). Barometric pressure data was obtained from Woodring Municipal Airport for the duration of the June 2007 sampling event and sub-slab to indoor air pressure differential monitoring was conducted using a Zephyr II+ data-logger for a 12-hour period (overnight, June 5 to 6, 2007).

**QUALITY ASSURANCE/QUALITY CONTROL**

Soil vapor sampling and analysis has drawn criticism from several regulatory agencies in the United States (New York, New Jersey and Massachusetts, to name a few) because empirical data show considerable variability and generally poor correlation to indoor air quality. It is not known the extent to which this may be attributable to artifacts of the sampling and analytical procedures, although there has been considerable discussion on this topic. To minimize concerns over data quality, the following quality assurance and quality control (QA/QC) procedures were included in this investigation:

- QA/QC measures associated with the soil gas probe construction included:
  - Bentonite slurry seals were placed above the sand pack in the borehole annulus of all soil gas probes;
  - Swagelok™ fittings were used during soil gas and sub-slab probe sampling to reduce the risk of leaks; and
  - Equipment blanks were collected by assembling a soil gas probe and collecting a sample of outdoor air through the probe prior to installation to assess possible contributions of volatile organic compounds (VOCs) from soil gas probe materials.

- QA/QC measures associated with the soil gas sampling procedures included:
  - Shut-in tests were performed prior to sampling by connecting the sampling apparatus to the soil gas and sub-slab probe, then drawing a vacuum on the apparatus, and closing valves on both ends to seal in the applied vacuum. The vacuum level was then observed over a period of at least one minute to assess whether the vacuum dissipated. If the vacuum dissipated, fittings were adjusted as required until vacuum was sustained.
  - He tracer testing was performed to confirm the absence of leaks prior to sample collection using a portable He detector, and laboratory analysis of He concentrations was performed to allow a quantitative mass balance correction for any leaks greater than 5% of the sample volume; and
  - Field screening of O₂, CO₂, CH₄, total VOC and He concentrations was conducted prior to collection of soil gas samples to check for stability of soil vapor concentrations and verify adequacy of purging and absence of leaks.

- QA/QC measures associated with the laboratory procedures included:
Eight simultaneous soil gas samples (octuplet sampling) were collected from one soil gas probe (N-11B at 2.7 m bgs) for analysis as blind duplicates by four different laboratories to assess accuracy and analytical variability; 
- Duplicate samples were collected to assess sampling and analytical precision;
- Daily outdoor air sampling via 6 L Summa canister over 24 hour periods with analysis via EPA Methods TO-15 to assess whether ambient air concentrations were sufficient to contribute vapors to any shallow soil gas samples;
- Laboratory control samples were analyzed to assess analytical accuracy; and
- Data validation was conducted to assure the quality of the laboratory analyses.

**RESULTS**

Investigation results are described below.

**Geology**

Visual inspection of soil cores demonstrated that the geology is relatively uniform silty-clay materials above the water table, with minimal visible indication of any significant bedding. There appear to be some desiccation cracks in the shallow soil in the dry season, as indicated by mottled color (grey matrix and brown fracture surfaces). Results of index testing at boring N-21 are shown in Table 1, and grain size distribution curves are shown in Figure 6. The soils had very similar grading with 60 to 80% silt and clay, except for a slightly finer-grained soil at about 2.1 to 2.4 m bgs and a slightly coarser-grained soil at about 5.2 to 5.5 m bgs. Moisture contents were in the range of about 18% to 21% by weight, and porosities were about 34% to 40%, yielding water saturations of 74 to 96% in June 2007. Organic carbon ranged from about 0.20 to 0.73% by weight.

**Table 1. Soil Properties vs. Depth from Boring N-21 in June, 2007**

<table>
<thead>
<tr>
<th>Depth Range (m bgs)</th>
<th>In-Place Density (g/cm³)</th>
<th>Moisture Content (weight %)</th>
<th>Porosity (%)</th>
<th>Calculated % Saturation</th>
<th>Fraction of Organic Carbon (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-0.6</td>
<td>1.60</td>
<td>18.2</td>
<td>39.2</td>
<td>74%</td>
<td>7.20</td>
</tr>
<tr>
<td>1.2-1.5</td>
<td>1.62</td>
<td>18.9</td>
<td>38.8</td>
<td>79%</td>
<td>7.25</td>
</tr>
<tr>
<td>2.1-2.4</td>
<td>1.70</td>
<td>20.4</td>
<td>36.1</td>
<td>96%</td>
<td>3.50</td>
</tr>
<tr>
<td>3.0-3.3</td>
<td>1.58</td>
<td>21.1</td>
<td>39.7</td>
<td>84%</td>
<td>7.25</td>
</tr>
<tr>
<td>4.0-4.3</td>
<td>1.72</td>
<td>19.8</td>
<td>35.4</td>
<td>96%</td>
<td>1.95</td>
</tr>
<tr>
<td>5.2-5.5</td>
<td>1.75</td>
<td>15.8</td>
<td>34.1</td>
<td>81%</td>
<td>2.25</td>
</tr>
<tr>
<td>5.5-5.8</td>
<td>1.65</td>
<td>19.3</td>
<td>37.9</td>
<td>84%</td>
<td>2.05</td>
</tr>
<tr>
<td>5.8-6.1</td>
<td>1.65</td>
<td>19.3</td>
<td>38.1</td>
<td>83%</td>
<td>2.35</td>
</tr>
</tbody>
</table>
Headspace PID readings generally decreased from several hundred parts per million by volume (ppmv) near the water table to low ppmv levels in shallow soils, and FID readings generally decreased from ~10000 ppmv near the water table to low tens of ppmv near surface.

The CPT tool measures pressure at the tip and sleeve resistance in response to a constrained hydraulic driving force, which is correlated to the density, cohesion and inter-granular friction of the soil, and therefore, can be correlated to soil type. The CPT log generally indicates sandy soils where the tip resistance is high and the sleeve friction is low and silty soils where the sleeve resistance is high and the tip resistance is low, although this is also subject to variations in the degree of consolidation and water content. Figure 7 shows the CPT data, and Fugro’s interpretation of the geology (dots indicates sand, angled lines indicate silt and vertical lines indicate clay).

![Figure 6. Grain Size Distributions for Soil Samples from Boring N-21.](image)

**LNAPL Distribution**

The LIF probe produces an ultraviolet light that causes hydrocarbons to emit a corresponding fluorescence. The wavelengths that are emitted reflect the molecular weight of the compounds present, and the fluorescence intensity (%RE) reflects the percent saturation of the NAPL relative to a pure NAPL standard. The LIF log (Figure 8) shows the fluorescence vs. depth expressed as a percentage of the response measured compared to a standard where the device immersed in a pure NAPL reference (M1 standard). The response is very low throughout the unsaturated zone, but increases in the 6.1 to 11.6 m bgs interval, which is in the sandy aquifer materials below the overlying silt and clay-rich materials, and below the water table (i.e. confined).
Responses in the range of 300 to 500%RE were recorded at other locations at this site, so the low values recorded near the office building indicate that the LNAPL is likely present at low levels of saturation. The light blue color of the fluorescence plot indicates the LNAPL hydrocarbons present from 6.1 to 11.6 m bgs are predominantly light fuel range hydrocarbons.
<table>
<thead>
<tr>
<th>Well ID</th>
<th>Date</th>
<th>Helium Tracer Gas (%)</th>
<th>Percentage of Sample Volume Attributable to Influx from the Shroud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shroud Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>N-11A</td>
<td>17-Oct-06</td>
<td>30.9</td>
<td>44.2</td>
</tr>
<tr>
<td>N-11B</td>
<td>17-Oct-06</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>N-11C</td>
<td>22-Oct-06</td>
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<td>30</td>
</tr>
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<td>N-12C</td>
<td>19-Oct-06</td>
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</tr>
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<td>47</td>
</tr>
<tr>
<td>SSP-02</td>
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<td>31</td>
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</tr>
<tr>
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<td>25.0</td>
</tr>
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<td>N-12C</td>
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</tr>
<tr>
<td>N-18A</td>
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</tr>
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<td>N-18B</td>
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<td>56.0</td>
</tr>
<tr>
<td>N-19A</td>
<td>7-Jun-07</td>
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<td>38.0</td>
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<td>N-19B</td>
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<td>53.0</td>
</tr>
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<td>N-19C</td>
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<td>29.3</td>
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<tr>
<td>SSP-11</td>
<td>7-Jun-07</td>
<td>11</td>
<td>63</td>
</tr>
</tbody>
</table>
Data Quality

With the exception of a few probes where the soil gas permeability was too low to permit adequate purging, the data quality procedures demonstrated that the quality of the data collected was excellent. Some soil gas probes withheld a significant vacuum for several days after purging, which demonstrates both that those probes are screened in low permeability materials, but also that the slurry seals in the borehole annulus and compression-fit valves on top of the probes do not allow appreciable leakage. Cyclopentanone was detected in equipment blank samples collected through the soil gas probes prior to installation, but did not appear to have an adverse effect on the study results. Therefore, the probe materials and installation were amenable to providing high quality samples.

The shut-in tests all verified no obvious leaks prior to sample collection and the helium tracer test data (Table 2) demonstrated that most probes had no significant leakage. Field screening readings were generally consistent after the atmospheric air entrained during probe installation was removed, which was the case for all but a few probes (N18-A, B and C, noted with an asterisk “***” in Table 3). The results of the octuplet samples showed intra-laboratory variability of about 15%, and inter-laboratory variability less than a factor of 2 for most compounds detected. The average benzene concentration of the 8 samples was 17 parts per million by volume (ppm,v), and 1 L samples collected 3 weeks later and 6 months later showed a concentration of 15 ppm,v benzene (40,000 and 41,000 µg/m³, Table 3), indicating that the sampling and analysis procedures appear to be highly reproducible. Some compounds had elevated reporting limits in samples with total petroleum hydrocarbons as toluene (TPHs) concentrations that required dilution to be within the linear calibration range of the analysis. Other QA/QC activities showed the data met appropriate data quality objectives.

Vertical Concentration Profiles

Vertical profiles of benzene, TPHs, O₂, CO₂ and CH₄ from the nested probes immediately beside the building are shown in Table 3.

Temporal Variability

For nested probes N-11 and N-12, the data from October 2006 and June 2007 are similar for the 2.7 and 3.6 m probes, but notably different for the 1.8 m depth (Table 3). The wet conditions in the spring of 2007 may have limited the entry of oxygen into the subsurface and diminished the amount of biodegradation in the shallow soil gas.

The results of samples from sub-slab probes SS-1, SS-2 and SS-3 collected on 5 consecutive days in June 2007 are shown on Table 4. O₂ concentrations were relatively low and TPH concentrations relatively high in SS-1 and SS-2 compared to SS-3. Short-term temporal variability for both O₂ and TPHs were generally less than 1 order of magnitude, and often less than a factor of 3. Only two of the samples had reportable benzene concentrations.
Table 3. Long-Term Temporal Data and Vertical Profile data from Nested Probes

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>N-11</th>
<th>N-12</th>
<th>N-18**</th>
<th>N-19</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oct-06</td>
<td>Jun-07</td>
<td>Oct-06</td>
<td>Jun-07</td>
</tr>
<tr>
<td>1.8 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene $\mu g/m^3$</td>
<td>&lt;3.2</td>
<td>2,200</td>
<td>7.9</td>
<td>500/418*</td>
</tr>
<tr>
<td>TPHs $\mu g/m^3$</td>
<td>2,000</td>
<td>8,000,000</td>
<td>1,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Oxygen %</td>
<td>18</td>
<td>0.0</td>
<td>20.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbon Dioxide %</td>
<td>3</td>
<td>7.7</td>
<td>2.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Methane %</td>
<td>6.4</td>
<td>19.4</td>
<td>0.2</td>
<td>5.0</td>
</tr>
<tr>
<td>2.7 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene $\mu g/m^3$</td>
<td>40,000</td>
<td>41,000</td>
<td>12,000</td>
<td>16,000</td>
</tr>
<tr>
<td>TPHs $\mu g/m^3$</td>
<td>46,000,000</td>
<td>40,000,000</td>
<td>700,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Oxygen %</td>
<td>1.0</td>
<td>0.6</td>
<td>4.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Carbon Dioxide %</td>
<td>14.3</td>
<td>14.6</td>
<td>8.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Methane %</td>
<td>70</td>
<td>70</td>
<td>11.7</td>
<td>27</td>
</tr>
<tr>
<td>3.6 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene $\mu g/m^3$</td>
<td>42,000</td>
<td>NA</td>
<td>33,000</td>
<td>44,000</td>
</tr>
<tr>
<td>TPHs $\mu g/m^3$</td>
<td>40,000,000</td>
<td>NA</td>
<td>10,000,000</td>
<td>10,000,000</td>
</tr>
<tr>
<td>Oxygen %</td>
<td>4.1</td>
<td>NA</td>
<td>5.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Carbon Dioxide %</td>
<td>13.3</td>
<td>NA</td>
<td>6.9</td>
<td>11.4</td>
</tr>
<tr>
<td>Methane %</td>
<td>NM</td>
<td>NA</td>
<td>36.7</td>
<td>39.3</td>
</tr>
</tbody>
</table>

* - unable to collected field measurements, laboratory data substituted
** - N-18 probes were not purged as much as planned prior to sampling because of low flow rates and time constraints, and may have therefore contained relict atmospheric air entrained during probe installation.
NA – not available because of water in the probe.
NM – not measured because of insufficient sample volume

Table 4. Results of sub-slab samples collected on 5 consecutive days

<table>
<thead>
<tr>
<th>Day</th>
<th>SS-1</th>
<th>SS-2</th>
<th>SS-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TPHs $\mu g/m^3$</td>
<td>Benzene $\mu g/m^3$</td>
<td>O$_2$ %</td>
</tr>
<tr>
<td>1</td>
<td>10,000</td>
<td>11</td>
<td>1.21</td>
</tr>
<tr>
<td>2</td>
<td>400,000</td>
<td>&lt;190</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>300,000</td>
<td>&lt;87</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>200,000</td>
<td>&lt;68</td>
<td>1.27</td>
</tr>
<tr>
<td>5</td>
<td>200,000</td>
<td>&lt;41</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The results of seasonal sampling at sub-slab probes SS-1, SS-2 and SS-3 are shown in Table 5. There was an increase of over one order of magnitude in the TPH concentrations in SS-1 and SS-2, corresponding with a decrease in oxygen, with similar results at SS-3, except that the TPH concentration decreased.
Table 5. Long-Term Temporal Data from Sub-Slab Probes inside the Office Building

<table>
<thead>
<tr>
<th></th>
<th>SS-1</th>
<th>SS-2</th>
<th>SS-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-06</td>
<td>Jun-07</td>
<td>Oct-06</td>
<td>Jun-07</td>
</tr>
<tr>
<td>Benzene (µg/m³)</td>
<td>&lt;48</td>
<td>&lt;41</td>
<td>&lt;12</td>
</tr>
<tr>
<td>TPHs (µg/m³)</td>
<td>10,000</td>
<td>200,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Oxygen (%)</td>
<td>6.6</td>
<td>0.0</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Spatial Variability

Concentrations of benzene, TPHs and oxygen in sub-slab soil gas samples collected in June 2007 are plotted on Figures 9a, 9b and 9c. TPH and benzene concentrations are expected to be very low and oxygen concentrations near atmospheric levels at the perimeter of the sub-slab region. These data demonstrate more than 3 orders of magnitude spatial variability in sub-slab soil gas TPH concentrations, and at least one order of magnitude spatial variability in benzene concentrations, although over half of the benzene results are truncated by elevated reporting limits. Oxygen concentrations are very low in most locations, but also show at least 2 orders of magnitude range.

Figures 9a, 9b and 9c: Oxygen, TPHs and Benzene in June 2007 Sub-slab Samples
Climatic and Meteorological Data

Water level data (Figure 10) from a monitoring well located about 15 m from the office building shows the range of water table depths from a prolonged drought in 2006 through an unusually wet Spring in 2007 (approximately 5.4 to 3.6 m below top of casing). The upper silt and clay rich soils extend to a depth of about 6.1 m bgs and the LNAPL is trapped in the sand aquifer from 6.1 to about 11.3 m bgs, so the LNAPL was below the water table for both sampling events.

Figure 10. Water level data between first and second sampling rounds

Barometric pressure and temperature varied over typical ranges for each sampling event (June data shown in Figure 11). The sub-slab to indoor air pressure differential monitoring data showed no net pressure differential over a 12 hour period in June 2007 at SS-3 (Figure 12); however, there are fluctuations of up to a few Pascals in magnitude. Pressure fluctuations could have an influence on reversible flow of soil gas and indoor air in both directions across the slab. During intervals of a downward pressure gradient, there may be an associated supply of oxygen to the sub-floor, depending on the locations of floor penetrations. In June 2007, the highest sub-slab oxygen readings were near the bathroom, which had a floor drain.

Benzene was consistently detected in outdoor air at concentrations ranging from 0.068 to 0.18 ppbv in October 2006 and from 0.075 to 0.48 ppbv in June 2007; however, this is at least an order of magnitude lower than any of the detected concentrations in soil gas or sub-slab samples, so the outdoor air quality did not appear to have influenced the soil gas concentrations. Toluene and n-hexane were detected intermittently at similarly low levels.
Mathematical Modeling

Mathematical modeling was conducted to evaluate the impact of vadose-zone biodegradation on the migration of petroleum compounds and the potential for vapor
A Case Study on the Influence of Aerobic Biodegradation on Vapor Intrusion

Two models were used, both of which are one-dimensional analytical models; the Johnson and Ettinger (1991) model (J and E Model) and Dominant Layer Model (Johnson et al. 1999), the latter of which incorporates first order decay within one layer, and is otherwise comparable to the J and E Model. The models were used to simulate vertical profiles of soil gas concentrations with and without biodegradation for comparison to the measured concentrations from nested soil gas probe and sub-slab probe samples. Comparison between the field data and model simulations was used to evaluate the potential for vapor intrusion and the role of biodegradation for October 2006 and June 2007 monitoring events.

The following assumptions were used in the modeling:

- The average benzene concentration at 3.6 m bgs in 2006 and 2007 was assigned as the source concentration,
- Based on the results of the soil physical properties (Table 1), the vadose zone was treated as a two-layer system. Average soil properties for samples collected between 0 and 1.8 m bgs were used for the upper zone and average soil properties for samples collected between 1.8 and 3.6 m bgs were used for the lower zone.
- For the biodegradation case, a biodegradation zone from 0 – 0.3 m bgs was assumed. First order degradation kinetics were assumed, with a rate constant of 0.079 per hour, which is an average value for aromatic hydrocarbons based on a literature review of degradation rates in aerobic groundwater (DeVaull 2007).

Input values for the modeling are presented in Table 6.

<table>
<thead>
<tr>
<th>Model Input Parameter</th>
<th>Value Used</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Soil / Groundwater Temperature (Ts), °C</td>
<td>18</td>
<td>Area-specific average</td>
</tr>
<tr>
<td>Depth below grade to bottom of enclosed space floor (Ls), cm</td>
<td>15</td>
<td>Slab construction</td>
</tr>
<tr>
<td>Thickness of soil stratum A (hA), cm</td>
<td>183</td>
<td>Based on Soil Borings, 6 ft</td>
</tr>
<tr>
<td>Stratum A soil total porosity, unitless</td>
<td>0.380</td>
<td>Based on soil physical property measurements</td>
</tr>
<tr>
<td>Stratum A soil water-filled porosity, cm3/cm3</td>
<td>0.390</td>
<td>Based on soil physical property measurements</td>
</tr>
<tr>
<td>Thickness of soil stratum B (hB), cm</td>
<td>183</td>
<td>Based on Soil Borings, 6 ft</td>
</tr>
<tr>
<td>Stratum B soil total porosity, unitless</td>
<td>0.380</td>
<td>Based on soil physical property measurements</td>
</tr>
<tr>
<td>Stratum B soil water-filled porosity, cm3/cm3</td>
<td>0.348</td>
<td>Based on soil physical property measurements</td>
</tr>
<tr>
<td>Crack-to-total-area ratio (k), unitless</td>
<td>0.005</td>
<td>Default assumption</td>
</tr>
<tr>
<td>Building Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enclosed space floor thickness (Lcrack), cm</td>
<td>10</td>
<td>Default assumption</td>
</tr>
<tr>
<td>Enclosed space floor length (LB), cm</td>
<td>1000</td>
<td>Default assumption (10 meters)</td>
</tr>
<tr>
<td>Enclosed space floor width (WB), cm</td>
<td>1000</td>
<td>Default assumption (10 meters)</td>
</tr>
<tr>
<td>Floor-wall seam crack width (wv), cm</td>
<td>0.1</td>
<td>Default assumption</td>
</tr>
<tr>
<td>Average vapor flow rate into building (Qs), L/m</td>
<td>5</td>
<td>Based on 5 L/min per 100 m² of building floor space</td>
</tr>
<tr>
<td>Residential Building Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enclosed space height (HB), cm</td>
<td>300</td>
<td>Proposed ceiling height (6 feet or 1.84 meters)</td>
</tr>
<tr>
<td>Indoor air exchange rate (ER), hour⁻¹</td>
<td>0.5</td>
<td>Residential building assumption</td>
</tr>
</tbody>
</table>

Comparison between measured vertical soil gas concentration profiles of benzene and model results is shown on Figure 13. For both 2006 and 2007, the average measured benzene concentration at 2.7 m bgs was consistent with both models, indicating that degradation was minimal from 3.6 m bgs to 2.7 m bgs. Data from 1.8 m bgs showed significant temporal variability from 2006 (~2 orders of magnitude lower average concentration than either model would predict) to 2007 (not much different than either model prediction). The Dominant Layer Model showed about 2 orders of magnitude reduction in vapor concentrations relative
to the no-degradation model at a depth of about 0.5 m bgs, and significantly more (up to 10 orders of magnitude) degradation in shallower (i.e., sub-slab) sample depths. Note that sub-slab concentrations were mostly (2007) or all (2006) non-detect values, some with elevated reporting limits, and average sub-slab concentration was calculated using $\frac{1}{2}$ of the reporting limit as a surrogate for non-detect results, which imposes a positive bias in the average measured values, by an unknown amount.

One dimensional modeling was also used to calculate the vapor intrusion attenuation factor, $\alpha$, for the degradation and no-degradation scenario. The calculated vapor intrusion attenuation factors for the degradation and no-degradation scenario are $2E-6$ and $1E-23$, respectively. This indicates that very significant attenuation due to biodegradation is possible even with a very limited (e.g., 0.3 m thick) degradation zone. Considering that the 1.8 m depth samples in October 2006 indicated a much thicker degradation layer, the model simulations presented here are considered to represent a minimum estimate of the actual amount of attenuation.

**DISCUSSION**

This case study provides a significant amount of new information regarding the subsurface distribution of hydrocarbon vapors and the influence of biodegradation as an attenuation mechanism in the assessment of subsurface vapor intrusion to indoor air. Very high hydrocarbon vapor concentrations occur in the lower vadose zone, based on samples at depths of 2.7 and 3.6 m bgs, with elevated carbon dioxide and very little oxygen. Shallower soil gas (1.8 m bgs) and sub-slab soil gas samples have significantly lower hydrocarbon vapor
concentrations, indicating that there is a biologically active layer in the shallow subsurface. Concentrations of benzene are reduced from tens of thousands of micrograms per cubic meter (µg/m³) to less than 100 µg/m³ over a vertical distance of as little as about 1.8 m, and possibly to much lower levels, because most of the sub-slab samples had benzene concentrations below the analytical reporting limit.

Spatial variability of up to several orders of magnitude was observed within the study area, which was no larger than a typical domestic residence. Seasonal variability of up to two orders of magnitude is demonstrated in the shallow samples, although deeper soil vapor samples showed much less or no significant seasonal variability, despite dramatic changes in rainfall between the two monitoring events. For the shallow (1.8 m and subslab) intervals, there is an apparent correlation between increases in the hydrocarbon vapor concentrations and the significant increase in rainfall prior to the June 2007 sampling event, which may have limited oxygen supply to the subsurface, relative to the prolonged drought that preceded the October 2006 sampling event. Short-term temporal variability does not appear to be significant, even in shallow (sub-slab) samples.

The QA/QC procedures demonstrated that high quality soil gas samples can be collected with appropriate care and rigorous protocols, even from moderate to very low permeability materials. Compression-fittings and a bentonite slurry seal throughout the borehole annulus were considered key to collecting samples with little or no leakage. In very low permeability soils, it may require some time and effort to evacuate atmospheric air entrained during probe installation prior to collection of a representative sample for laboratory analysis.

ACKNOWLEDGEMENTS

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REFERENCES

Effects of Alternate Petroleum Hydrocarbon Sources in the Vadose Zone on the Vapor Intrusion Pathway beneath a Residential Community

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ABSTRACT
Vapor intrusion (VI) evaluations at hydrocarbon sites often include installation of nested vapor wells to assess the nature, extent, fate, and transport of volatile constituents from the source at depth to the shallow subsurface. The impact of localized, alternate sources of petroleum hydrocarbons from shallow/surface releases are rarely defined yet have the potential to significantly affect the VI pathway, primarily by depleting oxygen as it diffuses through the vadose zone. This paper presents data demonstrating the effects of alternate sources on the VI pathway beneath a community situated above a petroleum hydrocarbon plume.

The subsurface consists of homogeneous coarse-grained glacial and alluvial deposits. Groundwater is located between 40 and 60 feet below ground. The limits of the smear zone and dissolved phase plume are well defined. Eight nested vapor wells were installed at locations over the smear zone, dissolved phase plume, and background areas (at 5- and 10-foot intervals). The VI pathway has been extensively studied over the past 13 years, and migration of volatile constituents has been shown to be incomplete due to aerobic biodegradation.

Vapor extraction has been performed to enhance mass reduction of the smear zone since 1999 and was suspended for 22 months during an independent VI investigation between 2008 and 2009. Monitoring results in areas of known alternate petroleum releases were unique from those in areas not affected by alternate sources. Lines of evidence considered in assessing the differences in the migration pathway include the evaluation of hydrocarbon and fixed gas profiles, numeric modeling, and analysis of the percent composition of selected hydrocarbons. These lines of evidence all support the conclusion that alternate sources of hydrocarbon vapors are limiting the supply of oxygen, thereby reducing the rate of aerobic degradation of the hydrocarbons originating at the source at depth and contributing to volatiles measured in shallow and intermediate probes.

INTRODUCTION
At many petroleum release sites, light non-aqueous phase liquids (LNAPL) and dissolved phase hydrocarbons migrate in the subsurface and may be present beneath structures both at and nearby the area of release. Some petroleum hydrocarbons associated with these releases are sufficiently toxic to pose a health risk due to volatilization and migration of vapors into structures. The primary mechanism for vapor migration into overlying buildings is the upward diffusion of hydrocarbon vapors from the LNAPL or dissolved phase source at the water table. Along this pathway, the migration of hydrocarbon vapors can be retarded by dissolution into pore moisture or adsorption to soil particles. Where oxygen \(O_2\) is present at sufficient concentrations, soil microbes will
metabolize the petroleum hydrocarbons in the pore moisture, while consuming O\textsubscript{2} and producing carbon dioxide (CO\textsubscript{2}). Microbiologic degradation also occurs in the absence of O\textsubscript{2}, producing methane (CH\textsubscript{4}). The CH\textsubscript{4} will subsequently diffuse upward and be degraded aerobically along with other hydrocarbons at shallower depths where O\textsubscript{2} concentrations are (typically) higher. Anaerobic biodegradation of hydrocarbons generally occurs at a much slower rate compared to aerobic degradation.

Aerobic biodegradation of hydrocarbon vapors often occurs in a relatively thin zone, where the concentrations of O\textsubscript{2} and volatile constituents in the soil vapor are optimal for the growth of petrophyllic bacteria, as described by DeVaull et al. 1997\textsuperscript{1}. Aerobic biodegradation has the potential to reduce soil gas concentrations by several orders of magnitude, as long as the supply of O\textsubscript{2} is not rate limiting (DeVaull et al. 1997\textsuperscript{1}, DeVaull et al. 2002\textsuperscript{2}, Roggemans et al. 2001\textsuperscript{3}, Abreu et al. 2009\textsuperscript{4}).

Oxygen in the atmosphere diffuses down into the unsaturated zone when a concentration gradient is present. Atmospheric O\textsubscript{2} also migrates downward advectively via barometric pumping and by infiltration of dissolved O\textsubscript{2} in rainwater. Barometric pumping occurs in response to changes in atmospheric pressure and the compressibility of gas; typical barometric pressure changes are 1,000 to 3,000 Pascals per day, which is about 1 to 3% of atmospheric pressure (Massmann 1992\textsuperscript{5}). This process ensures that the upper 1 to 3% of the thickness of the vadose zone is well aerated (O\textsubscript{2} concentrations similar to atmospheric levels). In the absence of aerobic degradation, O\textsubscript{2} levels will approach atmospheric levels throughout the vadose zone. Where O\textsubscript{2} is consumed, a concentrations gradient will develop, which is the driver for downward diffusion.

Indoor air and shallow soil gas often contain measurable concentrations of volatile and semivolatile compounds from household activities, consumer products, building materials, furnishings, and ambient air sources. Discussions of background sources of chemicals and typical concentrations in indoor air can be found in NJDEP 2005\textsuperscript{6}, NYSDOH 2005\textsuperscript{7}, Batterman 2007\textsuperscript{8}, USEPA 2008\textsuperscript{9}, MADEP 2008\textsuperscript{10}, Dawson and McAlary 2009\textsuperscript{11}, and in numerous other documents. Complexities from background sources make it very difficult to assess whether VI is significant at hydrocarbon sites using indoor air data, which is one of the main reasons soil vapor characterization is very important. Evaluating hydrocarbon distributions in the vadose zone often involves installation of nested soil vapor monitoring wells to assess the vertical profile of volatile constituents, O\textsubscript{2}, and CO\textsubscript{2} from the source at the groundwater table to the shallow subsurface.

In many cases, the alternate sources of volatile petroleum hydrocarbons within and beneath structures contain many of the same chemicals present from a LNAPL or dissolved-phase source that has migrated from a petroleum release (e.g., benzene is commonly present in a wide variety of products, and is often the compound posing the greatest potential risk via the VI pathway at hydrocarbon sites). Data collected from nested vapor monitoring wells are typically assumed to be unaffected by alternate petroleum hydrocarbon sources. However, as discussed herein, alternate sources have the ability to affect soil vapor data collected from nested wells in the same way alternate indoor air sources complicate evaluations of the VI pathway within the structures.

An understanding of the spatial variability of aerobic biodegradation mechanisms within the vadose zone has primarily been limited to studies (Laubacher et al. 1997\textsuperscript{12}, Hers and Zapf-Gilje 1998\textsuperscript{13}).
McAlary et al. 2007, Luo et al. 2009) and numerical modeling (Abreu and Johnson 2005 and 2006) of a single building scenario. Roggemans et al. 2001 evaluated aerobic biodegradation of petroleum hydrocarbons using data collected from nested soil vapor monitoring wells at a number of petroleum hydrocarbon release sites. Only sites with data sets consisting of petroleum hydrocarbons and fixed gases (i.e., O$_2$ and CO$_2$) were considered in the assessment of the significance of aerobic biodegradation mechanisms and resulting flux of volatile petroleum hydrocarbons from the vapor source. Four general categories were identified (described by Roggemans et al. as Behaviors A through D) that described the relationship of the hydrocarbon and fixed gas profiles at the petroleum release sites. The behaviors were not predicted by thickness of the vadose zone or ground surface cover (e.g., pavement versus uncovered). The four categories can be summarized as follows:

- **Behavior A ("Transport-Limited Biodegradation Settings")** – hydrocarbon vapor concentrations decrease with increasing distance above the source more rapidly than expected due to diffusion alone, with three distinct zones:
  1. The first zone is from the source to a depth where active aerobic biodegradation occurs. This zone is anoxic, and diffusion is the primary transport mechanism. Petroleum hydrocarbon vapor concentrations decrease marginally, if at all, with little or no evidence of aerobic degradation (CO$_2$ production, loss of hydrocarbons).
  2. The second portion of the profile represents the active zone of aerobic biodegradation, with dramatic reduction of hydrocarbon concentrations, consumption of O$_2$ and production of CO$_2$, typically over a short vertical interval.
  3. In the third zone (above the biologically active layer), hydrocarbon concentrations are typically very low or not detectable, and O$_2$ concentrations usually approach atmospheric conditions at ground surface.

- **Behavior B ("Aerobic Biodegradation Rate-Limited Settings")** – hydrocarbon vapor concentrations decrease and O$_2$ concentrations increase above the source at depth to the ground surface, similar to the Behavior A wells. However, O$_2$ is never reduced below 5%, and aerobic conditions prevail throughout the vadose zone. This category might be expected where the vapor source is weak compared to Behavior A sites, or at sites with a thinner vadose zone and vapor transport from the source is greater than the aerobic biodegradation rate.

- **Behavior C ("O$_2$ Deficient Subsurface Settings")** – hydrocarbon vapor concentrations are persistent and O$_2$ is depleted throughout the vertical profile. Volatile petroleum constituents migrate by diffusion from the source to the shallow subsurface. Roggemans et al. 2001 theorized that Behavior C sites would be observed in the presence of surface covers (i.e., pavement), structures, or elevated moisture content in the soils, which would limit O$_2$ transport. However, this hypothesis was not supported by data collected at several locations representative of this behavior-type.

- **Behavior D ("Near-Source High Diffusion Resistance Soil Gas Profiles")** – hydrocarbon vapor concentrations show a rapid decrease ("several orders of magnitude") in volatile petroleum concentrations located directly above the vapor source and O$_2$ concentrations decrease as a function of diffusion through the soil vapor profile with a steeper decline directly above the vapor source. The decrease is a result of a higher diffusive resistance zone directly above the source (e.g., thick capillary fringe) combined with rapid aerobic biodegradation.
Roggemans et al. 2001 concluded that all of the evaluated petroleum release sites showed evidence of aerobic biodegradation of petroleum hydrocarbons in the data collected from the nested soil vapor monitoring wells. However, the hydrocarbon flux (assessed using a no-biodegradation base case) was attenuated from 0% at some Behavior C wells to more than 99.99% at several Behavior A locations. This variability is one of the main reasons regulatory guidance for VI has been slow to allow for consideration of biodegradation.

It is important to understand the processes contributing to or limiting aerobic biodegradation and the affect on vapor flux at petroleum release sites. This becomes particularly important when multiple sources are present because shallow alternate sources are rarely well characterized yet have the potential to significantly affect the VI pathway, primarily by depleting O$_2$ as it diffuses through the vadose zone. The data collected during this study provide information regarding the spatial and temporal variability of O$_2$ and volatile concentrations across a petroleum release site and may have implications for evaluating the VI pathway using nested monitoring wells as a primary line of evidence.

**Site Description**

The subject site is a mixed residential and commercial community, situated in the Midwestern United States. The community lies within a glacial-incised valley that was subsequently filled with coarse-grained outwash and alluvial deposits, with an overall coarsening sequence with increasing depth. The soil gas permeability of these deposits are generally between 1E-7 to 1E-9 square centimeters, typical for medium to coarse grained sands.

Groundwater is located between 40 and 60 feet below ground surface (ft-bgs). A portion of the town overlies LNAPL associated with historical petroleum releases from an adjoining facility. LNAPL is present within a vertical smear zone approximately 15 to 20 feet thick, associated with seasonal fluctuation of the water table. A stable dissolved phase hydrocarbon plume extends beyond the smear zone but is limited in extent due to aerobic and anaerobic natural attenuation.
mechanisms within the saturated zone. The limits of the smear zone and dissolved phase plume are well defined, as shown on Figure 1.

**SCOPE AND METHODS**

Eight nested vapor monitoring wells, with probes installed at 5- and 10-foot intervals, have been installed over the smear zone, dissolved phase plume, and background areas (Figure 1). The first three monitoring wells (VW-93, VW-96, and VW-99) were installed in 1997 and are located within the limits of the smear zone beneath the community. The wells were constructed with soil vapor monitoring probes above the vapor source at 60 ft-bgs to 10 ft-bgs, with probes situated at 5-foot intervals throughout the vadose zone. Soil vapor probes were constructed of a 1-inch Schedule 40 polyvinyl chloride screen with a slot size of 0.010-inches and a screen interval of approximately 3 inches. A silica sand filter pack was placed from approximately 6 inches below to 12 inches above the screened interval. Bentonite emplaced and hydrated in 6-inch lifts separates the filter pack surrounding each probe. Monitoring began in 1997 using the three nested vapor monitoring wells installed over the smear zone and five monitoring events were performed from 1997 to 1999.

In June 1999, a vapor extraction system was installed beneath the community as part of interim measures to reduce the smear zone mass. The soil vapor extraction system was designed to remove volatile petroleum hydrocarbons at a high rate initially, with an expectation that the mass removal rate would gradually diminish as the hydrocarbons within the smear zone were depleted, at which time the system would be operated intermittently and ultimately shut down. The system was constructed with the capacity to extract and treat vapors at a flow rate of 3,500 standard cubic feet per minute (scfm), but is typically operated using a single extraction line at flow rates between 1,200 and 1,600 scfm. The system commenced operation in November 1999 and operated nearly continuously through May 2001. The system was then operated by cycling each line for a period between one day and four months beginning May 29, 2001 through December 27, 2007. More than 530,000 pounds of petroleum hydrocarbons have been removed from the vadose zone beneath the community since 1999.

Between June 1999 and 2004, field measurements of fixed gases and total organic vapor were used to monitor the vapor extraction system and its effectiveness at removing hydrocarbon mass. These measurements were also used to evaluate O₂ transport to the deep portions of the vadose zone and the impact of the system on aerobic biodegradation rates beneath the community. Soil vapor samples were not collected from the nested wells for laboratory analysis.

In 2004, additional vapor sampling was requested by the regulatory agency. A shallow soil vapor probe was installed at the 5 ft-bgs interval within nested monitoring wells VW-93, VW-96, and VW-99. The shallow vapor probes were constructed in a similar fashion to those installed in 1997. Four additional nested monitoring wells were installed in 2005. Two of the nested wells (VW-127 and VW-128) were installed above the dissolved phase plume, and the other two wells (VW-129 and VW-130) were installed in areas outside the distribution of petroleum hydrocarbons associated with historic releases (Figure 1). These four wells were installed with probes located at 5, 10, 15, 20, 30, 40 and 50-ft-bgs.
The final vapor nested monitoring well (VW-139) was installed in 2009 in an area outside the residential community but overlying the smear zone. The vadose zone is only 40 feet thick in this portion of the plume, and probes were completed at 5, 10, 15, 20, 30, and 40 ft-bgs. Probes installed in 2005 and later were completed with a 6-inch long, stainless steel GeoProbe™ screen in a similar fashion as that described previously. In 2005 and 2009, seal testing was conducted within each of the nested wells to ensure that there was no leakage across the seals between vapor monitoring probes.

Soil vapor sampling conducted from 1997 to 1999 consisted of measuring total petroleum hydrocarbons (generally using USEPA Method TO3) and fixed gases (via Landtec™ GEM 500). Between 2005 and 2007, additional monitoring was performed using the seven nested monitoring wells installed in the community. Six monitoring events were performed targeting a range of seasonal and remedial system operating conditions. Soil vapor sampling conducted between 2005 and 2007 followed the procedures described in the EPRI Reference Handbook for Vapor Intrusion Assessment (2005) using helium as a tracer gas to confirm the integrity of the sample. Samples were analyzed for volatile petroleum related constituents via USEPA Method TO15 and fixed gases using ASTM Method 1945/1946. The soil vapor sampling methodology was modified again in early 2008 to include helium tracer testing across the entire sample manifold in conformance with procedures later described in McAlary et al. 2009.

RESULTS AND DISCUSSION
The VI pathway has been extensively studied over the past 13 years. Monitoring has been conducted during 11 separate months, including each of the four calendar quarters. Soil vapor samples have been collected during both high and low groundwater conditions, during periods of elevated precipitation and periods of drought, and during periods of high and low seasonal temperatures.

The data collected between 1997 and 1999 indicated that aerobic biodegradation limited the flux of volatile petroleum hydrocarbons to within 20 feet above the smear zone, and the VI pathway was incomplete. The vertical profiles of total volatile petroleum hydrocarbons (TVPH) and \( O_2 \)

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a. The vertical profiles for total volatile petroleum hydrocarbons (TVPH) provided herein represent a mixture of hydrocarbon constituents whose composition can vary significantly both spatially (sample interval in each nest) and temporally (across sample events). TVPH was reported as a single concentration in the soil gas samples collected prior to 2005. For samples collected since 2005, TVPH was estimated by summing the concentration of the individual petroleum-related constituents reported via SW846 Method TO15. For constituents reported as “non-detect,” half the detection limit was used as a surrogate in the estimation of the TVPH concentration given the uncertainty associated with the actual concentration for those constituents. The analyte list has varied during the monitoring events conducted since 2005; therefore, the profiles may show changes related to these variations in the analyte list and not as a result of an increase or decrease in the petroleum-related constituent concentrations throughout this timeframe. Methane was not included in the TVPH concentration calculations. Methane data is generally available for monitoring events performed from September 2005 and forward. The methane data is generally dominated by non-detect results with detections observed directly above the vapor source for most of the events (exceptions would include events which occurred in the summer months prior to operation of the soil vapor extraction system, as the water table falls and moisture content decreases throughout the vadose zone). Methane results are provided on Figure 10 presenting the 2008 and 2009 results for wells VW-96 and VW-99. Inclusion of the methane data would serve to complicate the TVPH and \( O_2 \) profiles for the 2005 through 2007 results provided as Figures 5 through 9.
for wells VW-93, VW-96, and VW-99, shown on Figures 2 through 4, resembled those classified as Behavior A by Roggemans et al. 2001. Elevated concentrations of TVPH above the 30-foot interval in well VW-96 and the 25-foot interval in nested well VW-99 can be observed on the vertical profiles, appearing as a reversal in the concentration gradient. These wells are located outside of any potential release areas associated with hydrocarbons present within the smear zone.

The results from monitoring conducted between 2005 and 2007 supported previous findings and demonstrate that upward migration of vapors via diffusion is offset by aerobic biodegradation. TVPH concentrations decrease rapidly to non-detectable levels and/or below human health risk-based screening levels at depths shallower than approximately 30 ft-bgs. For two of the three wells (VW-96 and VW-99) installed above the smear zone in the community, the vertical profiles, as shown on Figures 5 and 6, were once again similar to the Behavior A locations described by Roggemans et al. 2001. The zone of aerobic biodegradation, where there is rapid attenuation of hydrocarbon concentrations coinciding with consumption of O₂, fluctuates within the vertical profile, likely as a function of groundwater table elevation (vapor concentrations are generally higher at low water table elevations) as well as changes in soil moisture content.

The vertical profile for the remaining nested well situated over the smear zone (VW-93) shown on Figure 7, and the two wells located above dissolved phase petroleum hydrocarbons (VW-127 and VW-128) shown on Figures 8 and 9, were similar to Behaviors D and B, respectively. The shift in the profile for nested well VW-93 from Behavior A to D is attributable to reduction in the vapor source concentration due to aerobic biodegradation enhanced by soil vapor extraction.

In 2008 and 2009, an independent VI investigation was conducted by state and federal public health and environmental regulatory agencies. During the investigation, operation of the soil vapor extraction system was suspended for 22 months, which was longer than any other period.
since the soil vapor extraction system was commissioned. Vapor samples were collected from each of the nested monitoring wells by the facility owner during four events (April 2008, September 2008, December 2008, and October 2009) for comparative purposes to agency-collected results. In addition, during the October 2009 monitoring event, soil vapor samples were collected from nested well VW-139 for comparison to results from the wells within the community situated over the smear zone.

In general, the results from the 2008 and 2009 investigation support the conclusion that migration of volatile petroleum-related constituents from the vapor source was limited by aerobic biodegradation mechanisms. However, the data collected from nested vapor monitoring wells VW-96 and VW-99 between December 2008 and October 2009 were not consistent with previous soil vapor monitoring results, indicating that previously unidentified or new conditions were present that warranted further analysis. The results from these latest monitoring events showed low $O_2$ and elevated TVPH concentrations in shallower samples than observed previously.

**ALTERNATE SOURCE ASSESSMENT**

Nested soil vapor monitoring wells VW-96 and VW-99 are located in portions of the community associated with residential and commercial vehicle parking and maintenance activities. In addition, individual septic systems were used to treat household wastewater prior to the extension of a municipal sanitary sewer system into the community in 2006. Several studies, including DeWalle et al. 1985 and Conn and Seigrist 2009, document releases of volatile petroleum-related constituents from septic systems. Robertson et al. 1991 evaluated concentrations of inorganic constituents and plume lengths associated with septic systems installed within a sand and gravel lithology. They reported reduced $O_2$ concentrations and inorganic plumes associated with a single household septic system that extended more than a mile from the source. Inadequately abandoned individual septic systems may continue to use available $O_2$ as it diffuses through the vadose zone. Releases of petroleum constituents associated with
discharges from household products, underground and aboveground storage tanks, and commercial businesses (e.g., automotive repair, long-haul trucking, construction, etc.) may continue to volatilize in the shallow and intermediate portions of the vadose zone. Considering the number of potential alternate sources, additional assessment activities were conducted within the community.

Analytical results from April and September 2008 for wells VW-96 and VW-99, shown on Figure 10, are consistent with sampling conducted during 2005 through 2007, as well as historical data collected from 1997 to 1999. These data generally show a rapid decrease in vapor concentrations from the vapor source to approximately 30 to 50 ft-bgs. A corresponding consumption of O₂ is noted in deep portions of the vadose zone, indicating that aerobic degradation is the primary mechanism for these reductions.

An increase in vapor concentrations is observed in the vapor profile for nested wells VW-96 and VW-99 above 30 feet during monitoring performed between 1997 and 1999, and again in April and September 2008 and 2009. This increase in the TVPH concentrations observed in the shallow and intermediate portions of the vadose zone are not consistent with diffusion of vapors from a single source located at the groundwater table. Diffusion occurs as a result of concentration gradients, where chemicals move from areas of high concentration to areas of low concentration. The reverse concentration gradients observed in these two wells during selected events are consistent with the presence of an alternate source of petroleum hydrocarbons that may have migrated downward into the vadose zone from a release at or near ground surface.

During monitoring performed between 2005 and 2007, contributions from these alternate sources were not observed in the vertical profiles from these two wells. Soil vapor conditions within the vadose zone during these events were affected by the soil vapor extraction system, which was operated on a seasonal basis beginning in 1999. Soil vapor extraction advectively transports atmospheric O₂ into the vadose zone, enhancing the rate of aerobic biodegradation. Monitoring in October 2005 (Figures 5 through 9), conducted during operation of the vapor extraction system,
show that $O_2$ concentrations are enhanced, approaching atmospheric levels throughout much of the vadose zone. As a result, petroleum-related constituents volatilizing from the alternate sources above the vapor source were aerobically degraded to non-detect or background levels.

During events conducted in December 2008 and October 2009, the vertical profiles (Figure 10) show a decrease in TVPH concentrations from the vapor source in the smear zone to shallower depths; however, the reduction in concentrations is less dramatic than observed during previous events. The fixed gas data for these events show that $O_2$ is being consumed at shallower depths in the vadose zone. Soil vapor samples were collected during low water table conditions in December 2008 and October 2009, following shutdown of the soil vapor extraction system for more than 12 and 22 months, respectively.

The profiles for data collected in 2008 and 2009 show little or no $O_2$ in the upper portions of the vadose zone, which in turn limits degradation in deeper portions of the unsaturated zone. The time sequence plots show consumption of $O_2$ occurring at increasingly shallower depths over the timeframe that the vapor extraction system remained idle. There is a shift from Behavior A-like profiles as described by Roggemans et al. 2001, with a clear distinction between the vapor source at depth and the alternate sources present in the shallow and intermediate portions of the vadose zone during the April and September 2008, to Behavior B-like profiles with anoxic conditions present throughout much of the vadose zone, as observed during the December 2008 and October 2009.

For comparative purposes, soil vapor samples were collected from nested well VW-139 during the October 2009 monitoring event. The vertical profile is provided on Figure 11. The vadose zone is approximately 40 feet thick at this location, compared to 60 feet near nested wells VW-96 and VW-99. The vapor source TVPH concentration approaches 10,000 milligrams per cubic meter (mg/m$^3$) in all three of these wells located above the smear zone (VW-96, VW-99, and
VW-139). There are no potential alternate sources of petroleum-related constituents observed at VW-139. Therefore, $O_2$ was able to diffuse into deeper portions of the vadose zone, resulting in a significant reduction (by 30 ft-bgs) of TVPH concentrations. Even with the thinner vadose zone, concentrations are reduced to non-detect or background levels within 10 feet above the smear zone at VW-139. It is anticipated that if alternate sources were not present near nested vapor wells VW-96 and VW-99, the profiles from these locations would be similar to those observed at nested well VW-139.

Rapid Optical Screening Tool (ROST) Assessment
A subsurface assessment was performed in 2009 to more fully define potential alternate sources of petroleum hydrocarbons in the shallow and intermediate portions of the vadose zone near well VW-96. As part of this assessment, ROST borings were installed to provide physical and chemical characteristics of the vertical distribution of petroleum hydrocarbons within the vadose zone and upper portions of the saturated zone during two events performed in December 2009. The ROST uses a laser induced fluorescence system to detect petroleum hydrocarbons present as LNAPLs in the subsurface. The laser was calibrated prior
to each event using a standard containing the spectrum of petroleum hydrocarbons that can be detected by the laser fluorescence system. The fluorescence data collected using the ROST is consistently normalized as a percentage of the intensities measured within the reference standard because the power output of the laser can change due to environmental conditions (i.e. temperature, humidity, etc.) and aging of the system. The area of each waveform taken during a test is reported as a percentage of the area of the standard waveform.

The December 2009 ROST profile, provided on Figure 12, shows high fluorescence intensities between 5 and 15 ft-bgs, as well as between 25 and 30 ft-bgs, representing proportionally higher concentrations of petroleum hydrocarbons when compared to lower fluorescence intensities with relatively little to no response between 30 and 50 feet (with the exception of a spike near 47 ft-bgs associated with the upper limits of the smear zone). The elevated intensities observed within the upper 30-feet of the profile during these two events are indicative of alternate petroleum-related sources in the vadose zone, because these responses are well above the seasonal high water table and corresponding upper limit of the smear zone.

Changes in the relative proportions of the four wavelengths and color of the fluorescence response represent change in the LNAPL chemistry. The colors observed in the upper 30 feet of the ROST profiles during the June and December 2009 events are different LNAPL from those observed within the smear zone. The shallower data shows a higher proportion of low wavelength response, which is indicative of lighter weight hydrocarbons. Lighter compounds usually volatilize and degrade faster than heavier hydrocarbons, so this may indicate the shallower regions contain LNAPL released more recently than LNAPL within the smear zone.
Percent Compositional Profiles
Individual petroleum-related constituents are expected to degrade at different rates based on the availability of O₂, as well as other sources of energy (i.e., more degradable constituents) for petrophyllic bacteria. The degradation rates can be compared by evaluating the vertical profile of the percent composition of each hydrocarbon constituent. Monoaromatic (e.g., benzene) and n-alkane (e.g., n-hexane) hydrocarbons are generally more degradable than highly branched alkanes (e.g., 2,2,4-trimethylpentane). As such, if there is a single source of petroleum hydrocarbons at depth and aerobic biodegradation within the vadose zone, the branched alkanes and other less degradable hydrocarbons should show an increase in the percent composition from the source to the ground surface while the more degradable monoaromatics and n-alkanes should show a decrease in percent composition within soil vapor moving away from the source. Figure 13 shows the percent composition of selected petroleum-related constituents (including isopentane; 2,2,4-trimethylpentane; butane; hexane; cyclohexane; and methylcyclohexane) present in samples collected from nested wells VW-96, VW-99, and VW-139 during the October 2009 monitoring event.

The percent composition profile for nested well VW-96 shows an increase in the percentage of 2,2,4-trimethylpentane and a decrease in the more degradable constituents from the source at 60 ft-bgs to 20 ft-bgs that is consistent with degradation of hydrocarbons from a single source at the water table. However, the percent composition of 2,2,4-trimethylpentane decreases, and the
other degradable constituents increase from 20 ft-bgs to 10 ft-bgs, which is not consistent with the expected profile from a single source. This reversal of the expected trend may be indicative of an alternate source of petroleum hydrocarbons in the upper portion of the vadose zone, which yields vapors that are less extensively degraded because of their proximity to the alternate source.

The percent composition of 2,2,4-trimethylpentane in samples collected from well VW-99 in October 2009 shows an increasing trend between the vapor source and 35 ft-bgs, followed by a slight decreasing trend to 15 ft-bgs, with a sharp increase to the ground surface. This trend is notably different than the expected trend in the 15 to 35 foot depth interval. Isopentane shows an inverse relationship to 2,2,4-trimethylpentane (as expected because faster degradation of isopentane should result in an increased proportion of 2,2,4-trimethylpentane in the remaining vapors); therefore, the isopentane data are also not consistent with the trend expected for a single source at the water table. Cyclohexane and methylcyclohexane show an increase in the percent composition present in the soil vapor samples from 35 ft-bgs to 20 ft-bgs, which is also not expected for a single source at the water table.

The percent composition of the constituents measured in samples collected from well VW-139 in October 2009 show a dramatic decrease from the smear zone at 40 ft-bgs to non-detect concentrations throughout the remainder of the profile. This profile is expected in cases where O\textsubscript{2} transport is not limited (i.e., no alternate sources present in the vadose zone) and complete aerobic biodegradation of the source is present at depth. The percent composition profiles for nested wells VW-96 and VW-99 demonstrate the presence of an alternate hydrocarbon source in the shallow vadose zone near these wells, resulting in O\textsubscript{2} consumption and decreased hydrocarbon degradation.

Mathematical Modeling
Mathematical models provide a benchmark for comparison to field measurements, which can be used to infer the processes and mechanisms affecting chemical transport through the subsurface. The data collected in October 2009 from nested wells VW-96, VW-99, and VW-139 were analyzed using a mathematical model that solves equations representing diffusion and first-order degradation, referred to as the Dominant Layer Model (DLM) by Johnson, et al. 1999\textsuperscript{23}. The time series profiles (Figure 10) for wells VW-96 and VW-99 show an evolution in the O\textsubscript{2} and CH\textsubscript{4} profiles from an initial condition that is predominantly aerobic throughout the vadose zone to predominantly anaerobic conditions with a nearly linear CH\textsubscript{4} profile during October 2009. This would be consistent with diffusion dominated transport with minimal aerobic biodegradation. In October 2009, the concentrations of CH\textsubscript{4} in shallow samples were higher than previously observed (about 5% in samples from 10 to 20 ft-bgs in nested well VW-96 and 15 to 25 ft-bgs in VW-99); inversely, the concentrations of O\textsubscript{2} in the shallow samples were lower than previously observed (minimal concentrations at depths of 5 ft-bgs in nested well VW-96 and 15 ft-bgs within monitoring well VW-99). Considering that the concentration of CH\textsubscript{4} was far greater than the remainder of petroleum hydrocarbons, it would impose the highest O\textsubscript{2} demand. As such, DLM simulations were performed using CH\textsubscript{4} for data collected from wells VW-96, VW-99, and VW-139 during the October 2009 monitoring event. The simulations were used to assess whether the first order aerobic biodegradation rate (\(\lambda\)) that generated the best match
between the data and the model was consistent with literature cited values. According to a compilation by DeVaull 2007\textsuperscript{22}, aerobic biodegradation rates are typically in the range of about 96 to 28,000 day\textsuperscript{-1} for straight-chain aliphatic hydrocarbons. However, longer-chained hydrocarbons generally degrade at slower rates, so CH\textsubscript{4} would be expected to degrade with a higher rate constant. DLM simulations for wells VW-96, VW-99, and VW-139 are provided as Figure 14.

The CH\textsubscript{4} data collected from nested well VW-139 shows a dramatic decrease from 2\% in the deepest sample near the smear zone at 40 ft-bgs to non-detect concentrations (less than 0.0005\%) throughout the remainder of the profile (Figure 11). The gas permeability measured at well VW-139 is relatively constant over the vertical profile, so a consistent moisture content of 5.3\% was assigned for the entire profile. The DLM was assigned an active layer from 30 to 40 ft-bgs, which yielded a first-order degradation rate of 1,700 day\textsuperscript{-1}, which is the median rate for aliphatic compounds reported by DeVaull 2007\textsuperscript{24}. This profile is consistent with expectations where O\textsubscript{2} transport is not rate limited and CH\textsubscript{4} is completely degraded within a very short distance of the source, typical of Behavior A profiles described by Roggemans et al. 2001\textsuperscript{3}.
The CH₄ data collected from nested well VW-96 in October 2009 shows very little decrease in concentration from 60 ft-bgs to 30 ft-bgs that is consistent with diffusion only and no degradation. The DLM was assigned an active layer (zone of aerobic degradation) from 1 to 25 ft-bgs. Soil gas permeability data from well VW-96 indicate decreased permeability from approximately 15 to 25 feet deep. Less permeable materials often retain moisture at higher field capacity levels, resulting in a lower diffusion coefficient. Therefore, the lower diffusion coefficient in this portion of the vadose zone is reasonable. A water-filled porosity of 18% was assigned for the dominant layer. A degradation rate constant of 0.5 day⁻¹ resulted in the best fit with the CH₄ data (a profile for a degradation rate of zero was also plotted for comparison). The fitted degradation rate of 0.5 day⁻¹ is more than two orders of magnitude below the low end of the range of degradation rates for aliphatic hydrocarbons described by DeVaull 2007. Furthermore, some of the measured CH₄ concentrations remain higher than the modeled curve, indicating either a slower degradation rate or CH₄ production in the shallow portions of the unsaturated zone. The comparison of the DLM model and the measured data at nested well VW-96 indicates that the processes of diffusion and aerobic biodegradation from a single source at the water table are not consistent with the measured CH₄ profile during the October 2009 event. An alternative hypothesis is that a second source of petroleum hydrocarbons is present in the shallow vadose zone and is contributing to O₂ consumption and CH₄ production, yielding higher shallow CH₄ concentrations than would be expected from the smear zone at depth.

The CH₄ profile measured in nested well VW-99 during the October 2009 event shows a pronounced decrease in concentrations between the 10- and 20-foot intervals; therefore, this interval was assigned as the dominant layer for the model simulations. The gas permeability measured at well VW-99 is relatively constant over the vertical profile, and a consistent moisture content of 5.3% was assigned for the entire profile. A simulation with no aerobic biodegradation and a source concentration of 10% v/v CH₄ at 55 ft-bgs showed that most of the samples between 15 and 55 ft-bgs contained CH₄ concentrations higher than the zero attenuation simulation would predict. A second simulation with a source concentration of 10% v/v CH₄ at a depth of 35 ft-bgs was performed, and an aerobic biodegradation rate for the dominant layer was adjusted until a reasonable match with the samples collected at 5 and 10 feet deep was achieved. This yielded a first-order degradation rate of 20 day⁻¹, which is below the lower end of the range for aliphatic compounds; however, the measured concentrations at 15 and 20 ft-bgs remained higher than the modeled values. Considering that neither of these two scenarios could fit most of the data, a third simulation was performed with a source concentration of 8% v/v CH₄ at a depth of 20 ft-bgs. The degradation rate was adjusted until the model provided a reasonable fit to the concentrations measured at 5 and 10 ft-bgs. This yielded a first-order degradation rate of 100 day⁻¹, which is near the lower end of the range of degradation rates for aliphatic compounds, and therefore considered more reasonable than the other two simulations. The comparisons between the model simulations and measurements at well VW-99 indicate that diffusion and degradation from a single source at the water table are not consistent with the observed CH₄ profile, and there appear to be other factors contributing to CH₄ production at shallower depths.
SUMMARY
The hydrocarbon and fixed gas profiles from the nested soil vapor monitoring wells described herein show that aerobic biodegradation has been an important process limiting the upward migration of vapors during monitoring events performed since 1997. During sampling conducted in 2008 and 2009, O₂ was consumed in shallower portions of the vadose zone near nested wells VW-96 and VW-99 thereby reducing the rate of aerobic biodegradation. Several lines of evidence were assessed including (1) ROST assessment, (2) analysis of the percent composition of highly degradable (e.g., isopentane) and more recalcitrant (e.g., 2,2,4-trimethylpentane) petroleum constituents across the vertical profile, and (3) comparisons between the DLM simulations and measured concentrations of CH₄, particularly the differences in these profiles at different locations. Collectively, these analyses support the conclusion that the differences in the vertical profiles of hydrocarbon concentrations for wells VW-96 and VW-99 observed between 2008 and 2009 are attributable to the presence of alternate sources of petroleum hydrocarbon vapors in the shallow and intermediate portion of the vadose zone, which likely resulted from near-surface releases.

Where there is the potential for VI associated with petroleum releases, nested wells are often recommended as a primary means of evaluating the pathway from the source to the shallow subsurface. One of the underlying assumptions in this approach is that the vadose zone conditions and the distribution of volatile petroleum hydrocarbons are adequately represented by the placement of a few nested wells within the distribution of petroleum hydrocarbons present at the water table. The results of this study suggest that there may be considerable spatial and lateral variability in aerobic biodegradation mechanisms and resultant vapor flux at petroleum release sites, particularly where alternate sources are present. This should be considered in the design of a site characterization program as well as evaluation VI pathway. Further studies at other petroleum release sites, as well as bench scale studies may be warranted to better understand spatial and temporal variations in aerobic biodegradation rates within the vadose zone. A more comprehensive understanding of the relationship between O₂ and vapor source concentrations may allow for improved methodologies for predicting the vapor flux associated with petroleum releases at the water table.

REFERENCES


Todd A. McAlary  subsurface vapor transport and inhalation exposure
Principal  groundwater investigation and remediation
chemical fate and transport modeling
innovative technology development

EDUCATION

University of Waterloo:  M.Sc., Earth Sciences - Hydrogeology/Geochemistry, 1989
  Thesis: Comparison of Measured and Calculated Vapor Diffusion Coefficients
  in Unsaturated Sands
University of Waterloo:  B.A.Sc., Geological Engineering, 1986, Dean’s List
  Thesis: The Behaviour of Volatile Organic Compounds in Groundwater
  Monitoring Piezometers
University of Waterloo: Ph.D. Candidate, Chemistry, 2009 to present.
  Thesis: Comparison of Four Passive Samplers for Vapor Intrusion Assessment

CAREER SUMMARY

Todd is an expert in the evaluation of contaminant fate and transport in groundwater
and the vadose zone. He has over 25 years of consulting experience on environmental
investigation and remediation projects. He is especially experienced with the migration
of volatile organic compound (VOC) vapors originating beneath and around buildings
and the assessment of inhalation exposures from subsurface vapor intrusion to indoor
air. He conducted his first assessment of vapor intrusion beginning in 1992, and has
been the Technical Director of one of the world’s largest studies of vapor intrusion
since 1997. He was invited by the USEPA in 2000 to participate in the development of
the RCRA Supplemental EI Guidance on vapor intrusion, and was one of the 3 primary
collectors (2001). He was the only non-regulator on the Steering Committee for the
U.S EPA Seminar on Indoor Air Vapor Intrusion following release of the OSWER 2002
draft Guidance and was a Panel Member for several subsequent EPA Workshops at the
AEHS conferences aimed at addressing comments on the 2002 Draft OSWER Vapor
Intrusion Guidance. He was the primary author for the Electric Power Research
Institute’s (EPRI’s) Vapor Intrusion Reference Handbook, and a contributing author or
editor to vapor intrusion or soil gas sampling guidance documents prepared by the
Interstate Technical and Regulatory Consortium (ITRC), New Jersey DEP, California
DTSC, The US Navy, Atlantic Provinces Partnership for RBCA Implementation (PIRI),
Health Canada, Ontario MOE, the UK CIRIA Group and the UK Energy Institute. Mr.
McAlary is the Practice Leader for vapor intrusion services at Geosyntec, and
coordinates inter-office staffing, training and marketing activities.
Applied Research

Passive Venting for VOC Mitigation, Army Corps of Engineers, Raritan, NJ. Principal Investigator for applied research into the use of solar and wind-powered venting systems for mitigating subsurface vapor intrusion to indoor air at a former arsenal that has subsequently been redeveloped in New Jersey for the Army Corps of Engineers.

Demonstration/Validation of Passive Samplers for Vapor Intrusion Assessment, Navy SPAWAR Division, CA. Principal Investigator for a Demonstration/Validation Study comparing five different quantitative passive samplers for use in vapor intrusion investigations for the US Navy.

Applied Research on the Use of Passive Samplers for Vapor Intrusion Assessment, Department of Defense, ESTCP Program. Principal Investigator for a 3 year, $1 Million research project for the U.S. Department of Defense (DoD) Environmental Security and Technology Certification Program (ESTCP) to demonstrate the performance of four different passive sampling technologies for soil vapor and indoor air quality monitoring compared to each other and conventional sampling methods, including laboratory and field-testing components.

Expanding the Capabilities and Applications of the Waterloo Membrane Sampler, Ontario Ministry of the Environment. Industrial Advisor for a 3-year, $150K research project to develop innovative applications for the polydimethylsiloxane (PDMS) membrane sampler for monitoring concentrations of VOCs in soil, soil vapor and groundwater to be conducted at the University of Waterloo.

In-Situ Characterization of BioAttenuation of Hydrocarbon Vapors Beneath a Building, American Petroleum Institute, OK. Principal Investigator for a detailed assessment of soil vapor transport and biodegradation in the vicinity of an office building at a former refinery in Oklahoma, sponsored by the American Petroleum Institute. The study included multiple nested soil vapor probes and a dozen sub-slab probes for sampling and analysis of hydrocarbon, vapors, oxygen, carbon dioxide and methane, in-situ measurement of vapor diffusion coefficient using helium tracer method, seasonal (wet/dry) monitoring, pneumatic testing, mathematical modeling, forensic hydrocarbon analysis and stable carbon isotope analysis.

Mathematical Modeling Study of Hydrocarbon Vapor Fate and Transport, American Petroleum Institute. Peer Reviewer for research conducted using the Abreu and Johnson (2006) 3-dimensional model for subsurface vapor transport degradation and vapor intrusion sponsored by the American Petroleum Institute and the U.S. Environmental Protection Agency. Simulations of a wide variety of generic scenarios
were performed to demonstrate the conditions expected in response to a variety of different source concentrations, depths, soil types, and building types in order to help regulators and practitioners develop conceptual models of vapor intrusion, design sampling programs, and interpret results in the context of theoretical expectations.

**Building Pressure Cycling to Discern Vapor Intrusion from Background Sources, Confidential Client, Santa Clara, CA.** Technical Director for a field demonstration in 2003 of using building pressure cycling to assess vapor intrusion at a redeveloped and re-occupied structure in central California. Indoor air samples were collected before and after using the building ventilation system to pressurize the building, and the difference in indoor air concentrations correlated very strongly to the indoor air concentrations predicted from soil vapor sampling and analysis and mathematical modeling of the soil gas to indoor air attenuation factor.

**Development of Tracer Gas Applications for Vapor Monitoring, Various Sites.** Technical Director for several applications of helium tracer testing to evaluate subsurface gas flow and transport, including: 1) soil gas sampling for vapor intrusion investigations; 2) aerobic co-metabolic degradation pilot testing; 3) in-situ respirometry testing; 4) pneumatic testing in fractured bedrock; and, 5) confirmation of the removal of drill air prior to baseline sampling of gas monitoring wells when installing soil vapor monitoring wells in bedrock using air-rotary methods.

**Soil Vapor Sampling in Low Permeability Materials, Anadarko Petroleum Corporation, Enid, OK.** Technical Director for development of specialized protocols for soil gas sampling in low-permeability soils, including pneumatic testing, tracer testing, multiple incremental sample collection and several independent lines of quality assurance and quality control.

**Development of High Purge Volume Sampling for Soil Vapor Intrusion Assessment, Hewlett Packard, Malaysia.** Technical Director for development of a High Purge Volume sampling method for vapors in soil gas, including monitoring of vapor concentrations as a function of volume removed to assess the distribution of concentrations between and beyond probe locations, volume-integrated sampling via passive samplers in flow-through cells and canister samples via slip-stream, transient monitoring of vacuum vs time and analysis using a leaky aquifer model of pumping tests to assess vadose zone stratigraphy, and helium tracer testing to verify mass balance and leakage.

**Spatial and Temporal Variability in Soil Vapor Concentrations, Chevron, WY & OH.** Invited Peer Reviewer of two extensively monitored field research sites assessing
the fate and transport of hydrocarbon vapors in the unsaturated zone at two former refinery properties led by Arizona State University and funded by Chevron.

**Soil Vapor Sampling Demonstration, Midwestern States Risk Assessment Symposium, IN.** Technical Director of the Soil Gas Monitoring Demonstration at the Midwestern States Risk Assessment Symposium in Indianapolis in August, 2006. Designed a program of sampling and analysis using multiple lines of evidence and coordinated the activities of over 30 volunteers to execute the demonstration, including three field mobilizations, two classroom sessions, field sampling and analysis, laboratory analysis, statistical correlations and field demonstrations. Tools included active soil gas sampling with Summa canisters, syringes, Tedlar bags, and ATD tubes, passive diffusive sampling, field analyses by the Trace Atmospheric Gas Analysis (TAGA) unit, two portable GCs, Method 8021, the ppbRAE™ and the TVA1000™, laboratory analyses by TO-15 and TO-17, sampling via Continuous MultiChannel Tubing™, Post-Run Tubing™, soil gas inserts and sub-slab probes, and alternative testing methods, including helium tracer testing, gas permeability testing, barometric pressure logging, and differential pressure logging (sub-slab to building).

**Demonstration of the “Fresh Water Lens” as a Barrier to Vapor Intrusion, Confidential Client, MA.** Project Manager/Technical Director of applied research to demonstrate the effect of a fresh-water lens (a.k.a. “diving plume”) as a barrier to prevent off-gassing of VOCs in groundwater at a site in Massachusetts. Depth discrete groundwater samples collected using the Waterloo Profiler™ were used to demonstrate the presence of a 5 ft thick layer of uncontaminated groundwater below the water table table (8 ft bgs), over dissolved concentrations of trichloroethylene approaching the solubility limit at shallow as 20 ft bgs. Over a decade of water level and seasonal soil vapor monitoring has been conducted to demonstrate the stability and persistence of the fresh water lens as a barrier to prevent vapor intrusion.

**Multi-Level Soil Vapor Monitoring and Numerical Modeling For Soil Vacuum Extraction Design, General Electric, Merced, CA.** Project Manager/Technical Director for field research to verify soil vapor extraction (SVE) system design at a site in Central California. Mr. McAlary designed and installed multi-level soil gas probes to a depth of 50 feet in layered alluvium, conducted individual well pneumatic tests, and monitored vacuum as a function of time, depth and distance in 1988. The data were used to calibrate a finite element model of soil gas flow and the model results agreed very well with the field measurements. The pneumatic testing and analytical/numerical analysis was subsequently applied at several other sites and used to refine the design of several full-scale SVE systems.
Assessment of Subsurface Vapor Intrusion to Indoor Air

Vapor Intrusion Assessment and Management, Confidential Client, England. Technical Director since 1997 of one of the largest investigations of subsurface vapor intrusion to indoor air in the world to date adjacent to two former sandstone quarries subsequently used for waste disposal by a chlorinated solvent production facility. The study consisted of several events of indoor air sampling and analysis at 145 properties, soil gas sampling and analysis from over a dozen events at 48 vapor monitoring wells, and was supplemented by over 300 samples of outdoor air quality, subsurface pneumatic testing, borehole and surface geophysics, building pressure and ventilation testing, applied research into phase partitioning in the unsaturated zone, statistical analysis, mathematical modeling, remedial alternatives development and cost-benefit analysis, public meetings, litigation support, and regulatory meetings.

Vapor Intrusion Assessment and Regulatory Negotiation, Confidential Client, MA. Project Manager/Technical Director/Peer Reviewer of a detailed investigation of indoor air quality in a residential area adjacent to a former industrial manufacturing facility in Massachusetts since 1992, including indoor air sampling and analysis at about 30 properties, followed by more than a decade of annual indoor air monitoring at several properties, semi-annual soil gas monitoring at 15 permanent soil gas probes, and soil vacuum extraction as a proactive preventative measure. Mr. McAlary was the first to employ depth-discrete groundwater sampling to demonstrate the presence of a “fresh-water lens” which acts as a barrier to off-gassing of vapors from the water table, maintaining a condition of no significant risk.

Vapor Intrusion Assessment, Regulatory Negotiation and Litigation Support, Chevron, OH. Technical Expert for a Site-Specific Assessment of subsurface vapor fate and transport in support of a Human Health Risk Assessment in a residential community adjacent to a former refinery in Ohio, responsible for developing protocols and work plans, training field sampling personnel for the collection of ~300 soil gas samples over a period of a few months with multi-depth nested probes, near-slab and sub-slab sampling, regulatory negotiation and support for public meetings.

Vapor Intrusion Assessment and Regulatory Negotiation, Anadarko Petroleum Corporation, Enid, OK. Project Manager and Technical Director for a Site-Specific Assessment of subsurface vapor fate and transport in residential and institutional areas adjacent to a former refinery in Oklahoma, responsible for regulatory negotiation, workplan development, protocol development, implementation of a sampling program consisting of vertical profiles of soil vapor at 6, 9 and 12 feet below ground in 43 locations during wet and dry seasons, implementing a data quality program designed to
provide unassailable quality, and development of two comprehensive reports of the monitoring program results.

**Vapor Intrusion Assessment and Mitigation, Confidential Client, Bridgewater, NJ.**
Project Director for an assessment of subsurface vapor intrusion in a residential community adjacent to a former manufacturing facility in New Jersey, consisting of a multi-stage investigation of shallow groundwater, soil gas, sub-slab soil gas, indoor air and outdoor air, along with pneumatic testing, installation of sub-slab venting systems, in both commercial and residential buildings, verification testing and regulatory negotiation.

**Vapor Intrusion Assessment, Mitigation and Regulatory Negotiation, Army Corps of Engineers, Raritan, NJ.**
Technical Expert for Regulatory Negotiation for a former military arsenal in New Jersey that has been redeveloped for multi-use commercial property. Three years of sub-slab soil gas and indoor air sampling by a previous consultant culminated in a pending Order for sub-slab mitigation systems in 4 large buildings, with an estimated cost of over one million dollars. Mr. McAlary used an innovative sampling system in development at the University of Waterloo, pressure-transducers and data loggers, building ventilation assessment and the Trace Atmospheric Gas Analysis (TAGA) unit to demonstrate that subsurface vapor intrusion was not contributing to indoor air concentrations above NJDEP screening levels in any of the four buildings, and successfully negotiated a scope of future activities that reduced the estimated costs of regulatory compliance by about $800,000.

**Vapor Intrusion Assessment and Regulatory negotiation, Aberdeen Proving Grounds, MD.**
Technical Director for an assessment of vapor intrusion including over 300 buildings. Negotiated a tiered approach starting with the buildings most likely to have unacceptable vapor intrusion to reduce the scope of indoor air and sub-slab sampling and analysis to a reasonable level. Developed innovative sampling strategies to address compounds that are not typically included in vapor intrusion assessments.

**Vapor Intrusion Assessment and Mitigation, Northrop Grumman, Utica, NY.**
Project Director for a soil vapor mapping and sub-slab venting system installation program in residences near a former manufacturing facility. Responsible for regulatory negotiation, scoping, workplan development, site characterization, installation and testing of mitigation systems in potentially affected properties, and reporting.

**Vapor Intrusion Assessment and Regulatory Negotiation, Atlantic Richfield, Upstate New York.**
Project Manager/Technical Director for a vapor intrusion assessment in upstate New York. Demonstrated that clay till overburden provides...
sufficient additional attenuation of vapor transport compared to generic attenuation factors to obtain No Further Action Letter with a single round of data collection.

**Portfolio Review for Vapor Intrusion Assessment, Jersey Central Power & Light, NJ.** Technical Expert for a review of a portfolio of former Manufactured Gas Plant Sites in New Jersey for developing a strategy to achieve compliance with the recently released NJDEP Vapor Intrusion Guidance in the most cost-effective manner possible.

**Vapor Intrusion Assessment and Regulatory Negotiation, JCP&L, NJ.** Project Director for a site-specific assessment of sub-surface vapor intrusion to indoor air at a former Manufactured Gas Plant site in New Jersey that has since been developed to multi-use commercial property. Developed a scope of work for soil gas, indoor air and outdoor air sampling, and performed data interpretation, forensics analysis, reporting and regulatory negotiation to demonstrate that chemicals detected in indoor air were from interior or outdoor sources, and not subsurface vapor intrusion.

**Vapor Intrusion Assessment and Mitigation, Several Clients, International.** Technical Director or Peer Reviewer for international assessments of vapor intrusion at sites in Loncin Belgium, Nottingham England, Makati Malaysia, Kuala Laumpur Philippines, Thayez France, Vallejo Mexico, Camilia Australia.

**Groundwater Investigation, Remedial Design and Remediation**

**Soil Vapor Extraction and Treatment, General Electric, Hickory, NC.** Technical Director for soil vapor extraction system that removed 4.7 tons of chlorinated solvents from beneath a former manufacturing building in 1 year, using the G.E.O. compressor/condenser technology for off-gas removal. Mass removal rates were estimated within about 10% accuracy via mathematical modeling and professional judgment in advance of the remediation activities.

**Soil Vapor Extraction System Optimization, Operation and Closure, General Electric, Ontario, CA.** Project Manager/Technical Director for soil and groundwater remediation at an active aircraft engine maintenance facility in Chino Basin, Southern California, including soil vacuum extraction to a depth of 250 feet below ground, regulatory negotiation of Monitored Natural Attenuation of VOCs with concentrations up to about 10 times higher than their respective MCLs in a fully prescribed drinking water supply basin, periodic monitoring and regulatory reporting.

**Comprehensive Site Investigation, Risk Assessment and Remedy Optimization, General Electric, West Lynn, MA.** Project Manager/Technical Director for environmental investigations, remediation, risk assessment and regulatory negotiations
at a 100-year-old industrial manufacturing facility near Boston, involving several subcontractors, multiple chemicals of concern (VOCs, metals, PAHs, CN, etc.), public involvement and re-design of the existing groundwater extraction and treatment system. Demonstrated that extraction wells installed by previous consultant had a very low efficiency, and improved operations through a systematic program of well development, including surging and purging, disinfection, and jetting.

RI/FS/RA and Cost Allocation Support, Confidential Client, Cupertino, CA. Technical Director of a team of a dozen geoscientists and engineers for the preparation of a RI/FS at a proposed Superfund site in the South San Francisco Bay area, including 3-D geostatistical analysis of vadose zone VOC mass for a non-binding allocation of responsibility, peer review of reports by consultants for the other Responsible Party, effectiveness analysis of a groundwater extraction and treatment system, remedy modification studies and property redevelopment strategic planning.

RI/FS and RD/RA, Confidential Client, Ontario, CA. Technical Specialist for a site investigation/remediation in Southern California involving a 2.5-mile long plume of TCE in groundwater, including detailed assessment and modeling of vapor transport through a 350 ft thick unsaturated zone, peer review of the design of a groundwater extraction and treatment system, and development of an innovative investigation technique (case-and-bail sampling) for mapping the vertical profile of VOCs in alluvium.

RCRA RFI/CMS and Remedy Optimization, General Electric, Hickory, NC. Technical Director and Geologist in Responsible Charge for a groundwater extraction and treatment system to contain PCE and TCE in residuum and partially weathered rock in North Carolina, including re-assessing the aquifer hydraulics and developing multiple lines of evidence to demonstrate the effectiveness of containment, and semi-annual monitoring for the past several years, and regulatory reporting.

RI/FS Manager, Fike Artel Superfund Site, Nitro, WV. Project Manager for a team of over a dozen professionals who inherited data from previous consultants to produce the reports in less than 3 months, including PRP group meetings, regulatory negotiation, mathematical modeling of monitored natural attenuation, remedial design and costing.

Remedial Design, General Electric, Taoyuan, Taiwan. Technical Advisor for regulatory decision-making and remediation strategies at a manufacturing facility with chlorinated solvents in groundwater beneath a residential area with private drinking water supply wells, including presenting a lecture to the Taiwan EPA on the DNAPL Paradigm.
Plume Mapping, Natural Attenuation Remedy Negotiation, and Cost Allocation Support, Cooper Tire and Rubber, Bowling Green, OH. Technical Director for a bedrock hydrogeologic investigation at a manufacturing facility with DNAPL contamination in Ohio, including development and application of the High Purge Volume sampling technique, mathematical modeling and sampling for a variety of parameters to successfully negotiate a monitored natural attenuation remedy.

Remedy Optimization, General Electric Company, Multiple Locations. Peer Review of multiple groundwater extraction and treatment systems for cost-effectiveness improvements for a large multi-national manufacturing company. Developed a systematic approach to identifying whether extraction flow rates were optimal using a simple graphical technique and identified operational changes for cost savings.

Mathematical Modeling of Groundwater Hydraulics and Contaminant Transport

Remedy Effectiveness and Optimization Simulations, Tenneco Automotive, Cozad, NE. Technical Director for a large-scale aquifer hydraulics analysis to evaluate the effectiveness of a 1,500 gpm groundwater extraction and treatment system in Cozad, NE, including aquifer testing, analytical modeling, numerical modeling and 3-D visualization. Calibrated groundwater flow and transport models to 5 different historic pumping configurations, using data from 150 monitoring wells, and achieved numerical simulations that calibrated exceptionally well to 15 years of field data. Used the mathematical model to demonstrate the effectiveness of the existing system, and was able to successfully negotiate with NDEQ to avoid unnecessary expansion of the system, saving our client more than 5 times our fees.

Natural Attenuation Mathematical Modeling Support, Multiple Clients and Locations. Principal Investigator or Peer Technical Reviewer for modeling of fate and transport of chemicals in groundwater and the effect of intrinsic biodegradation on the natural attenuation of a plume of contaminants in California (3), New Hampshire, Ohio and Taiwan using screening level (Bioscreen, BioChlor), and numerical models (visualModflow with RT3D).

Groundwater Hydraulic Testing and Analysis in Support of Remedy Design, Multiple Clients and Locations. Principal Investigator for dozens of pumping tests at sites in Massachusetts, Indianapolis, California (several), Ohio, North Carolina, and Ontario (several), including corrections for baseline drift, barometric drift, and earth tides, using real-time data analysis via modem from data loggers, numerical and analytical solutions.
3-D Model Visualization, Multiple Clients and Locations. Principal Investigator for 3-D interpolation and visualization of contaminant distributions at sites in Central California, Southern California, and Germany for use in risk management, litigation support, public communication, using advanced geostatistical interpolation methods, medical imaging techniques, and post-processing to video for presentation.

Litigation Support

Vapor Intrusion Support, Multiple Confidential Clients and Locations. Expert Witness for sub-surface vapor fate and transport mechanisms for class action lawsuits related to subsurface vapor intrusion in New York State, Washington D.C., Ohio and Texas.

Cost Allocation for Non-Binding Arbitration, Confidential Client, Cupertino, CA. Principal Investigator for a cost allocation proceeding to assign responsibility for remediation costs between two potentially responsible parties in California, employing 3-D geostatistical interpolation and visualization, vadose zone transport modeling in aqueous and vapor phases, forensic analysis of chemical speciation, and comprehensive assessment of geologic structural controls on subsurface transport.

Deposition and Testimony for Cost Allocation, Vorys, Slater Seymour and Pease, Columbus, OH. Expert Witness for an arbitration proceeding involving historic and current landowners to assign responsibility for subsurface contamination in Ohio, contributing to favorable judgment through clear and simple communication of complex technical processes, synergistic relationships with other consultants, internal and external counsel, and timely delivery of high quality work product.

Regulatory and Other Guidance Documents


and participating author and reviewer of 3 white papers (in prep).

**EPRI Reference Handbook for Site-Specific Assessment of Subsurface Vapor Intrusion to Indoor Air:** Primary author of one of the most detailed resources on the subject of vapor intrusion available to date (http://mydocs.epri.com/docs/public/000000000001008492.pdf), March, 2005.

**NJDEP Vapor Intrusion Guidance:** Provided draft text, figures and technical review of the section on Conceptual Site Models in the Vapor Intrusion Guidance of the New Jersey Department of Environmental Protection and participated as an invited instructor in seminars to demonstrate soil vapor monitoring protocols. (http://www.state.nj.us/dep/srp/guidance/vaporintrusion/vig.htm), October, 2005.


**United Kingdom Construction Industry Research and Information Association (CIRIA):** Invited Peer Reviewer of “The VOCs Handbook: Investigating, assessing & managing risks from inhalation of Volatile Organic Compounds (VOCs) at land


Invited Presentations & Training Seminars

Invited Speaker for the ESTCP/SERDP Partners Conference Workshop on Vapor Intrusion, presenting a talk on the use of passive samplers in vapor intrusion assessment, Washington, D.C., December 1, 2011.

Invited Instructor for the ITRC 2-day Vapor Intrusion Classroom Training in Detroit, MI (June 2011), San Antonio, TX (January, 2010), Norfolk, WV (March 2010), Oklahoma City, OK (April 2009), Portland OR (October, 2008), and San Francisco, CA (July 2008).

Invited Speaker for the University Consortium for Field Focused Groundwater Research meeting, Guelph, ON, June, 2011, presenting a talk entitled “Recent Advances in Techniques for Measuring Soil Vapor Concentrations”.

Principal Lecturer for a 2.5-day short course on vapor intrusion presented to 75 members of the staff of the Ontario Ministry of the Environment, March 1-3 2011, Toronto.


Invited Speaker at the 2010 Air and Waste Management Specialty Conference on Vapor Intrusion, Chicago, IL, giving a talk entitled Quantitative Passive Diffusive-Adsorptive Sampling Techniques for Vapor Intrusion Assessment, September 30, 2010.
Invited Lecturer for a 1-day Short Course for the Australian Contaminated Land Consultants Association entitled Vapor Intrusion – International Perspectives and Lessons Learned in Sydney on August 25 and Melbourne on August 30, 2010.

Invited Speaker for a 1-day Technical Exchange Meeting on Vapor Intrusion hosted by ESTCP and SERDP on August 16, 2010 in Salt Lake City, giving a talk entitled Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air using Quantitative Passive Sampling Techniques.

Invited Lecturer for a 2-day Short Course for the Swedish Environment Agency in Stockholm entitled Assessing and Managing Subsurface Vapor Intrusion to Indoor Air, June 10 and 11, 2010.

Invited Lecturer for a 2-day Short Course for the Danish Regional Governments in Copenhagen entitled Assessing and Managing Subsurface Vapor Intrusion to Indoor Air, June 7 and 8, 2010.

Invited Speaker for the University Consortium for Field Focused Groundwater Research meeting, Guelph, ON, June, 2010, presenting a talk entitled “Recent Developments, Applications and Commercialization of the Waterloo Membrane Sampler”.

Invited Speaker at the 2010 Air Force Restoration and Technology Transfer Workshop, San Antonio, April 9, 2010 giving a talk entitled New Methods for Vapor Intrusion Assessment to Minimize Variability, Maximize Value and Optimize Mitigation in One Step.

Invited Speaker at the EPA Workshop on Vapor Intrusion at the AEHS Conference on Contaminated Soils and Sediments, San Diego, March 16, 2010 giving talks entitled Cutting Edge Vapor Intrusion Research, and Multiple Lines of Evidence for Assessing Vapor Intrusion.


Invited Speaker at the RTM Conference on Sustainable Property Transactions: Reconfiguring the Business of Contaminated Site Redevelopments, San Francisco, October 30, 2009, presenting a paper entitled Current Challenges and New Directions for Vapor Intrusion Assessment and Management.

Invited Speaker at the DoD Environmental Monitoring and Data Quality Workshop, San Antonio, TX, April 2009, presenting a talk entitled for A Review for the U.S. Navy of Best Practices, Knowledge and Data Gaps and Research Directions for Vapor Intrusion.
Invited Instructor for full day training session on soil gas sampling methods for the California Department of Toxic Substances Control, Sacramento, CA, May 27, 2009.

Invited Lecturer for graduate course in Environmental Engineering at the University of Western Ontario, including 3 hour lecture and 2 hour hands-on exercise on vapor intrusion, February 2009 and March 2010.

Invited Speaker, Session Chair and Panel Member at the Air and Waste Management Association’s Specialty Conference: Vapor Intrusion 2009 in San Diego, CA, January, 2009, presented papers entitled “PDMS Membrane Samplers for Quantitative Passive Sampling of Subsurface Vapor Intrusion to Indoor Air” and “Groundwater/Subslab/Indoor Air Relationships at the Billings and Lowery AFB Sites”.

Invited Lecturer for half-day short course on Soil Gas Sampling at the Vapor Intrusion Sampling for the Environmental Professional, sponsored by the Federation of Environmental Technologists and Wisconsin DNR Bureau of Remediation and Redevelopment, Milwaukee, WI, September 2008.

Invited Speaker and Session Chair at the Air and Waste Management Specialty Conference on Vapor Intrusion in Toronto, September 2008, presenting a talk entitled: “Guidance, guidance everywhere, but what does it all mean?”.


Invited Speaker for the University Consortium for Field Focused Groundwater Research meeting, Hockley Valley, ON, May, 2008, presenting a talk entitled “Current Tends and Research Directions for Vapor Intrusion”.

Invited Speaker and Session Chair at the Air and Waste Management’s Specialty Conference on Vapor Intrusion: Learning from the Challenges, September 26-28, 2007, Providence, RI.


Invited Speaker at the Symposium on Contaminated Property Transactions:
Navigating the Complex Deals, San Francisco, CA, October 2006 by RTM Communications, Inc. Presentation entitled “Screening and Evaluating Sites for Vapor Intrusion and Site Specific Risk Based Modeling”.

**Invited Speaker, Session Chair and Short-Course Instructor** and the Air and Waste Management’s Specialty Conference on Vapor Intrusion, Los Angeles, CA, September 2006.

**Invited Speaker and Soil Vapor Sampling Workshop Coordinator** at the Midwestern States Risk Assessment Symposium Soil Vapor Sampling Workshop, Indianapolis, IN, August, 2006, presenting a talk entitled “Soil Gas Sampling Methods” and organizing a comprehensive field sampling program.

**Invited Speaker** at the University Consortium for Field Focused Groundwater Research meeting in Denver, CO, November 2006, presenting two talks entitled “Sources of Variability in Soil Gas Data” and “Conceptual Models of Vapor Intrusion”.

**Invited Speaker** at the Rutgers University Vapor Intrusion Training Seminar, June 14, 2006, presenting a talk entitled “Sub-Slab Soil Gas sampling for Assessing Subsurface Vapor Intrusion to Indoor Air”, as well as a practical demonstration.

**Invited Speaker** at the Electric Power Research Institute (EPRI) annual meeting in Bar Harbor, ME, June 22, 2006.

**Co-Instructor** for a Short Course on “Managing Vapor Intrusion Sites” at the Battelle Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 2006.


**Invited Speaker and Workshop Coordinator** for the Aerospace Industry Association meeting in Salt Lake City, UT, February 2006.

**Invited Speaker and Session Chair** at the Air and Waste Management Association Specialty Conference on Vapor Intrusion, Philadelphia, PA, January, 2006 and Los Angeles, CA, September, 2006.

**Invited Speaker and Panel Member** at the American Bar Association Annual CL Meeting, San Francisco, CA, September, 2005.

**Invited Speaker and Panel Member** at the AEHS Vapor Intrusion Attenuation Workshop at the 15th Annual East Coast Conference on Soils, Sediments and Water, Amherst, MA, October 2005.

**Invited Speaker** at the California Groundwater Resources Association Symposium on
Vapor Intrusion, May 2005.


**Invited Speaker** at the Air and Waste Management Conference in Indianapolis, Session WR1A, Subsurface Vapor Intrusion to Indoor Air, Indianapolis, IN, June 2004.

**Invited Speaker and Panel Member** for AEHS Vapor Intrusion Attenuation Workshop at the 14th Annual West Coast Conference on Soils, Sediments and Water, San Diego, CA, March 2004.

**Chairman** of a two-day workshop on vapor intrusion at the Electrical Power Research Institute’s annual general meeting, Jupiter Beach FL, December 2003.

**Invited Speaker and Panel Member** for two seminars held by the California Groundwater Resources Association, entitled: “Subsurface Vapor Intrusion to Indoor Air: When is Soil and Groundwater Contamination and Indoor Air Issue?”, San Jose and Long Beach, CA, September and October 2003.

**Invited Speaker** at an Environmental Symposium on Indoor Air Pathway Evaluation for VOC Releases, by the Environmental Law Institute, San Francisco, June, 2003.

**Invited Speaker and Steering Committee Member** for the EPA seminar series introducing the OSWER Vapor Intrusion Guidance, San Francisco, CA, December 2002, Dallas, TX, January, 2002, and Atlanta, GA, February, 2003.

**Author and Presenter** of two on-line training seminars on subsurface vapor intrusion through the Environmental Institute for Continuing Education.

**Invited Speaker** on the subject of subsurface vapor intrusion at 3 consecutive annual meetings of remediation Project Managers for a large, multi-national corporation.

**Invited Lecturer** for a 3-day Short Course on Groundwater Remediation Technologies at the Politecnico di Torino in Italy, covering Bioremediation, Permeable Reactive Barriers, Phytoremediation, In-Situ Oxidation, Monitored Natural Attenuation and Bioaugmentation.

**Course Instructor** for the RTDF course on Accelerated Bioremediation, contributing specifically in the design and modeling of in-situ mixing systems.

**Industrial Advisor** for a Senior Year Chemical Engineering Design Course at the University of Toronto, 2003, 2004 and 2006.
REPRESENTATIVE PUBLICATIONS


11-4 McAlary, T., 2011. Overcoming the Challenges of Vapour Intrusion Assessment and Mitigation, invited platform presentation at the first International Sites and Spills Conference, Nov. 4 & 5 2011, Toronto, Canada.


10-3 Creamer, T., D. Larson and T McAlary, 2010. “Urban Infrastructure and the Challenges Posed for Assessing and Mitigating Vapor Intrusion Adjacent to a
Former Dry Cleaner: A Case Study,” Air & Waste Management Association - Vapor Intrusion 2010 (Chicago, IL; September 2010)


Project 08 EB-EBR-036, a platform presentation at the DOD Environmental Monitoring and Data Quality Workshop, Louisville, KT, April 15, 2010.


09-9 de Haven, P., H. Groenevelt, P. Dollar and T. McAlary, 2008. Long-Term Monitoring to Assess the Potential for Vapor Intrusion with Particular Focus on Data Quality and Data Management, Poster presentation, Department of
Defence, Environmental Monitoring & Data Quality Workshop, March 31 – April 4, 2008, Atlanta, GA.


09-14 Creamer, T., R. Ettinger and T. McAlary, 2009. “Knowledge (from High Quality Data) is Power: Vapor Intrusion Site Conceptual Models Really Work.” The 19th Annual AEHS (Association for Environmental Health and Sciences) Meeting & West Coast Conference on Soils, Sediments and Water (San Diego, CA; March 2009)


Management’s Specialty Conference on Vapour Intrusion, Toronto, September, 2008.


Management Association’s Specialty Conference on Vapor Intrusion, Providence, RI, September 27, 2007.


06-10 McAlary, T., 2006, “Regulatory Perspectives on Vapor Intrusion,” a talk at the Vapor Intrusion Short course “Managing Vapor Intrusion Sites” at the Battelle Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterrey, CA, May 2006.

http://iavi.rti.org/attachments/WorkshopsAndConferences/1515_-_-Abreu_7-31-06.pdf.


04-12 McAlary, T.A., P. Dollar, H. Groenevelt, P. DeHaven, J. Rosen, and R. Moss, 2004, “Calculated Vapor Attenuation Coefficients at the Weston Quarries Site,


03-5 McAlary, T.A., 2003, “Strategies for the Site-Specific Assessment: How to Protect Yourself from the Hidden Traps,” an invited seminar at the
Environmental Symposium on Indoor Air Pathway Evaluation for VOC Releases held by the Environmental Law Institute, San Francisco, June, 2003.


**PROFESSIONAL DEVELOPMENT**

*Florida Brownfields Conference, November 14 & 15, 2011, Orlando.*

*International Sites and Spills Conference, November 4 and 5, Toronto.*

*University Consortium for Field-Focused Groundwater Contamination, June, 2011, Guelph, Ontario*


*AWMA Specialty Conference: Vapor Intrusion, 2010. Chicago, IL, September, 2010.*

*ESTCP/SERDP Technical Exchange Meeting on Vapor Intrusion Salt Lake City, UT August, 2010.*

*University Consortium for Field-Focused Groundwater Contamination, May, 2010, Guelph, Ontario*

*Air Force Restoration and Technology Transfer Workshop, San Antonio, April 9, 2010.*

*AEHS Conference on Contaminated Soils and Sediments, San Diego, March 16, 2010.*

*North American Environmental Field Conference & Exposition, January 2010, Tampa, FL.*


*RTM Conference on Sustainable Property Transactions: Reconfiguring the Business of Contaminated Site Redevelopments, San Francisco, October 30, 2009.*

*DoD Environment, Energy and Sustainability Symposium, Denver, May 2009.*

*DoD Environmental Monitoring and Data Quality Workshop, San Antonio, TX, April 2009.*


*AWMA Specialty Conference on Vapour Intrusion, Toronto, September, 2008.*
WIDNR/FET Course Vapor Intrusion Sampling for Environmental Professionals, Milwaukee, WI, September, 2008.


AWMA Specialty Conference on Vapor Intrusion: Learning from the Challenges, Providence, RI, September 2007


AWMA Specialty Conference on Vapor Intrusion: The Next Great Environmental Challenge – An Update, Los Angeles, September 2006

Midwestern States Risk Assessment Symposium, Indianapolis, IN, August, 2006 and July, 2002

Rutgers University Vapor Intrusion Seminar, New Brunswick, NJ, June 14, 2006


University Consortium for Field-Focused Groundwater Contamination, Nov., 2006, Denver, CO.


California Groundwater Resources Association Seminar: “Subsurface Vapor Intrusion to Indoor Air: An Update”, May 25, 2005, San Jose, CA


Air and Waste Management Annual Conference, Indianapolis, IN, June 2004.


The Princeton Unsaturated Flow Short Course, Princeton University, 1990

Department of Labor Occupational Safety and Health Administration. 40-Hour training in compliance with SARA Title III and 29 CFR 1910.120, 1989. Annual 8-hour refreshers
Peer Reviewer Conflict of Interest Certification

Peer Review: “Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds”

A conflict of interest or lack of impartiality exists when the proposed peer reviewer personally (or the peer reviewer’s immediate family), or his or her employer, has financial interests that may be affected by the results of the peer review; or may provide an unfair competitive advantage to the peer reviewer (or employer); or if the peer reviewer’s objectivity in performing the peer review may be impaired due to other factors. When the Peer Reviewer knows that a reasonable person with knowledge of the facts may question the peer reviewer’s impartiality or financial involvement, an apparent lack of impartiality or conflict of interest exists.

The following questions, if answered affirmatively, represent potential or apparent lack of impartiality (any affirmative answers should be explained on the back of this form or in an attachment):

- Did you contribute to the development of the document under peer review, or were you consulted during its development, or did you offer comments or suggestions to any drafts or versions of the document during its development? ☑ No ☐ Yes
- Do you know of any reason that you might be unable to provide impartial advice on the matter under consideration in this peer review, or any reason that your impartiality in the matter might be questioned? ☑ No ☐ Yes
- Have you had any previous involvement with the review document(s) under consideration? ☑ No ☐ Yes
- Have you served on previous advisory panels, committees, or subcommittees that have addressed the topic under consideration? ☑ No ☐ Yes
- Have you made any public statements (written or oral) on the issue? ☑ No ☐ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? ☑ No ☐ Yes
- Do you, your family, or your employer have any financial interest(s) in the matter or topic under peer review, or could someone with access to relevant facts reasonably conclude that you (or your family or employer) stand to benefit from a particular outcome of this peer review? ☑ No ☐ Yes

With regard to real or apparent conflicts of interest or questions of impartiality, the following provisions shall apply for the duration of this peer review:

(a) Peer Reviewer warrants, to the best of his/her knowledge and belief, that there are no relevant facts or circumstances that could give rise to an actual, apparent, or potential organizational or personal conflict of interest, or that Peer Reviewer has disclosed all such relevant information to EMS or to EPA.
(b) Peer Reviewer agrees that if an actual, apparent, or potential personal or organizational conflict of interest is identified during performance of this peer review, he/she immediately will make a full disclosure in writing to EMS. This disclosure shall include a description of actions that Peer Reviewer (or his/her employer) has taken or proposes to take after consultation with EMS to avoid, mitigate, or neutralize the actual, apparent, or potential organizational conflict of interest. Peer Reviewer shall continue performance until notified by EMS of any contrary action to be taken.

Signature: [Signature]
Date: June 14, 2012

☐ Check here if any explanation is attached

Printed Name: [Printed Name]
Affiliation/Organization: Geosyntec Consultants, Inc.
Peer Review of *Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for PetroleumHydrocarbon Compounds*

Mark A. Widdowson, Ph.D., P.E.
Professor of Civil & Environmental Engineering
The Charles E. Via, Jr. Department of Civil & Environmental Engineering
Virginia Tech; Blacksburg, VA

The focus of this review is a report authored by Golder Associates and RTI International for the U.S. Environmental Protection Agency that describes and analyzes a database of environmental data collected at petroleum release sites. The report addresses the data and modeling studies related to separation distances pertinent to soil vapor intrusion. Specific questions to which answers are requested are:

1. Is the report written in a manner that is clear, robust, and transparent for its intended purpose?

Overall, the report is very clearly written in most aspects. The document is well-organized and is crafted in a logical manner. The scope of the report is robust. It includes description of the conceptual site model, case studies, modeling studies, presentation of an empirical database, analysis and discussion of results and a clear set of conclusions. There is no indication that would suggest that transparency is an issue of concern.

Description of the conceptual site model is based on a previous EPA publication cited in Section 2. It would be helpful to readers to repeat the key points that are pertinent to the transport of petroleum hydrocarbon vapors.

Other suggestions for improving the clarity of the report are inclusion of a Glossary of Terms and a List of Acronyms. For example, the term “vapor attenuation factor” or “attenuation factor” is used repeatedly but never adequately defined.

2. Does the report meet its stated objectives (listed above) for which it was conducted? If not, please indicate any identified gaps.

The report contains five objectives designed for the development of exclusion distances.

- Objective 1 is achieved. The empirical database assembled for the report built upon a previous study by Davis (2009). Additional data from sites in Maine is included. Data from a total of 70 sites are evaluated.
- Objective 2 is achieved. The data are checked against original sources and assembled electronically.
- Objective 3 addressed when and under what conditions there is the potential for a complete PVI pathway at a site. As noted on page 2, a complete PIV pathway is defined as measureable indoor petroleum hydrocarbon vapor concentrations that come from a subsurface contamination source. Two case studies are presented where a complete PIV pathway is noted. In one case (Section 2.5.2), building depressurization is noted as a factor. However, in the Discussion, this factor is
• Objective 4 is achieved. The report summarizes pertinent modeling studies on PHC vapor transport and intrusion.

• Objective 5 is achieved. The report provides a coherent discussion of methods and criteria that can be used to exclude (and include) petroleum release sites from further PVI investigation and concern.

3. Are there any additional scientific issues relating to the stated objectives that are not addressed in the report?

The report provides a thorough presentation of the scientific issues related to the stated objectives. As indicated in my response to Question 1, the lack of a thorough description of the conceptual site model hinders in complete presentation of the science. The report does not adequately address hydrologic factors such as drought conditions and atmospheric pressure changes that may impact the potential for a complete PVI pathway. Furthermore, the conceptual site model is based on an assumed steady-state depth to the water table and on sites with no perched water table. The report does not address these issues and impacts on PVI potential.

4. Are the criteria for data acquisition during the underlying studies (i.e., Davis, Eremita, Peargin and Kolhatkar) and into the assembled database adequately described? Do these criteria ensure that the estimated attenuation in vapor concentrations in the vadose zone at each site:
   ▪ can be reasonably attributed to aerobic biodegradation (versus other explanations); and
   ▪ is an appropriate value for predicting potential indoor air concentrations in nearby buildings?

The underlying studies are well summarized, but the criteria for data acquisition during are not fully described in this report. As noted in Table 5, oxygen (soil gas) data is not available at all sites. However, the absence of this data does not preclude the notion that attenuation of vapor concentrations in the vadose zone can be reasonably attributed to aerobic biodegradation. The phenomenon of aerobic biodegradation in the vadose zone is so widely observed at petroleum-contaminated sites that excluding these studies is not warranted.

5. Is the assembled database adequately large and sufficiently representative of subsurface conditions and indoor air concentrations for purposes of reliably determining presumptive criteria for each of the following scenarios:
   ▪ petroleum releases from USTs; and
   ▪ petroleum releases from other sites (e.g., refineries, terminals, transmission pipelines)?

As shown in Table 3, the assembled database is derived from 9 states accounting for 67 of the 70 sites. These locations reflect a range of hydrogeologic settings throughout the U.S. The database is dominated (75% of the 67 sites in the U.S.) by data from 3 states, but these states represent 3 distinct geologic regions of the country. Although UST sites make up the bulk of the database (90% of the 70 sites), the database is adequate in size. The database includes a large number of benzene and oxygen soil vapor records and pair benzene soil vapor and groundwater concentration data. Benzene data is included in 65
of the 70 sites. Subslab vapor samples were obtained at over 50% of the sites. Based on the information pertaining to foundation type in Table 4, the database appears sufficiently representative of subsurface conditions. However, it would be useful to include data on depth to the water table and surface cover here.

6. Are the statistical methods applied to the data appropriate for the data set and for the comparison being made?

A description of the statistical methods employed in the study is lacking in the report. The report should include a rationale for use of the Kaplan-Meier non-parametric method. It would be helpful to include this information to explain methods and assumptions employed with appropriate citations, above and beyond the limited description on page 27. This could easily be included in an appendix.

7. Are the findings of the report of adequate scientific integrity to support establishment of a vertical distance between a source of petroleum vapor contamination and an overlying receptor in determining whether an UST site could pose a significant health risk to building occupants? Have all the factors that influence, or potentially influence, biodegradation (e.g., soil moisture, seasonal and climatological effects, preferential transport pathways, type of petroleum fuel, surface cover) been adequately considered?

The preponderance of evidence from not just this study but also similar studies cited in this report (see Section 9.6) demonstrate that establishing a vertical distance of separation between a source of petroleum vapor contamination and an overlying receptor that include biodegradation is based on sound scientific principles. There is no indication that the findings of the report lack scientific integrity.

Regarding factors that influence or potential influence biodegradation, as noted in my response to Question 3, the report does not adequately address hydrologic factors. Water table elevation is subject to change with rainfall events and prolonged drought. The extent to which a water table rises or falls over time is site specific depending on the intensity and duration of recharge events, land cover, plant type and soil properties. The report did not address how temporal variability in the depth to the water table is considered. A related issue is the potential for perched water tables at some sites. In some cases, perched saturated zones are seasonal and may be discontinuous with space across a site.

8. Does the Golder/RTI Report provide a sound basis for applying the proposed vertical separation distances for aromatic and aliphatic petroleum hydrocarbons (e.g., benzene) to other common fuel constituents (e.g., naphthalene) and fuel additives (e.g., MtBE, 1,2-dichloroethane, ethylene dibromide)?

Reasons provided for application of the proposed vertical separation distances to other common fuel constituents and additives vary. Several fuel constituents and additives are addressed in the case studies. Data for these compounds are commonly collected at the database study sites (Table 5), but the number of data is less frequent. Besides benzene, other database constituents are analyzed (see page 26-27), but the report primarily addresses naphthalene and 2,2,4-TMP on this issue. Therefore, a thorough explanation of the rationale for applying the proposed vertical separation distances for benzene to other fuel constituents and additives is lacking.
9. Are you aware of additional references or other resources that could be added to the report, or would be useful in meeting the stated objectives of the report? Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?

The report provides an adequate list of references including field studies that pertain to the attenuation of petroleum hydrocarbon soil vapors. Some possible exceptions are the work performed at the U.S. Geological Survey study site at Laurel Bay, SC. MTBE vapor transport was evaluated at this UST site. A complete bibliography for this work is available at http://toxics.usgs.gov/bib/bib-MTBE.html. A study of naphthalene vapor transport and attenuation in the vadose zone published by Marr et al. in 2006 (Environmental Science & Technology, vol. 40, no. 17) may also prove useful.

10. Do you have any additional comments on the report itself or its intended use that have not been explicitly solicited? Please cite line number(s) in the report pertaining to specific comments.

- Going forward, some notion of “best practices” for the collection of data, what data to collect and how frequently, and methods for data analysis is warranted. This includes the need for technical guidance on methods to verify benzene attenuation and confirm oxygen levels in soil gas.

- As mentioned previously, the notion of a vertical exclusion is based on a static water table. Some consideration for a site-specific evaluation of the temporal variability in the depth to the water table is recommended.
Mark A. Widdowson, Ph.D., P.E.

The Charles E. Via, Jr. Department of Civil and Environmental Engineering 540-231-7153
Virginia Tech 540-231-7532 (fax)
Blacksburg, VA  24061-0105 mwiddows@vt.edu

EDUCATION

Ph.D., Civil Engineering, Auburn University, 1987.
BSCE, Civil Engineering, University of Cincinnati, 1982.

PROFESSIONAL EXPERIENCE AND REGISTRATION

Professor of Civil Engineering, Virginia Tech, 1993-present
Assistant Department Head, 2009-present
Program Coordinator, Environmental and Water Resources Engineering Program, 2003-2008
Professional Engineer Registration, #14257, South Carolina, 1991-present.
Assistant Professor, Department of Civil Engineering, University of South Carolina, 1988-92.
Post-Doctoral Fellow/Instructor, Department of Civil Engineering, Auburn University, 1988.
Graduate Research Assistant, Department of Civil Engineering, Auburn University, 1984-87.
Graduate Teaching Assistant, Department of Civil Engineering, University of Kansas, 1982-84.
Undergraduate Research Assistant, Department of Civil Engineering, University of Cincinnati, 1979-80.

PROFESSIONAL ACTIVITIES, HONORS AND NOTABLE RECOGNITIONS

American Society of Civil Engineers
National Ground Water Association
Outstanding Civil Engineering Faculty, 1996
Graduate Summer Fellowship, University of Kansas, 1983

PATENTS AND SOFTWARE PUBLISHED

U.S. Patent (No. 5,293,931) entitled “Modular Multi-Level Sampling Device”.

RESEARCH AND PROFESSIONAL INTERESTS

Mathematical modeling and experimental studies of the fate and transport of contaminants in soil, sediments and groundwater, including
- Chlorinated solvents (PCE, TCE, Vinyl chloride); Chlorinated compounds (PCB, perchlorate)
- Petroleum hydrocarbons (Benzene, BTEX, MTBE), Creosote (PAH compounds)
Groundwater resource development and management
Natural attenuation and engineered remediation of contaminants in groundwater and soil, including:
- Phytoremediation, bioremediation
- Computational modeling
- Laboratory and field studies
Software development (computational models and interface tools) for modeling contaminant fate and transport in groundwater systems, surface-groundwater interface, and river/streambed sediments.
RESEARCH AND SCHOLARLY PUBLICATIONS

Papers in refereed journals:


Peer-Reviewed Published Reports


Book chapters


Papers in refereed conference proceedings:


Recent Papers Presented at Professional Meetings


Widdowson, M., Q. Abdelal, and F. Chapelle. “Sustainability of reductive dechlorination at Type 2 chlorinated solvent sites”, Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, November 29 - December 1, 2005.


Novak, J.T. and M.A. Widdowson. “Incorporating natural attenuation into design and management strategies for contaminated sites”, Annual Meeting of the Midwest Hazardous Substance Research Center, Purdue University, IN, August 5, 2004.


Widdowson, M.A., F.J. Molz and L.D. Benefield. “Experimental and theoretical studies of microbial growth dynamics coupled to nutrient and oxygen transport in porous media”, Microbial Processes in the
Transport, Fate and In Situ Treatment of Subsurface Contaminants, American Geophysical Union Chapman Conference, Snow Bird, UT, October 1-3, 1986.


EXTERNALLY-FUNDED RESEARCH

National Science Foundation, “Affect of Petroleum Deposit Geometry on Biodegradation Potential and Long Term Persistence”, $60,000, 12 months, Amy Pruden (PI).


Environmental Security Technology Certification Program (ESTCP), “Improved Field Evaluation of NAPL Dissolution and Source Longevity at the Former Williams AFB”, $124,000, 24 months.


U.S. Environmental Protection Agency via Hazardous Substance Research Center at Purdue University/Virginia Tech, “Incorporating Natural Attenuation and Phytoremediation into Design”, $68,847, 6 months, J.T. Novak (PI).


Strategic Environmental Research and Development Program (SERDP), “Integrated Protocol For Assessment Of Long-Term Sustainability Of Monitored Natural Attenuation Of Chlorinated Solvent Plumes”, $807,490 ($1,662,667 total budget with ORNL and USGS), 48 months, J.T. Novak (co-PI).

Naval Facilities Engineering Service Center, “Estimation Of Timeframes for and Comparison of Groundwater Remediation Technologies”, $200,000, 24 months.

U.S. Navy/CH2M Hill, “Feasibility Study Modeling – NAB Little Creek”, $24,210, 12 months.

U.S. Environmental Protection Agency via Hazardous Substance Research Center at Purdue University/Virginia Tech, “Incorporating Natural Attenuation into Design and Management Strategies for Contaminated Sites”, $291,000, 36 months, J.T. Novak (PI).

Virginia Water Resources Research Center, “Evaluating processes that control natural attenuation of nitrate in natural waters”, $5,000, 12 months.


U.S. Army Waterways Experiment Station, “SEAM3D Reductive Dechlorination Package for Simulation of Intrinsic Bioremediation in Aquifers”, $30,000, 12 months.


U.S. Navy/CH2M Hill, “Investigation of Intrinsic Bioremediation at Site 12, Naval Amphibious Base Little Creek”, $234,700, 21 months, J.T. Novak and Duane Berry (co-PIs).


Norfolk Southern Corporation, “Phytoremediation of Creosote - Contaminated Soil and Groundwater at the Oneida Tie Yard Site”, $400,364, 36 months, J.T. Novak (PI).


Norfolk Southern Corporation, “An Investigation into the Use of Biologically-Based Treatment Technologies for Waste Oil Volume Reduction at Norfolk Southern Corp”, $119,916, 36 months, N.G. Love (PI) and J.T. Novak.

U.S. Department of Agriculture/Health Research Institute, “In Situ Determination of the Fate and Transport of Nitrate and Ammonium in a Sandy Aquifer”, $65,700, 36 months.

U.S. Army Waterways Experiment Station, “Three-Dimensional, Sequential Electron Acceptor Model for Simulating In Situ Bioremediation Coupled to Solute Transport”, $100,000, 24 months.


U.S. Geological Survey, "Numerical Simulation of In Situ Bioremediation", $17,892, 9 months.


National Science Foundation, Instrumentation and Laboratory Improvement program, "Development of Undergraduate Curriculum in Groundwater Hydrology: Experimental Investigation and Computer Simulation", $33,465, 30 months, M.E. Meadows and A.S. McAnally (co-PIs).


TEACHING EXPERIENCE

Virginia Tech

CEE 2804 Introduction to Civil and Environmental Engineering
CEE 3304 Fluid Mechanics for Civil and Environmental Engineers
CEE 3314 Water Resources Engineering
CEE 4314 Groundwater Resources
CEE 5354 Numerical Modeling of Groundwater Flow & Transport
CEE 5374 Dynamics of Groundwater
CEE 5774 Hazardous Waste Management
OTHER PROFESSIONAL EXPERIENCE

Consultant – Groundwater resource development and feasibility study, South-Central Virginia, 7/07-11/07.
Expert testimony - American Electric Power on Groundwater Contamination, 4/00-6/00.
Consultant and expert testimony (report) to U.S. Congress - U.S. Navy, Indian Head Division, Indian Head, MD. Recommendation for Long-Term Water Supply for the Indian Head Division, 11/94-1/95.
Post-Doctoral Fellow - Field Tests to Determine Hydraulic Conductivity Distribution in Heterogeneous Aquifers, Auburn University Mobile Site, USEPA funded research, 6/87-6/88.
Graduate Research Assistant - Forced-Gradient Tracer Experiments at the Auburn University Mobile Site, "Experimental and Theoretical Studies of Contaminant Dispersion in Groundwater", USEPA funded research, 8/84-6/87.

PUBLIC SERVICE, EXTENSION, AND PROFESSIONAL ACCOMPLISHMENTS

Continuing education contributions, course development, delivery of courses

Environmental Professionals’ Organization of Connecticut. “Combining Engineered Contaminant Source-Area Treatment Technologies with Monitored Natural Attenuation for Site Cleanup”, 1-day short course, 52 attendees, Hartford, CT, March 26, 2009.


Licensed Site Professional Association of Massachusetts. “Estimating cleanup times associated with combining source-area remediation with natural attenuation”, 1-day short courses, 80 attendees (total), Boston, MA, April 4-5, 2006.


Battelle Memorial Institute, “Reactive transport modeling of natural attenuation”, 1-day short course, 20 attendees, Baltimore, MD, June 5, 2005.

Battelle Memorial Institute, “Estimating remediation times using monitored natural attenuation”, half-day short course, 40 attendees, Baltimore, MD, June 8, 2005.


Battelle Memorial Institute, “Reactive transport modeling of natural attenuation”, 1-day short course, 28 attendees, Orlando, FL, June 1, 2003.


Virginia Department of Environmental Quality. “Modeling contaminant plumes at petroleum-contaminated sites”, 1-day short course, 40 attendees, Blacksburg, VA, June 24, 1997.

Virginia Department of Environmental Quality. “Intrinsic bioremediation”, 2-day short course, 36 attendees, Blacksburg, VA, November 18-19, 1996.


Professional and University Service

Session chair (“Sustainability of Monitored National Attenuation), Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-26, 2006.

Mark A. Widdowson, Ph.D., P.E.  Page 16
Chair and Organizer, expert scientific panel on “Sustainability of Monitored Natural Attenuation of Chlorinated Solvents – Microbial Processes” for Strategic Environmental Research and Development Program (SERDP), Alexandria, VA, October 1-2, 2003.

Chair and Organizer, expert scientific panel on “Sustainability of Monitored Natural Attenuation of Chlorinated Solvents – Physical Processes” for Strategic Environmental Research and Development Program (SERDP), Herndon, VA, May 28, 2003.


Chair and Coordinator of special technical session entitled “Modeling”, The Fifth International Symposium on In Situ and On-Site Bioreclamation, April, 1999.


Chair and Coordinator of special technical session entitled “Modeling”, The Third International Symposium on In Situ and On-Site Bioreclamation, April, 1995.

Chair and Coordinator of special technical session entitled “Low Permeability Application”, The Third International Symposium on In Situ and On-Site Bioreclamation, April, 1995.

Technical Advisor to Wildewood Company, Columbia, SC. Investigation of TCE contamination of groundwater, springs, and surface waters, Amphenol Spring Valley Site, Columbia, SC, 8/91-6/92.


Technical Advisor to Earth Science Program on In Situ Bioremediation, Lawrence Livermore National Laboratory, May 1, 1990.


Technical Advisor to Allied Chemical Corporation, Air quality emissions at the Irmo, SC, 1990.

Chair and Coordinator of special technical session entitled "Microbial Processes in Subsurface-Contaminant Geochemistry", Fall Meeting, American Geophysical Union (sponsorship from the Groundwater Committee of the AGU Hydrology Section), 1990.

Chair of technical session entitled "Water Quality Analysis: Research and Findings" at the Coastal Zone Symposium, American Society of Civil Engineers, 1989.


Manuscripts reviewed for presses and journals:
- *Environmental Science and Technology*, American Chemical Society.
- *Journal of Environmental Engineering*, ASCE, American Society of Civil Engineers.
- *Journal of Hydraulic Engineering*, ASCE.
- *Journal of Irrigation and Drainage Engineering Division*, ASCE.
- *Journal of Bioremediation*
- *Journal of Theoretical Biology*
• *Advances in Water Resources*
• *Water Research*
• *Journal of Hydrologic Processes*
• *Journal of the University of Kuwait (Science).*
• *McGraw-Hill*
• *J. Wiley*

Grant proposals reviewed for funding agencies:
• U.S. Environmental Protection Agency SBIR Program
• National Institute of Environmental Health Sciences Superfund Basic Research Program
• U.S. Department of Energy
• University of Wisconsin Water Resources Institute
• Environment Canada

Public Health Assessment Review:
• U.S. Agency for Toxic Substances and Disease Registry, US Department of Health and Human Services – Oak Ridge Reservation, TN.

Promotion and Tenure External Review:
• University of Kansas, Department of Civil, Environmental, and Architectural Engineering, promotion (to associate professor) and tenure case.
• Clemson University, Department of Environmental Engineering and Science, promotion (to full professor) case.
• Virginia Tech, Department of Biological Systems Engineering, College of Agriculture and Life Sciences, promotion (to associate professor) and tenure case.

Department Service:
Assistant Department Head and Graduate Director (2009-present)
Chair, Search Committee, Sustainable Infrastructure (2010-11)
Instructional Laboratory Equipment Committee (2009-present)
Coordinator, Environmental and Water Resources Engineering Graduate Program (2003-08)
Chair, Search Committees (3), Environmental and Water Resources Engineering (2007-08)
Departmental Representative, College of Engineering Promotion and Tenure Committee (2007-08)
Promotion and Tenure Committee (2005-08)
Computer Committee (2004-07)
Search Committee, Geospatial Faculty/Associate Director CGIT (2002-03)
Promotion and Tenure Committee (1999-2002); Chair (2001-02)
Environmental Faculty Search Committee I (1999-2000)
Environmental Faculty Search Committee II (2000-01)
Coordinator, Hydrosystems Graduate Program (1999-2001)
Hydrosystems Laboratory Coordinator (1993-1999)
ASCE Student Chapter Advisor (1996-1999)
Civil Engineering Advising, Working Group (1997)
Shop Technician Assessment Committee (1994-present)
Environmental Faculty Search Committee I (1996-97)
Environmental Faculty Search Committee II (1996-97)
Budget Advisory Committee (1995-1996)
Environmental/Hydrosystems/Geotechnical Research Initiative (1994-95)
Computer Committee (1993-96)
Hydrosystems Faculty Search Committee (1993-94)

College Service:
   COE Promotion and Tenure Committee, CEE representative (2007-2008)
   COE Executive Committee, CEE representative (2003-2005)

University Service:
   Commission on University Support (2006-present)
   Harry S. Truman Scholarship Committee
   Morris Udall Scholarship Committee
   Working Group on "Virginia Tech as an Environmental Role Model" (Chair)
   American Society of Civil Engineers, Student Chapter Advisor (1996-99)
   Virginia Tech Bicycle Club, Advisor (1995-96)
Peer Reviewer Conflict of Interest Certification

Peer Review: Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds

A conflict of interest or lack of impartiality exists when the proposed peer reviewer personally (or the peer reviewer’s immediate family), or his or her employer, has financial interests that may be affected by the results of the peer review; or may provide an unfair competitive advantage to the peer reviewer (or employer); or if the peer reviewer’s objectivity in performing the peer review may be impaired due to other factors. When the Peer Reviewer knows that a reasonable person with knowledge of the facts may question the peer reviewer’s impartiality or financial involvement, an apparent lack of impartiality or conflict of interest exists.

The following questions, if answered affirmatively, represent potential or apparent lack of impartiality (any affirmative answers should be explained on the back of this form or in an attachment):

- Did you contribute to the development of the document under peer review, or were you consulted during its development, or did you offer comments or suggestions to any drafts or versions of the document during its development? □ No □ Yes
- Do you know of any reason that you might be unable to provide impartial advice on the matter under consideration in this peer review, or any reason that your impartiality in the matter might be questioned? □ No □ Yes
- Have you had any previous involvement with the review document(s) under consideration? □ No □ Yes
- Have you served on previous advisory panels, committees, or subcommittees that have addressed the topic under consideration? □ No □ Yes
- Have you made any public statements (written or oral) on the issue? □ No □ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? □ No □ Yes
- Do you, your family, or your employer have any financial interest(s) in the matter or topic under peer review, or could someone with access to relevant facts reasonably conclude that you (or your family or employer) stand to benefit from a particular outcome of this peer review? □ No □ Yes

With regard to real or apparent conflicts of interest or questions of impartiality, the following provisions shall apply for the duration of this peer review:

(a) Peer Reviewer warrants, to the best of his/her knowledge and belief, that there are no relevant facts or circumstances that could give rise to an actual, apparent, or potential organizational or personal conflict of interest, or that Peer Reviewer has disclosed all such relevant information to EMS or to EPA.

(b) Peer Reviewer agrees that if an actual, apparent, or potential personal or organizational conflict of interest is identified during performance of this peer review, he/she immediately will make a full disclosure in writing to EMS. This disclosure shall include a description of actions that Peer Reviewer (or his/her employer) has taken or proposes to take after consultation with EMS to avoid, mitigate, or neutralize the actual, apparent, or potential organizational conflict of interest. Peer Reviewer shall continue performance until notified by EMS of any contrary action to be taken.

Mark A. Widdowson 4/26/12
Signature Date

☑ Check here if any explanation is attached

Mark A. Widdowson
Printed Name

Virginia Tech, The Charles E. Via, Jr. Dept. of Civil & Environmental Engineering
Affiliation/Organization
April 26, 2012

Catherine Sims
Environmental Management Support
8601 Georgia Ave., Suite 500
Silver Spring, MD 20910

Re: Peer Reviewer Conflict of Interest Certification pertaining to peer review a vapor intrusion document by U.S. EPA

Dear Ms. Sims,

The following is an explanation for an affirmative answer on the above-referenced Peer Reviewer Conflict of Interest Certification for the 5th question: *Have you made any public statements (written or oral) on this issue?*

- I have presented research findings at professional meetings and authored peer-review journal articles on the fate and transport of volatile organic compounds (VOCs) in soils at contaminated sites.

- More recently, I provided a scientific peer review of the technical justification for a Low-Threat UST Closure Policy proposed by the California State Water Resources Control Board. This review was completed on February 29, 2012 and made public in March.

In both instances, I did not make public statements that would indicate that I have advocated a position on the issue under consideration. Therefore, I answered "No" to the 6th question.

- In my research writings and presentations, I have not addressed policy issues.

- My review of the proposed California UST Closure Policy was performed independently for an outside party. My evaluation included both scientific strengths and potential weaknesses to the proposed policy.

Sincerely,

Mark A. Widdowson, Ph.D., P.E.
Professor and Assistant Department Head
The Charles Edward Via, Jr. Department of Civil and Environmental Engineering
Environmental and Water Resources Engineering Program