

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)

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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)

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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:

Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds; April 18, 2012 draft report prepared by Golder Associates and RTI International (“the Golder/RTI Report”).

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).

May 3, 2012

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10 **Draft Report**

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12 **Evaluation of Empirical Data and Modeling**
13 **Studies to Support Soil Vapor Intrusion**
14 **Screening Criteria for Petroleum**
15 **Hydrocarbon Compounds**

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21 Prepared by
22 Golder Associates and RTI International

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24 for

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

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31 **Draft Report – Do not Distribute or Cite**

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44 comment under applicable information quality guidelines. It has not been formally disseminated
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215 1. Introduction

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

225 1.1 Background

226 In support of its general guidance development effort for the VI exposure pathway, U.S.
227 EPA has compiled an empirical database of paired measurements of subsurface media
228 (groundwater, soil gas) and indoor air concentrations, which consists primarily of data for
229 chlorinated solvent chemicals, with very limited data for PHC compounds (approximately
230 3 percent of the database) (U.S. EPA, 2012a). The study discussed in this document is
231 exclusively directed at PHCs and only analyzes subsurface media (soil gas, soil, and
232 groundwater) concentrations and other supporting data for PHCs. The rationale for this focus on
233 subsurface PHC measurements is that PHC vapors can rapidly biodegrade in the presence of
234 oxygen and attenuate to much lower concentrations in soil gas (U.S. EPA, 2011).

235 Because the bioattenuation process is well documented and widespread (U.S. EPA,
236 2011), the analysis of subsurface soil gas data from sites provides an opportunity for developing
237 improved and more realistic screening evaluation methods for PHC compounds based on the
238 observed attenuation. These data can be used to identify “an exclusion distance,” defined in this
239 report as the contamination source-separation distance at which the potential for PVI is deemed
240 negligible. This exclusion distance, and much of the underlying data on which it is based,
241 primarily stems from the work of Robin Davis, a regulator with the Utah Department of
242 Environment’s UST program (see Davis, 2009, 2010, 2011a, and 2011b).

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

250 In addition, several similar parallel efforts are in progress in this country (Lahvis et al., In
251 prep.; Peargin and Kolhatkar, 2011), and Australia (Wright, 2011, 2012) using somewhat
252 different data sets than the one used in this document. Regarding these complementary database
253 evaluations, the benzene data from sites in the United States and Canada are identical for this

254 database study and the Lahvis et al. (In prep.) effort. The main differences between Lahvis et al.
255 (In prep.) and this U.S. EPA study are that:

- 256 1. The Lahvis et al. (In prep.) study includes data from sites in Wright's (2011)
257 Australian database, whereas the U.S. EPA database does not¹.
- 258 2. The U.S. EPA database includes a more extensive evaluation of a range of chemicals,
259 including aromatic and aliphatic hydrocarbon fractions, whereas the focus of Lahvis
260 et al. (In prep.) is benzene vapor attenuation.

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

263 **1.2 Goals and Objectives**

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

- 268 1. Sites with a relatively high potential for a complete PVI pathway² and possible
269 unacceptable risks.
- 270 2. Sites with a relatively high potential for an incomplete PVI pathway.
- 271 3. Sites with an unknown potential for a complete PVI pathway and risk, thus requiring
272 further assessment.

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

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

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

- 282 • Assemble an empirical database from petroleum release sites where the PVI pathway
283 has been evaluated via primarily soil gas and groundwater measurements;
- 284 • Consolidate and independently check existing databases and enter and check newly
285 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 measureable indoor petroleum hydrocarbon vapor concentrations that come from a subsurface contamination source.

- 286 • Analyze the database and available case studies to determine when and under what
287 conditions there is the potential for a complete PVI pathway at a site;
- 288 • Review published modeling studies on PHC vapor transport and intrusion as a
289 supporting line-of-evidence; and
- 290 • Identify methods and criteria that can be used to exclude (and include) petroleum
291 release sites from further PVI investigation and concern.

292 **1.3 Document Organization**

293 This report is organized as follows:

- 294 • Section 2 describes the conceptual site model (CSM) for aerobic biodegradation of
295 PHC vapors and select case studies where PVI has been documented.
- 296 • Section 3 provides a review of select modeling studies of the biodegradation of PHCs
297 in the subsurface.
- 298 • Section 4 provides a review of empirical database studies of PHC vapor attenuation.
- 299 • Section 5 provides a review of exclusion distances for PVI in existing state VI
300 guidance.
- 301 • Section 6 describes the PVI database development, structure, and content.
- 302 • Section 7 describes the PVI database analysis approach and methods.
- 303 • Section 8 describes the PVI database analysis results.
- 304 • Section 9 provides a discussion of the results and comparisons with other studies.
- 305 • Section 10 provides conclusions drawn based on this study.

306 **2. Conceptual Site Model and Select Case Studies**

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

311 **2.1 Aerobic Biodegradation Processes**

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

319 Volatilization of PHCs will occur from both LNAPL and dissolved (groundwater)
320 hydrocarbon sources. Methane and carbon dioxide gas may be generated through microbial

321 breakdown of PHC compounds in anaerobic source zones. Fuel oxygenates, such as ethanol and
322 methyl tert-butyl ether (MTBE), can also be present in the vapor phase in the unsaturated zone
323 proximate to LNAPL source zones.

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

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

343 **2.2 Factors Influencing Aerobic Biodegradation**

344 Biodegradation of petroleum hydrocarbons has been reported in more than 70 years of
345 publications (ZoBell, 1946; Atlas, 1981; Leahy and Colwell, 1990), including PHC liquids and
346 gases; straight, branched, and ring-structure PHC compounds with single and multiple carbon
347 bonds; by many microbial species, including 30+ genera of bacteria, 25+ genera of fungi, and
348 several algae (although not every chemical is degraded by every microbial species); in marine,
349 freshwater, sediment, and soils environments; and in direct metabolism and co-metabolism (co-
350 oxidation). Microbial degradation of petroleum produces biomass, intermediate products
351 (alcohols, aldehydes, organic acids), and the ultimate mineralization products carbon dioxide
352 (CO₂) and water (H₂O). In general, relatively fast acclimation times are observed, absent other
353 limits, by population enrichment (fast biomass growth) and/or plasmid transfer. Acclimation
354 times tend to be shorter with prior chemical exposure. Environmental conditions under which
355 petroleum biodegradation has been observed range from 0° to 70°C, salinity up to 25 parts per
356 thousand sodium chloride (NaCl), and pH from 6 to 10, although optimum conditions can be
357 narrower. Aerobic biodegradation is the primary mechanism in the unsaturated zone, but
358 anaerobic biodegradation near source zones may also occur through other electron acceptors
359 present (nitrate, sulfate, etc.) (strict or facilitative), or under fermentative or methanogenic
360 conditions (DeVuall et al., 1997; Madigan et al., 2010). There have been extensive compilations
361 of rates of aerobic degradation specific to vadose zone aerobic soils (e.g., DeVuall et al., 1997;
362 Hers et al., 2000; Ririe et al., 2002; Davis et al., 2009; DeVuall, 2011).

363 The U.S. Air Force Bioventing Initiative study of 125 sites indicated that environmental
364 factors, such as soil moisture, nutrients, and pH, did not significantly influence biodegradation
365 activity and respiration rates, except for one site located in the Mohave Desert with very dry soils
366 (moisture content of 2 percent), although some biological activity did still occur at this moisture
367 content (Leeson and Hinchee, 1996). Biological activity is limited when the moisture content is
368 at or below the permanent wilting point (Zwick et al., 1995; Holden et al., 1997), which is
369 expected to be rare in most geological and climatic environments (note that the empirical
370 database for this project includes sites in dry areas).

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

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

380 2.3 Dissolved versus LNAPL Vapor Sources

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

395 The differences in the PHC vapor concentrations and fluxes for LNAPL and dissolved
396 vapor sources are an important distinction for defining exclusion distances (**Figure 1**).
397 Conceptually, the source type (dissolved or LNAPL) will affect the position of the aerobic
398 reaction front in the unsaturated zone relative to the oxygen source. For dissolved sources, the
399 reaction front will be located close to the hydrocarbon source (Roggemans et al., 2001; Golder
400 Associates, 2006; Abreu et al., 2009), while for LNAPL sources, the reaction front position is
401 more variable, but typically is located at greater distances from the source compared with
402 dissolved sources (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009). For

403 dissolved vapor sources, case study meta analyses and database evaluations reported in the
404 literature indicate no confirmed cases of PVI for a wide range of site conditions (Davis, 2009;
405 McHugh et al., 2010).

406 **2.4 Conditions for Increased Potential for Petroleum Vapor Intrusion**

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

- 409 • *Direct contact between contamination (either dissolved or LNAPL) and a building*
410 *foundation.* Most documented cases of PVI are for this condition (McHugh et al.,
411 2010).
- 412 • *Insufficient separation distance.* For biodegradation to limit the potential for PVI, a
413 sufficiently thick layer of “clean,” oxygenated soil is needed between the building
414 foundation and the contamination (the required thickness will depend on source type).
415 Clean soil is defined as un-impacted by residual LNAPL.
- 416 • *Preferential transport pathways.* If a preferential pathway connects a contamination
417 source to a building, the chemical transport can be faster and extend farther than
418 transport through the surrounding soils.
- 419 • *Anaerobic (low oxygen) conditions.* Building foundations and adjacent land surfaces
420 with low effective diffusivity and soil-air permeability can reduce oxygen transfer to
421 the subsurface by serving as a surface cap. Natural conditions can also limit oxygen
422 availability, as evidenced by low oxygen concentrations found in the presence of
423 some highly organic soils (e.g., peat) or areas where methane is naturally high. The
424 relative importance of a potential capping effect is not well understood, although
425 significant diffusive oxygen transport through intact concrete can occur, as indicated
426 by measured rates reported in the literature (Branco and de Brito, 2004; Kobayashi
427 and Shuttoh, 1991; Tittarelli, 2009). Advective transport of atmospheric air to the
428 subsurface also can occur through openings (e.g., cracks, drains, sumps) in the
429 building foundation during time periods when the building is positively pressurized.
430 These mechanisms can limit the potential for low oxygen conditions beneath a
431 building.
- 432 • *Production of methane gas.* Methane may be produced through microbial breakdown
433 of PHC compounds in anaerobic source zones, and the presence of ethanol in a source
434 zone may increase the generation rate of methane compared with a gasoline LNAPL-
435 only source zone (Nelson et al., 2010; Spalding et al., 2011; Jourabchi et al., 2012).
436 Note that releases of fuel containing 10% ethanol (E10) are most likely included in
437 the reviewed database (this document, see Section 6.3) and in Lahvis et al. (In prep.).
438 Evaluation of methane generation from ethanol fuel blends is an area of active
439 research (Jewell and Wilson, 2011). Methane production can result in soil gas
440 pressures and flow toward receptors and may deplete oxygen that otherwise could be
441 used for biodegradation of the PHC vapors. Elevated methane therefore could
442 increase the potential for PVI at a PHC release site. However, to our knowledge, there
443 are no published data from UST sites where significant source zone advection has

444 been an issue. Concentrations of methane above the lower explosive limit can present
445 a flammability and explosion risk.

446 **2.5 Case Studies Indicating Confirmed or Likely Complete Transport Pathway for** 447 **Petroleum Vapor Intrusion**

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

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

460 **2.5.1 Refinery Site, Perth, Australia (Patterson and Davis, 2009)**

461 Monitoring at a former refinery site near Perth, Australia, with a kerosene LNAPL source
462 indicated elevated (up to 20 mg/L) PHC vapor concentrations and depleted oxygen (<1 percent)
463 below the interior of a building, but much lower hydrocarbon and near-atmospheric oxygen
464 concentrations near the edge and beside the building. The slab-on-grade building footprint area is
465 2,700 ft² (251 m²) with a 30-ft (9.1-m) wide concrete apron on three sides of the building, and
466 uncovered open ground on one side of the building. The building is underlain by sand with a
467 LNAPL zone across the water table at approximately 10 ft (3.0 m) below ground surface (bgs).
468 The effective diffusion coefficient for chemical transport through concrete was measured at the
469 site and was found to be relatively low compared with published data, indicating the concrete
470 slab was not overly porous. The relatively low diffusivity of the concrete may have reduced
471 oxygen transport to the subsurface under the building. In addition, because of the wide concrete
472 aprons, the effective area of the building with respect to oxygen transport restrictions may be
473 larger than its footprint.

474 **2.5.2 Chatterton Petrochemical Site, Vancouver, B.C., Site (Hers et al., 2000; Hers et al.,** 475 **2002)**

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

483 2.5.3 Refinery Site, Casper, Wyoming (Luo et al., 2009)

484 Monitoring at a site in Casper, Wyoming, indicated a complete PVI pathway at a refinery
485 site with a light distillate (gasoline-range) LNAPL source. LNAPL contamination was present in
486 the unsaturated zone at depths between about 1 and 5 ft (0.3 and 1.5 m²) below a small
487 warehouse-type building with a slab-on-grade foundation. Monitoring of subslab soil gas
488 indicated oxygen was depleted (<1 percent) below the interior regions of the building, but not
489 below the edges of the building.

490 2.5.4 Former Refinery Site (Unknown location) (Luo et al., 2010)

491 Monitoring at a former refinery site (unknown location) with a building overlying a light
492 distillate (gasoline-range) LNAPL source indicated relatively uniform and elevated (60 to
493 160 mg/L) PHC vapor concentrations and depleted oxygen beneath and around the building
494 foundation. The building footprint area is 2,100 ft² (195 m²) with a basement depth of 5 ft (1.5
495 m) bgs. The ground surface is predominantly grass covered, except on one side of the building
496 where there is an asphalt/concrete parking lot. Soils with LNAPLs were first encountered at
497 about 30 to 35 ft (9.1 to 10.7 m) bgs; therefore, the separation distance between the building
498 foundation and contamination (LNAPL) is approximately 25 to 30 ft (7.6 to 9.1 m). Detailed soil
499 respiration and soil-air permeability test results suggest two possible reasons for the observed
500 behavior: 1) significant background oxygen uptake in surface soils and/or 2) physically limited
501 oxygen transport from the atmosphere. Soil oxygen uptake rates in shallow soil ranged from 2 to
502 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
503 to 8 ft (2.1 to 2.4 m) bgs, both with soil-air permeabilities of less than 1×10^{-14} m². The results
504 from Luo et al. (2010) suggest both of these reasons are plausible.

505 2.5.5 Refinery Site, Hartford, Illinois (Illinois Department of Public Health, 2010)

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

510 2.5.6 UST Site, Stafford, New Jersey (Sanders and Hers, 2006)

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

519 **2.5.7 UST Site, Ogden, Utah, Mini-Mart Release (McHugh et al., 2010)**

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

523 **2.5.8 UST Site, Gunnison, Utah, Top Stop Release (McHugh et al., 2010)**

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

531 **3. Review of Modeling Studies**

532 Numerous modeling studies of aerobic biodegradation have been conducted to evaluate
533 biodegradation processes, identify factors influencing biodegradation, compare modeled to
534 predicted hydrocarbon vapor attenuation, and estimate first-order biodegradation rates (e.g., Jury
535 et al., 1983; Lahvis and Baehr, 1999; Hers et al., 2000; Ririe et al., 2002; Grathwohl and Maier,
536 2002; Robinson and Tursczynowisz, 2005; Abreu and Johnson, 2005; Abreu and Johnson, 2006;
537 DeVaul, 2007b; Abreu et al., 2009; Davis et al., 2009; DeVaul, 2011; Hers et al., 2012; U.S.
538 EPA, 2012b).

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

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

553 **3.1 Abreu Three-Dimensional Model Simulations**

554 Abreu and Johnson (2005) present the theoretical basis for a three-dimensional model for
555 predicting soil vapor-to-indoor air attenuation factors incorporating subsurface processes of
556 diffusion, gas-phase advection through building depressurization, oxygen-limited first-order

557 biodecay, and uniform mixing of vapors entering a building. Subsequent three-dimensional
558 modeling studies of interest are summarized below.

559 **3.1.1 Three-Dimensional Model Simulations—Below-Building Contamination Source and** 560 **Homogeneous Soil Conditions**

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

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

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

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

592 Abreu et al. (2009) also present a chart that provides representative attenuation factors
593 that apply to all source hydrocarbon vapor concentrations below 10 mg/L and for a range of
594 biodegradation rates (**Figure 4**). There are significant reductions in attenuation factors when
595 aerobic biodegradation is included, relative to the non-biodegradation case; for example, for a
596 separation distance of 5 ft (1.5 m), there is an approximate three orders-of-magnitude reduction
597 in the attenuation factor with biodegradation at a first-order decay rate of 0.79 h^{-1} .

598 **3.1.2 Three-Dimensional Model Simulations—Lateral Migration Scenario and** 599 **Homogeneous Soil Conditions**

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

616 **3.1.3 Three-Dimensional Model Simulations—Surface Capping Scenario**

617 U.S. EPA (2012b) also presents aerobic biodegradation modeling simulations of the
618 influence of variable soil moisture and layered soil deposits, including a two-layer capping
619 scenario with a 1-m (3.3-ft) thick surface soil layer with higher moisture content (60 percent
620 saturation) underlain by a soil layer with a lower moisture content (20 percent saturation). The
621 hydrocarbon source for these simulations was located at 8-m (26-ft) depth, below a house with a
622 2-m (6.6-ft) deep basement. For a high source hydrocarbon vapor concentration (200 mg/L), the
623 attenuation factor predicted for the two-layer scenario was one order of magnitude greater than
624 the single-layer scenario (**Table 2**). For a lower source vapor concentration (2 mg/L), the vapor
625 attenuation factor for the two-layer scenario was 7.1×10^{-15} . Although a single-layer simulation
626 was not performed for the lower source strength, the two-layer scenario attenuation factor is very
627 low and indicates essentially complete biodegradation, and the cap had no effect on the
628 hydrocarbon vapor attenuation below the building.

629 **3.1.4 Comparison of Modeled to Measured Soil Vapor Concentration Data**

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

639 factor of approximately 100. The first-order rate incorporated in the Luo et al. (2010) model
640 simulations was 0.18 h^{-1} .

641 **3.2 DeVaul (2007b) Study (BioVapor Model Development)**

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

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

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

664 **3.3 DeVaul (2010) Study of BioVapor Application**

665 DeVaul (2010) presents BioVapor model simulations where the sensitivity of the model
666 predictions was evaluated for a residential house scenario, dissolved gasoline source
667 concentrations, and a hydrocarbon vapor source–building separation distance of 5 ft (1.5 m). The
668 model simulations, in part, were designed to provide insight on the applicability of the dissolved-
669 source exclusion distance of 5 ft (1.5 m) proposed by Davis et al. (2009). The source
670 groundwater concentrations were 1 mg/L benzene and 3 mg/L each for toluene, ethylbenzene,
671 and xylenes, for a total benzene, toluene, and xylene source concentration of 10 mg/L. The
672 source vapor concentrations were estimated from the Henry's Law constant and a groundwater-
673 to-source vapor attenuation factor of 0.1, resulting in source benzene and total benzene, toluene,
674 and xylene vapor concentrations of 12 mg/m^3 and 120 mg/m^3 , respectively. The oxygen mass
675 transfer to below the building, a key model input parameter for the BioVapor model, was
676 estimated from 13 studies where the soil gas advection rate and/or diffusive oxygen mass transfer
677 rate were measured for small buildings.

678 Devaull (2010) presents model-predicted indoor air concentrations as a function of the
679 effective foundation airflow rate, which is conceptually easier to understand than the oxygen
680 mass transfer rate (**Figure 5**). For modeling purposes, the foundation airflow rate is converted to
681 an oxygen mass transfer rate. The model predicts low indoor air benzene concentrations (less
682 than $1 \mu\text{g}/\text{m}^3$) for the range of effective foundation airflow rates considered. It is also instructive
683 to note that the model results for recalcitrant non-degrading chemicals show an opposite trend in
684 that the indoor air benzene concentration increases as the effective foundation airflow rate
685 increases.

686 **3.4 Summary of Modeling Studies**

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

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

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

701 **4. Review of Empirical Database Studies of Petroleum Hydrocarbon** 702 **Vapor Attenuation**

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

705 Davis (2009) obtained soil gas data from 53 geographical locations in the United States
706 and Canada and from an analysis of 259 benzene and 210 TPH samples and then estimated that
707 5 ft and 30 ft (1.5 m and 9.1 m) of vertical thicknesses of clean soil are required to significantly
708 attenuate benzene and TPH vapors emanating from the dissolved-phase and LNAPL sources,
709 respectively. Dissolved-phase sites were defined on the basis of benzene concentrations in
710 groundwater $< 1,000 \mu\text{g}/\text{L}$. The data obtained by Davis (2009) are incorporated in this study.

711 Peargin and Kolhatkar (2011) evaluated 218 pairs of benzene soil vapor and groundwater
712 concentration data from 25 sites. Data were categorized in bins based on 10^{-2} to 10^{-6} excess
713 cancer risk and assuming a soil vapor-to-indoor air attenuation factor of 0.01 (U.S. EPA, 2002).
714 No benzene soil gas concentrations exceeding $300 \mu\text{g}/\text{m}^3$ (risk-based air concentration for 10^{-5}
715 cancer risk multiplied by 0.01) were observed at vertical separation distances greater than 15 ft
716 (4.6 m). Benzene soil vapor concentrations exceeding $300 \mu\text{g}/\text{m}^3$ were only observed above

717 groundwater sources where benzene concentrations exceeded 1,000 µg/L. The authors concluded
718 that the data support a CSM where benzene vapor transport at concentrations exceeding target
719 screening values can only occur where groundwater source concentrations are high, defined for
720 this study as a dissolved benzene concentration greater than 1,000 µg/L. Some of the data
721 analyzed by Pearn and Kolhatkar (2011) that were provided to Davis (2009) are incorporated
722 in this study. The remaining Pearn and Kolhatkar (2011) data were not readily accessible
723 during the time frame of this study.

724 Wright (2011) presents data from 124 sites in Australia. There are 1,080 pairs of benzene
725 soil vapor and groundwater concentration data; 41 percent of the data were obtained at sites with
726 fractured rock aquifer systems and 12 percent represent data obtained below building
727 foundations (i.e., subslab). The analysis resulted in vertical exclusion distances of 5 to 10 ft (1.5
728 to 3.0 m) for relatively “low-strength” dissolved-phase sources (benzene < 1 mg/L and TPH
729 < 10 mg/L), and ~30 ft (~10 m) for LNAPL and poorly characterized dissolved-phase sources
730 (including sites with large building slabs). The lower threshold benzene and TPH soil vapor
731 concentration for estimating the exclusion distances was based on 5 percent of the lowest
732 Australian Health Screening Levels (Friebel and Nadebaum, 2011). None of the Australian data
733 analyzed by Wright (2011) were incorporated in this study but are analyzed by Lahvis et al. (In
734 prep). A preliminary analysis of the Australian data suggested that the conclusions of the
735 empirical analysis would not change if the Australian data were included; therefore, the data
736 were not incorporated into this study.

737 **5. Review of Exclusion Distances in Existing Vapor Intrusion Guidance**

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

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

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

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

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.

754 related free product contamination. As an alternative approach, NJ DEP (2012)
755 allows for an exclusion distance approach based on benzene concentrations for
756 gasoline contamination. A PVI investigation is not necessary if the vertical separation
757 distance between the water table (all references to water table are for seasonal high
758 conditions) and building slab is:

- 759 – At least 10 ft (3.0 m), for a benzene groundwater concentration $\leq 1,000$ $\mu\text{g/L}$;
- 760 – At least 5 ft (1.5 m), for a benzene groundwater concentration ≤ 100 $\mu\text{g/L}$; or
- 761 – At least 5 ft (1.5 m), for oxygen ≥ 2 percent (v/v) in the unsaturated zone, and a
762 benzene groundwater concentration $\leq 1,000$ $\mu\text{g/L}$.

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

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

773 – **Scenario 1—Unweathered LNAPL on groundwater:**

- 774 ■ A 30-ft (9.1-m) vertical bioattenuation zone between an unweathered LNAPL
775 (residual or free-phase) source and a building foundation.

776 – **Scenario 2—Unweathered LNAPL in soil:**

- 777 ■ A 30-ft (9.1 m) lateral and vertical separation distance between an
778 unweathered LNAPL (residual or free-phase) source in soil and a building
779 foundation.

780 – **Scenario 3—Dissolved phase benzene concentrations in groundwater:**

- 781 ■ With no oxygen measurements:

- 782 – A 5-ft (1.5 m) vertical separation distance between a dissolved-phase
783 benzene source < 100 µg/L and a building foundation.
- 784 – A 10-ft (3.0 m) vertical exclusion distance for a dissolved-phase benzene
785 source < 1,000 µg/L and a building foundation.
- 786 ■ With oxygen > 4 percent:
- 787 – A 5-ft (1.5 m) vertical separation distance between a dissolved-phase
788 benzene source < 1,000 µg/L and a building foundation.
- 789 – **Scenario 4—Direct measurement of soil gas concentrations:**
- 790 ■ Application of a bioattenuation (additional attenuation) factor of 1,000 times
791 to risk-based soil gas criteria (i.e., vapor sources) located within 5 ft (1.5 m) of
792 a building foundation.
- 793 • Wisconsin’s Department of Natural Resources (2010) in their guidance states that
794 where no petroleum odors are detected, PVI can be ruled out at most petroleum
795 release sites with low source concentrations where there is 5 ft (1.5 m) in the
796 horizontal and vertical direction of clean, unsaturated soil with an oxygen content
797 greater than or equal to 5 percent between the residual petroleum and the building.
798 Larger exclusion distances are specified when free product is present (30 ft [9.1 m])
799 or benzene concentrations in groundwater exceed 1 mg/L (20 ft [6.1 m]). When the
800 above distance thresholds and other criteria (e.g., no preferential pathways, no
801 fractured bedrock) are met, a PVI assessment is not required.

802 **6. Database Development, Structure, and Content**

803 **6.1 Database Development and Checking**

804 The starting point for the PVI database developed for this study is a database compiled by
805 Ms. Robin Davis of the State of Utah (the “Davis” database). Ms. Davis compiled data on PHC
806 vapor behavior from over 50 sites starting in 2003; the May 2011 version of the Davis database

807 was imported and used for this analysis. The Davis database includes information on primarily
808 groundwater and soil vapor chemistry, soil properties, and other site data.

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

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

821 6.2 Database Structure

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

827 The different data types are summarized as follows:

- 828 • **Background data:** Site location, geologic setting, contamination type, and generic
829 soil description.
- 830 • **Facility type:** UST, fuel terminal, petroleum refinery, and petrochemical plant.
- 831 • **Site conditions:** Soil type, water-filled and total porosity, and surface cover at soil
832 vapor probe (bare ground, asphaltic pavement, building).
- 833 • **Sampling data:** For each probe, vertical depth from ground surface to water table, to
834 top of contamination, and to media sampling locations. Lateral distance between soil
835 gas probe and groundwater monitoring well and between soil gas probe and UST
836 facility infrastructure (e.g., tanks, fuel dispensers) and buildings.
- 837 • **Analytical data:** Sampling date, analytical method, quality control data, and
838 chemistry data for soil, groundwater, and soil vapor. Analytes in the database are
839 fixed gases (oxygen, carbon dioxide, methane); benzene, toluene, and xylene; TPH;
840 naphthalene; MTBE; 1,3-butadiene; hexane; heptane; and aromatic and hydrocarbon
841 fractions according to methods prescribed by the State of Massachusetts.
- 842 • **Building data:** Building use (e.g., residential, commercial, institutional), foundation
843 type, and building size, for example.

844 As part of the data verification process, certain data quality indicators were reviewed to
845 ensure data of known and acceptable quality. The database was processed to remove data of
846 unacceptable quality or type, as follows: 1) analytical data obtained by unacceptable methods, or
847 no reported methodology or evidence of quality assurance/quality control processes, to remove
848 suspect quality data; 2) soil gas data from fractured rock systems due to the potential for
849 preferential soil gas flow; 3) benzene concentrations in groundwater below detection level
850 because it is not meaningful to conduct an analysis when no contamination source exists, and
851 4) lateral spacing between groundwater monitoring well and soil gas probe (for paired data)
852 greater than about 30 ft (9.1 m) because of variability in sources (this information was not
853 available for all data).

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

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

865 **6.3 Database Content**

866 The number of sites and site locations in the PVI database are listed in **Table 3**. The
867 contents of the database for key fields are summarized in **Tables 4** and **5**. The majority of the
868 sites are UST release sites, although the database also includes data from fuel terminals and
869 petroleum refineries. Most sites were affected by gasoline releases, although a small number of
870 sites have other types of PHC contamination (e.g., diesel, kerosene). The gasoline composition
871 was unknown and assumed to be variable with respect to fuel oxygenate composition, given the
872 relatively broad time span for data collection (1995 to 2011). Gasoline containing ethanol
873 (10 percent vol/vol) was generally introduced to the United States in 2000 with a large increase
874 in use in 2006 (U.S. EPA, 2009), so some sites in the database where recent releases occurred
875 likely have gasoline containing ethanol.

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

880 The database is populated to varying degrees depending on the data type. It contains data
881 for most sites and records on facility type, vertical distances, surface cover, soil type, and
882 benzene and TPH vapor concentrations. Groundwater benzene and TPH concentration data are
883 also available for many sites, and the database also includes data on fixed gases for a majority of
884 the sites. For the other analytes listed above (e.g., toluene, ethylbenzene, xylenes, naphthalene),

885 the database includes data for fewer sites, although the data set for aromatic and aliphatic
886 hydrocarbons is substantial because recent data from 11 Maine sites are included. Although
887 indoor air data are included for a limited number of sites, indoor air data were not used in the
888 analysis because of the limited number of data points and the known effect of background in
889 introducing bias in soil vapor-to-indoor air attenuation factors for PHC compounds.

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

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

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

898 **7. Database Analysis Approach and Methods**

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

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

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

911 **7.1 Source Zone Identification Methods (LNAPL versus Dissolved Indicators)**

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

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

919 Indirect or secondary indicators are as follows:

- 920 • **Groundwater Concentration Data:** Benzene and/or TPH groundwater
921 concentration data from which the presence of LNAPL near the soil gas probe was
922 inferred. This was the determining indicator for approximately 13 percent of the sites.
- 923 • **Soil Concentration Data:** Benzene and/or TPH soil concentration data from which
924 the presence of LNAPL near the soil gas probe was inferred. This was the
925 determining indicator for approximately 2 percent of the sites (one site).
- 926 • **Proximity to Fuel Storage/Dispensing Facilities:** Soil gas probes installed within
927 20 ft (6.1 m) of the tank field or dispenser. This was the determining indicator for
928 approximately 5 percent of the sites.

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

934 **7.1.1 Groundwater Concentration Data**

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

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

949 **7.1.2 Soil Concentration Data**

950 Concentrations of chemicals in soil that approach an estimated LNAPL saturation
951 concentration are indirect evidence for LNAPL. The soil saturation concentration is highly
952 dependent on chemical and soil properties. Concentrations representative of possible LNAPLs
953 suggested in the literature include a TPH gasoline range concentration (gasoline range organics
954 or GRO) greater than 100 to 200 mg/kg and a TPH diesel range organics (DRO) concentration
955 greater than 10 to 50 mg/kg (e.g., ASTM, 2006; Alaska Department of Environmental
956 Conservation, 2011).

957 The thresholds adopted for identifying LNAPL sites are a benzene soil concentration of
958 10 mg/kg and a TPH (gasoline) soil concentration of 250 mg/kg. The benzene concentration
959 (10.7 mg/kg rounded down to 10 mg/kg) was estimated from the equation for soil saturation
960 (“ C_{sat} ”) and the default input parameters in Exhibit 9 of the U.S. EPA Soil Screening Guidance
961 (U.S. EPA, 1996). A TPH soil concentration of 250 mg/kg was adopted to provide for a slightly
962 more conservative screening basis (i.e., more sites are included as dissolved sites with higher
963 thresholds) than the ranges reported in the literature cited above. An LNAPL source site was
964 identified on the basis of either the benzene or TPH soil concentration exceeding the threshold.

965 **7.1.3 Proximity to Fuel Storage/Dispensing Facilities**

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

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

978 **7.2 Data Analysis Methods**

979 The data analysis consisted of three main parts:

- 980 1. Exploratory data analyses to evaluate data trends and relations between different
981 media (e.g., groundwater versus soil gas) and analytes (e.g., hydrocarbon versus
982 oxygen),
- 983 2. Plots of benzene and other hydrocarbon soil vapor concentrations versus the vertical
984 separation distance of the vapor probe above the contamination source (“vertical
985 distance method”), and
- 986 3. Estimated thickness of un-impacted soil for benzene vapors to attenuate to below a
987 threshold (“clean soil method”). This technique required establishing rules for data
988 interpolation.

989 The analysis focused on benzene given its importance for risk evaluations; however, it
990 was also performed for select other compounds, including those analyzed at the Maine sites
991 where full-spectrum hydrocarbon analyses are available (e.g., hexane, aliphatic and aromatic
992 fractions).

993 Given that the database was set up to allow for filtering, the influence of site type (UST,
994 fuel terminal, petroleum refinery), soil properties, presence or absence of buildings, and other
995 factors was evaluated.

996 **7.2.1 Exploratory Data Analysis**

997 The exploratory data analysis involved evaluating the relations between groundwater and
998 soil vapor concentrations, and oxygen and hydrocarbon concentrations to assess whether there
999 were thresholds for minimum concentrations where aerobic biodegradation readily occurs (Davis
1000 et al., 2009; Sweeney, 2012). The rationale for this analysis is described in Section 8.1.

1001 **7.2.2 Vertical Distance Method**

1002 The vertical distance method involved plotting soil vapor concentration versus distance
1003 above a source and estimating either statistically the soil vapor concentrations or the probability
1004 for the soil vapor concentration to be less than a concentration threshold for variable distances
1005 above the contamination source. The conditional probabilities were estimated as follows:

1006
$$P (C_v \leq C_{\text{threshold}}/z > d, \text{Contamination } (z = 0) = \text{LNAPL or dissolved})$$

1007 where C_v is the soil vapor concentration, $C_{\text{threshold}}$ is the soil vapor concentration threshold, z is
1008 the vertical direction, d is the vertical distance from the top of the contamination to the soil gas
1009 probe, and source contamination is characterized as either an LNAPL or dissolved source.

1010 The data were sorted in a cumulative distribution of specified vertical separation
1011 distances from the source (e.g., $\geq 0, \geq 2, \dots, \geq n$ ft). The conditional probabilities were calculated
1012 for two different benzene vapor concentration thresholds (50 or 100 $\mu\text{g}/\text{m}^3$ for benzene) using
1013 two different methods:

- 1014 1. Probability $P = N [C_v < C_{\text{threshold}}]/N [\text{total}]$ where $N [C_v < C_{\text{threshold}}]$ is the number of
1015 benzene vapor concentrations less than the threshold and $N [\text{total}]$ is the total number
1016 of concentration measurements; for this analysis, concentrations below the reporting
1017 limits were replaced with half the reporting limit, a common first approximation for
1018 non-detect measurements.
- 1019 2. Probability was estimated from the concentration distribution calculated by the non-
1020 parametric Kaplan-Meier method (Kaplan and Meier, 1958).

1021 Approximately 31 percent and 57 percent of benzene soil vapor concentrations associated
1022 with LNAPL and dissolved-phase sources, respectively, were non-detects, i.e., below specified
1023 reporting limits. The Kaplan-Meier method is a robust, non-parametric method for considering
1024 data below reporting limits, particularly when there are multiple reporting limits (Helsel, 2005;
1025 2006).

1026 The next step was to estimate the depth to contamination, which is important for an
1027 accurate estimation of the thickness of un-impacted soil needed for attenuation of soil vapor
1028 concentrations. For LNAPL sites, this depth was estimated from boring logs and indications of
1029 LNAPL zones (e.g., observations of product, high headspace organic vapor concentrations above

1030 500 to 1,000 parts per million [ppm], and soil chemistry data); in the absence of data, the depth
1031 to contamination was assumed to be the seasonal high water table. For dissolved sites, the depth
1032 to contamination was the depth to the water table closest to the time the soil gas data were
1033 obtained.

1034 **7.2.3 Clean Soil (Davis) Method**

1035 The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-
1036 impacted clean soil required for soil vapor benzene concentrations to attenuate to below a
1037 defined threshold, which for this analysis is $100 \mu\text{g}/\text{m}^3$. The purpose of conducting this analysis
1038 was to enable comparison to published exclusion distances based on this method previously
1039 reported by Davis (2009; 2010). A clean soil thickness was calculated except when the vertical
1040 distance between soil gas probes was greater than 10 ft (3.0 m), because there is insufficient
1041 resolution (i.e., spacing between probes) for meaningful estimation of the thickness when the
1042 vertical distance between probes is greater than about 10 ft (3.0 m). Two methods were used to
1043 estimate the clean soil thickness:

- 1044 • Method A: Distance to first soil gas probe with benzene $C_{\text{vapor}} < 100 \mu\text{g}/\text{m}^3$ where:
 - 1045 – Lower depth = D_l = Depth to top of contamination
 - 1046 – Upper depth = D_u = Depth to first probe with benzene $C_{\text{vapor}} \leq 100 \mu\text{g}/\text{m}^3$
 - 1047 – Distance = $D_l - D_u$
- 1048 • Method B: Interpolated distance to between a soil gas probe with benzene $C_{\text{vapor}} >$
1049 $100 \mu\text{g}/\text{m}^3$ and a soil gas probe with $C_{\text{vapor}} < 100 \mu\text{g}/\text{m}^3$ where:
 - 1050 – Lower depth = D_l = Depth to top of contamination
 - 1051 – Upper depth = D_u = Interpolated as halfway between the depths to a probe with
1052 benzene $C_{\text{vapor}} \leq 40 \mu\text{g}/\text{m}^3$ and $C_{\text{vapor}} > 100 \mu\text{g}/\text{m}^3$; however, if the lower
1053 concentration is greater than $40 \mu\text{g}/\text{m}^3$, then D_u = depth to first probe with
1054 benzene $C_{\text{vapor}} \leq 100 \mu\text{g}/\text{m}^3$
 - 1055 – Distance = $D_l - D_u$, subject to minimum thickness of 0.5 ft (0.2 m).

1056 For both Methods A and B, benzene concentrations below reporting limits were replaced with
1057 half the reporting limit.

1058 A lower concentration threshold was considered warranted for Method B because of the
1059 potential for the halfway distance interpolation to be non-conservative when the lower
1060 concentration is much greater than $100 \mu\text{g}/\text{m}^3$ (which is often the case) and the upper
1061 concentration is just less than $100 \mu\text{g}/\text{m}^3$. The $40 \mu\text{g}/\text{m}^3$ threshold is subjective, but when the
1062 upper benzene vapor concentration is less than this threshold, the halfway interpolation method
1063 is more accurate. Although more complicated and possibly more accurate interpolation rules
1064 could have been developed, Method B was intended as a simple, approximate method.

1065 For locations where the measured soil vapor benzene concentration does not attenuate to
1066 less than $< 100 \mu\text{g}/\text{m}^3$, a clean soil thickness cannot be calculated, but a minimum clean soil

1067 thickness (i.e., greater than) is reported as the distance between the shallowest soil gas probe and
1068 the top of contamination.

1069 An example calculation of clean soil thicknesses and exclusion distances is presented in
1070 **Figure 6**. For the Area 1A soil gas probe profile, the Method A and B distances are 11 ft (3.4 m)
1071 and 9 ft (2.7 m), respectively. For Site D, the benzene concentration in the shallowest probe is
1072 greater than $100 \mu\text{g}/\text{m}^3$ in the shallowest probe; therefore, the clean soil thickness is identified as
1073 greater than 11 ft (3.4 m) in the database.

1074 **7.3 Soil Vapor Concentration Thresholds**

1075 An important part of the analysis was defining a soil vapor concentration threshold when
1076 soil PVI would typically not be of potential concern. The concentration threshold was based on
1077 the expected attenuation in vapor concentrations between shallow soil vapor and indoor air, and
1078 the toxicity of the chemical under consideration.

1079 The processes that affect the vapor concentration in indoor air for a shallow soil vapor
1080 source are primarily soil gas advection and ventilation and mixing of the chemical within the
1081 enclosed space (Hers et al., 2003; Johnson, 2005), although some additional biodegradation and
1082 sorption could also occur between a shallow vapor source and an indoor environment. Several
1083 modeling studies provide insight on the attenuation factor for a typical residential house. Yao et
1084 al. (2011) reported attenuation factors between 2×10^{-4} and 7×10^{-3} for a numerical modeling
1085 study. Johnson (2005) in a modeling study using the Johnson and Ettinger (1991) model
1086 calculated attenuation factors between 4.4×10^{-3} and 7.3×10^{-3} for a shallow soil vapor source
1087 and representative input parameters for a residential house. A similar study by Hers et al. (2003)
1088 included a sensitivity analysis where the maximum attenuation factor for a range of conditions
1089 was 9×10^{-3} and a relatively good comparison (within an order of magnitude) was obtained
1090 between Johnson and Ettinger model predictions and measured attenuation factors for
1091 chlorinated solvent chemicals. Although this comparison is for chlorinated solvent chemicals, it
1092 is relevant here because it identifies typical attenuation factors between shallow or subsurface vapor
1093 and indoor air, irrespective of possible biodegradation processes.

1094 The U.S. EPA database of empirical vapor attenuation factors (U.S. EPA, 2012a) is
1095 another information source, although selection of a representative attenuation factor was
1096 challenging. This is because the empirical attenuation factors vary over several orders of
1097 magnitude, due to the variability in both indoor air and subsurface vapor concentrations, and
1098 background sources of chemicals in indoor air.

1099 The U.S. EPA database 50th and 95th percentiles of the subsurface attenuation factor are
1100 5.0×10^{-3} and 1.8×10^{-1} , respectively, for the data set limited to indoor air concentrations above
1101 the 90th percentile literature background concentration. For the data set filtered based on subsurface
1102 vapor concentrations greater than 100 times the literature background, the 50th and 90th
1103 percentiles of the subsurface attenuation factor are 2.5×10^{-3} and 2.0×10^{-2} , respectively. Based on
1104 the above review, a shallow soil vapor-to-indoor air attenuation factor of 0.01 was considered a
1105 reasonably conservative factor for the analysis.

1106 Risk-based indoor air concentrations for a residential scenario are provided in **Table 7** for
1107 the chemicals of potential concern considered in this analysis. The risk-based indoor air
1108 concentrations assume a residential scenario, continuous life-time exposure to vapors, and no
1109 exposure amortization. For chemicals other than benzene, a risk-based soil vapor concentration
1110 (RBC_v) was calculated as 100 times the risk-based air concentration. The thresholds adopted for
1111 benzene, 50 and 100 $\mu\text{g}/\text{m}^3$, were based primarily on practical considerations relating to the
1112 detection limit (i.e., the frequency of non-detects increases as the benzene concentration
1113 decreases). For comparison, assuming an attenuation factor of 0.01, the calculated benzene
1114 threshold is 29 $\mu\text{g}/\text{m}^3$ for an incremental lifetime cancer risk (ILCR) of 1×10^{-6} , and 290 $\mu\text{g}/\text{m}^3$
1115 for an ILCR of 1×10^{-5} .

1116 **8. Database Analysis Results**

1117 **8.1 Exploratory Data Analysis**

1118 The cumulative distributions of benzene concentrations in groundwater are plotted in
1119 **Figure 7** for hydrocarbon sources classified as dissolved phase and LNAPL. The groundwater
1120 benzene concentrations for LNAPL sites are higher than for dissolved sites, but for a proportion
1121 of the LNAPL site data, there are relatively low benzene groundwater concentrations. This may
1122 be due to spatial variability in groundwater concentrations, highly weathered residual-phase
1123 LNAPL that is relatively depleted of benzene, variable well screen intervals relative to the water
1124 table, and vadose zone LNAPL sources.

1125 The relations between benzene concentrations in groundwater and deep soil vapor probes
1126 (within 3 ft [0.9 m] of the contamination source) for dissolved and LNAPL sources are shown in
1127 **Figure 8**. There is no apparent correlation for dissolved-source data, but a weak proportional
1128 relation exists between groundwater and soil vapor concentrations for LNAPL source data.

1129 For dissolved-source data, the measured deep benzene vapor concentrations are, in
1130 almost all cases, at least an order of magnitude (10 times) and, in many cases 2 orders of
1131 magnitude (100 times), less than the predicted soil vapor concentration based on Henry's Law
1132 partitioning. A dimensionless Henry's Law constant of 0.14 was used for benzene, which is
1133 based on a groundwater temperature of 15°C, considered a representative value based on the
1134 groundwater temperature map in U.S. EPA (2004).

1135 For the LNAPL source data, the measured benzene vapor concentrations are significantly
1136 less than predicted for benzene groundwater concentrations less than approximately 1 mg/L. For
1137 concentrations greater than 1 mg/L, the benzene vapor concentrations for some data points are
1138 close to the predicted concentrations by Henry's Law, which is consistent with an LNAPL
1139 source and limited attenuation between the source and deep soil vapor sample.

1140 The poor correlation between groundwater and soil vapor concentrations is likely due to
1141 1) variable well screen intervals relative to the water table, 2) variable biodegradation between
1142 the groundwater and lowermost soil gas sampling location, and 3) spatial variability and
1143 differences in dissolved-phase concentrations at groundwater and soil gas sampling locations.

1144 The relation between co-located oxygen and PHC vapor concentrations has been
1145 hypothesized as potentially providing insight on biodegradation processes and a possible lower
1146 oxygen limit for occurrence of aerobic biodegradation. The expectation is low oxygen at high
1147 hydrocarbon vapor concentrations and high oxygen (near atmospheric) at low hydrocarbon vapor
1148 concentrations, excluding sites where there is high natural oxygen demand. The oxygen versus
1149 TPH vapor concentration data indicate general trends consistent with expected behavior and
1150 notably no data indicating depleted oxygen for dissolved sources, but considerable scatter in the
1151 data (**Figure 9**). For LNAPL sources, the low oxygen concentrations (less than 2 percent) occur
1152 when TPH vapor concentrations exceed approximately 1 mg/L. Some data points where oxygen
1153 and TPH vapor concentrations are both elevated may be due to the introduction of oxygen during
1154 sampling or analysis. Although the data suggest that aerobic biodegradation can occur at low
1155 oxygen concentrations (on the order of 1 to 2 percent), of greater relevance for the aerobic depth
1156 is the oxygen flux into the soil from the atmosphere and not the lowest oxygen concentration
1157 measured in soil.

1158 The database includes methane data for 23 sites. Methane concentrations exceeded 5
1159 percent (lower explosive limit in air) at four sites (three UST sites and one petroleum refinery
1160 site), but were less than 1 percent at the remaining 19 sites. There was no apparent correlation
1161 between methane and benzene vapor concentrations in this limited data set. Three of the four
1162 sites with elevated methane concentrations were investigated prior to 2000, so the methane at
1163 these sites was not associated with ethanol in the gasoline leaked into the subsurface.

1164 The relations between benzene and ethylbenzene and benzene and xylenes soil vapor
1165 concentrations are shown in **Figure 10**. As shown, qualitatively there is a relatively good
1166 correlation between these two analyte pairs, although for the benzene-xylenes comparison, the
1167 xylenes' vapor concentrations for low concentrations are generally (up to two orders of
1168 magnitude) higher than the benzene concentrations.

1169 **8.2 Vertical Distance Method**

1170 For the vertical distance method, soil vapor concentrations (of the PHC compounds listed
1171 below) are compared with risk-based vapor concentrations, RBC_v (risk-based indoor air
1172 concentrations multiplied by 100), and for benzene, the probability that the soil vapor
1173 concentration is less than a defined threshold (50 and 100 $\mu\text{g}/\text{m}^3$) for varying source-separation
1174 distances was estimated. For definition of exclusion distances, a probability greater than 95
1175 percent was considered a reasonable threshold.

1176 **8.2.1 All Data**

1177 The data analysis was conducted for 1) dissolved sources; 2) LNAPL sources,
1178 incorporating data for just UST sites; and 3) LNAPL sources, incorporating data for all facility
1179 types (UST, fuel terminal, petroleum refinery, and petro-chemical) (**Figures 11 through 15**).
1180 There are only PHC fraction and hexane data for UST sites; hence, we do not include a figure for
1181 the all-LNAPL sites category for these compounds. The following compounds were evaluated:
1182 benzene, xylenes, hexane, 2,2,4-TMP, and Massachusetts Department of Environmental

1183 Protection (MADEP) hydrocarbon fractions (C9-10 aromatics, C5-8 aliphatics, and C9-12
1184 aliphatics).⁴

1185 For the benzene analysis, nondetects were addressed both by the common practice of
1186 substituting half the detection limit for non-detects and by using the more statistically robust
1187 Kaplan-Meier non-parametric method. The Kaplan-Meier method resulted in similar or slightly
1188 higher (0 to 7 percent) probabilities than the substitution method. The probabilities the soil vapor
1189 concentration being less than a threshold was estimated for 5 and 30 mg/L groundwater
1190 concentration thresholds for benzene and TPH, respectively, which are part of the LNAPL
1191 hydrocarbon indicators (**Table 6**). A sensitivity analysis was conducted where the threshold for
1192 the benzene groundwater concentration was varied between 1 and 10 mg/L, and the TPH
1193 groundwater concentration was varied between 10 and 50 mg/L. The resulting variation in
1194 probability (estimated using the substitution method) for this range was less than 0.5 percent,
1195 indicating the results are not sensitive to the concentration thresholds (possibly because
1196 groundwater is a poor predictor of soil vapor concentrations).

1197 The analysis results show distinct differences between the three scenarios considered
1198 (**Table 8**).

1199 For dissolved sources, greater than 97 percent and 94 percent of the benzene soil vapor
1200 concentrations are less than the specified thresholds of 50 and 100 $\mu\text{g}/\text{m}^3$, respectively, for
1201 source-separation distances as small as 0 ft (**Table 8** and **Figures 11** and **12**). Comparisons for
1202 other compounds evaluated indicate that soil vapor concentrations above risk-based soil vapor
1203 concentrations occurred only for separation distances smaller than 3 ft (0.9 m). The analysis
1204 indicates there is a low probability of exceeded risk-based thresholds for small separation
1205 distances for dissolved sources.

1206 For LNAPL sources, the PHC vapor concentrations were plotted against the separation
1207 distance between the soil gas probe and hydrocarbon source (**Figures 13** through **15**). The
1208 maximum concentrations of benzene and other hydrocarbon vapor concentrations were several
1209 orders of magnitude greater than for dissolved sources, but concentrations of benzene soil vapor
1210 concentrations decreased rapidly between 10 and 15 ft (3.0 and 4.6 m) separation distance and
1211 for other compounds at smaller separation distances, although it should be noted that the data
1212 sets for other compounds are relatively small. For LNAPL sources that are limited to UST sites,
1213 approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds
1214 (50 and 100 $\mu\text{g}/\text{m}^3$) at a source-separation distance of approximately 15 ft (4.6 m), which
1215 increases to approximately 30 ft (9.1 m) when all LNAPL facility types are included.

1216 Soil vapor data for 2,2,4-TMP for LNAPL sources (all facility types) were limited
1217 (**Figure 16**). There were elevated 2,2,4-TMP vapor concentrations (0.01 to 10 mg/L)
1218 representing data from two sites; at one site, concentrations remained elevated for separation

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 $\mu\text{g}/\text{m}^3$ for dissolved sources and 180 $\mu\text{g}/\text{m}^3$ 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.

1219 distances as great as 50 ft (15 m). The U.S. EPA IRIS database does not contain toxicity
1220 reference factors for 2,2,4-TMP.

1221 The analysis results indicate benzene is the risk driver, with greater occurrences of
1222 exceedances of risk-based vapor concentrations for larger separation distances, when compared
1223 with the other compounds evaluated.

1224 **8.2.2 Influence of Surface Cover**

1225 The potential influence of a surface cover was evaluated through comparison of the
1226 probabilities of benzene soil vapor concentrations that are less than $100 \mu\text{g}/\text{m}^3$ for varying soil-
1227 separation distances and through analysis of oxygen concentrations for three different surface
1228 covers: building concrete foundations, pavement, and bare-ground cover (**Figures 17 and 18**).
1229 The data sets evaluated were limited to LNAPL sources because oxygen is not limiting for
1230 dissolved-source sites.

1231 When all the facility types were considered (which yields the largest data set), the
1232 analysis of probabilities for varying soil-separation distances indicated different results
1233 depending on surface cover. The probabilities of benzene soil vapor concentrations less than 100
1234 $\mu\text{g}/\text{m}^3$ were between 5 and 20 percent greater for the ground cover scenario, compared with the
1235 pavement and building scenarios, which yielded similar results (**Figure 17**). The oxygen
1236 concentration results were generally consistent with the above probabilities, with no oxygen
1237 concentrations below 2 percent for the ground cover scenario (excluding results for zero
1238 separation distance); however, several data points indicated oxygen concentrations less than 2
1239 percent for separation distances up to 11 ft (3.4 m).

1240 The above analysis was repeated for just LNAPL sources and UST sites. The results were
1241 different in that the probabilities for benzene concentrations less than $100 \mu\text{g}/\text{m}^3$ were similar for
1242 the ground cover and building scenarios, but were between 5 and 20 percent lower for the
1243 pavement scenario (**Figure 18**). The reason for this difference is not known, although it is noted
1244 that LNAPL sources and buildings will tend to be smaller at UST sites, compared with petroleum
1245 refinery or fuel terminal sites. There was a lower frequency of data points with low oxygen
1246 concentrations for UST sites, compared with the analysis where all facility types were
1247 considered.

1248 These analyses suggest surface cover type can affect oxygen availability and PHC vapor
1249 transport. However, because the vertical distance method evaluation includes soil vapor
1250 concentration data from below buildings at 33 UST sites (**Table 4**), the results are considered
1251 sufficiently robust with respect to including the potential influence of surface cover.

1252 **8.2.3 Influence of Soil Type**

1253 The potential influence of soil type is evaluated through comparison of the probabilities
1254 of benzene soil vapor concentrations less than $100 \mu\text{g}/\text{m}^3$ for varying soil-separation distances
1255 and for two general soil types: fine grained and coarse grained (**Figure 19**). The probabilities of
1256 benzene soil vapor concentrations less than $100 \mu\text{g}/\text{m}^3$ were similar for dissolved-source sites for
1257 the two soil types. For LNAPL source sites, the probabilities are between 6 and 16 percent

1258 greater for coarse-grained soils than those for fine-grained soils for small separation distances,
1259 but at larger separation distances, there is a reversal in the trend. Based on the analysis, it is not
1260 possible to identify if soil type has an influence on benzene soil vapor concentrations and
1261 probabilities of exceedances.

1262 **8.3 Clean Soil (Davis) Method**

1263 The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-
1264 impacted clean soil required for soil vapor benzene concentrations to attenuate to below a
1265 defined threshold, which for this analysis is $100 \mu\text{g}/\text{m}^3$. As described in Section 7, two
1266 interpolation methods were used as part of the estimation process. The results of the analyses are
1267 shown in **Figures 20** through **22** and can be summarized, as follows:

- 1268 • For dissolved-source sites, there is no trend relative to dissolved benzene groundwater
1269 concentrations, and the 95th percentile clean soil thicknesses (calculated using Excel)
1270 for Methods 1 and 2 are 10 ft (3.0 m) and 5.4 ft (1.6 m), respectively.
- 1271 • For LNAPL (UST-only) source sites, there is an increase in the clean soil thicknesses
1272 for benzene groundwater concentrations greater than approximately 5 mg/L. The 95th
1273 percentile clean soil thicknesses (incorporating all the data) for Methods 1 and 2 are
1274 13.9 ft (4.2 m) and 13.5 ft (4.1 m), respectively. A small percentage of the data points
1275 represent vertical profile data where the shallowest benzene soil vapor concentration
1276 is greater than $100 \mu\text{g}/\text{m}^3$; therefore, an attenuation distance could not be calculated
1277 (green symbols on **Figures 20** through **22**).
- 1278 • For LNAPL (all sites) source sites, there is a similar trend to UST-only sites with
1279 respect to clean soil thickness versus benzene groundwater concentrations. The 95th
1280 percentile clean soil thicknesses for Methods 1 and 2 are 20.0 ft (6.1 m) and 16.2 ft
1281 (4.9 m), respectively. A small percentage of the data points represent vertical profile
1282 data where the shallowest benzene soil vapor concentration was greater than
1283 $100 \mu\text{g}/\text{m}^3$.

1284 **9. Discussion**

1285 **9.1 Conceptual Site Model and Mathematical Models**

1286 The CSM for PHC vapor behavior is the basis for the framework developed for
1287 identifying exclusion distances and inclusion criteria. At sites with dissolved PHC contamination
1288 in groundwater, aerobic biodegradation is expected to result in the attenuation of PHC vapors,
1289 such that there is limited potential for a complete PVI pathway, except for sites with very
1290 shallow contamination. For sites with shallow LNAPL contamination, there is greater potential
1291 for oxygen limitations below buildings and a complete PVI pathway, depending on site
1292 conditions. Case studies reviewed suggest that the potential for a complete PVI pathway may
1293 exist at non-UST (i.e., petroleum refinery) sites with large-volume LNAPL releases, particularly
1294 where there are large buildings or a capping effect based on geologic conditions.

1295 The mathematical modeling studies reviewed, in general, support the empirical analysis
1296 in that model simulations for dissolved PHC sources predict very low vapor attenuation factors,

1297 except for small source-separation distances (i.e., less than about 5 ft [1.5 m]). For LNAPL
1298 sources, the modeling simulations suggest hydrocarbon vapor attenuation behavior consistent
1299 with the case studies and empirical data. Although the modeling studies are instructive, there has
1300 been limited evaluation of the range of possible mechanisms for oxygen migration to below
1301 buildings, including diffusive oxygen transport through concrete foundations and processes for
1302 advective soil gas transport, which could be important at LNAPL source sites.

1303 9.2 Methods and Characteristics of the Database

1304 The results of the analysis may be used to derive exclusion distances based on the
1305 probability of benzene vapor concentrations being less than defined thresholds for varying
1306 contamination source-building separation distances and qualitative comparisons of soil vapor
1307 concentrations to risk-based soil vapor concentrations for other compounds. The clean soil
1308 method is an alternative method for defining exclusion distances, but requires interpolation to
1309 avoid overly conservative results. This site-by-site interpolation process introduces uncertainty
1310 particularly for sites where there is poor resolution with respect to vertical concentration
1311 gradients (i.e., from soil gas probes that are too far apart).

1312 The database is representative of a broad range of environmental site conditions, climatic
1313 conditions (including dry areas), soil types, and land-surface covers that may be found at UST
1314 sites. Although the data analysis indicates that the type of surface cover (e.g., building
1315 foundation, pavement, open ground) can have an effect on the attenuation of benzene vapor and
1316 oxygen concentrations, the database includes subslab or vapor data from deeper distances below
1317 buildings for 38 sites with small- to medium-sized buildings. This is considered a sufficiently
1318 large data set, such that exclusion distances derived from the analysis will include the potential
1319 influence of surface cover.

1320 The sites in the database were investigated between 1995 and 2011. Gasoline containing
1321 ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large
1322 increase in use in 2006 (U.S. EPA, 2009). Information on whether gasoline containing ethanol is
1323 present at specific sites is not available in the current database, but some sites in the database
1324 with recent releases likely have gasoline containing ethanol.

1325 The sources of uncertainty associated with the analysis, and for which additional
1326 validation studies should be considered, include the influence of ethanol content in gasoline on
1327 methane generation rates and aerobic biodegradation of PHC vapors (particularly high ethanol
1328 content fuels), sites with extensive high organic matter content soils (e.g., peat) with potentially
1329 high natural oxygen demand, and large buildings where there may be increased potential for
1330 oxygen limitations for certain foundation conditions. Although this analysis included an
1331 evaluation of data for non-UST (e.g., petroleum refinery, fuel terminal) sites, uncertainty about
1332 aerobic biodegradation of PHC vapors remains for larger volume NAPL releases than typically
1333 encountered at UST sites.

1334 Subsurface utilities are commonplace in urban areas, but their presence does not
1335 necessarily equate to a preferential pathway of significance for PVI. However, a utility corridor
1336 that directly connects an LNAPL source and the interior of a building may represent a significant
1337 preferential pathway and is considered an inclusionary factor for PVI assessment. This analysis

1338 also does not include results for fractured rock unsaturated zone systems between the PHC
1339 source and building receptor.

1340 **9.3 Data Analysis Results**

1341 For dissolved sources, the vertical distance method indicates that the probability of
1342 benzene vapor concentrations being less than the defined concentration thresholds (50 and
1343 100 $\mu\text{g}/\text{m}^3$) is 94 to 97 percent (Kaplan-Meier statistics) for small source-separation distances (as
1344 little as 0 ft), meaning that PVI is unlikely to occur unless a dissolved source is very close to a
1345 building foundation. For development of exclusion distances for dissolved sites, allowance
1346 should be made for uncertainty in water table elevations due to seasonal variability. For LNAPL
1347 sources, the vertical distance method indicates that there is a very low probability of benzene
1348 vapor concentrations being less than the defined thresholds at distances less than about 15 ft
1349 (4.6 m) when just UST facilities are considered and about 30 ft (9.1 m) when all facility types
1350 evaluated are considered.

1351 The data indicate a weak correlation between benzene concentrations in groundwater and
1352 deep soil vapor, but for the clean soil method, a trend was observed when the clean soil
1353 thicknesses needed for benzene vapor attenuation increased when dissolved benzene
1354 concentrations were above approximately 5 mg/L (i.e., indicative of LNAPL source zones).

1355 **9.4 Exclusion Distance Assessment Framework**

1356 The assessment framework for vertical exclusion distances requires identification of the
1357 PHC source type (dissolved phase or LNAPL) based on a multiple lines of evidence approach
1358 similar to that described earlier in this report (see **Table 6**). This framework could include
1359 groundwater concentration thresholds for benzene (and potentially other chemical parameters),
1360 but given the uncertainty in the relation between groundwater and soil vapor concentrations, this
1361 should not be the primary factor for screening sites. Thresholds for soil vapor concentrations
1362 (e.g., minimum oxygen thresholds) could also be considered; however, this is not considered
1363 mandatory as long as there is sufficient rigor in the site characterization approach to delineate
1364 PHC sources and define clean soil zones along with robust methods for identifying LNAPL
1365 versus dissolved sites. For sites with dissolved-phase contamination, it will also be important to
1366 characterize water table fluctuations in relation to building structures.

1367 An exclusion distance approach for LNAPL sources should also include inclusionary
1368 criteria designed to capture sites that fall outside of the findings of the above analysis, including
1369 non-UST facilities (related to size of petroleum release), high organic-rich soils (e.g., peat), large
1370 building foundations (e.g., associated with apartment complexes or commercial/industrial
1371 buildings), and significant subsurface preferential pathways. Future research may indicate certain
1372 ethanol contents in gasoline may also warrant inclusion and PVI assessments because of their
1373 tendency to generate methane that can interfere with the biodegradation of PHCs.

1374 **9.5 Lateral Exclusion Distances**

1375 Greater attenuation of PHC vapors is expected when hydrocarbon sources are offset
1376 laterally from buildings compared with sources that are directly below buildings. Although the

1377 modeling studies reviewed for this effort suggest that conceptually similar lateral exclusion
1378 distances could be applied as the vertical distances addressed in this document, from a practical
1379 standpoint, the uncertainty associated with delineating a PHC source near existing or future
1380 buildings warrants larger lateral distances than those suggested based on the analysis for the
1381 dissolved and LNAPL UST-only cases.

1382 **9.6 Comparison with Other Studies**

1383 Five different PHC data analysis efforts conducted in roughly the same time frame (this
1384 one, Davis [2009], Lahvis et al. [in prep.], Wright [2011], and Peargin and Kolhatkar [2011])
1385 support essentially the same exclusion distances for PHC UST sites, in spite of differences in the
1386 base data analyzed and each study's approach to the analysis. This suggests an underlying
1387 consistency in mechanisms for PHC biodegradation in the subsurface and supports the
1388 protectiveness of the use of these distances as exclusion criteria for UST petroleum release sites.

1389 **10. Conclusions**

1390 Approaches for assessing PVI that do not account for aerobic biodegradation processes
1391 are typically highly conservative. The statistical analysis of soil gas data from 70 sites presented
1392 in this study, along with four other similar but distinct efforts, provided an opportunity for
1393 developing improved and more efficient screening evaluation methods for PHC compounds
1394 based on the observed attenuation and an exclusion distance approach, defined as the
1395 contamination source-separation distance at which there is limited potential for a complete PVI
1396 pathway. The focus of this analysis was primarily on characterizing PVI at UST sites with
1397 petroleum fuel releases, although data from other types of sites (fuel terminals, petroleum
1398 refineries) were also considered. Important findings of this study include the following.

- 1399 1. Knowledge of the PHC source type (dissolved versus LNAPL) and the vertical
1400 separation distance between the source and receptor (building foundation) is a critical
1401 factor affecting PVI and is an important metric for site screening.
- 1402 2. For dissolved sources:
 - 1403 a. For the vertical distance method, greater than 97 percent and 94 percent of the
1404 benzene soil vapor concentrations (based on Kaplan-Meier statistics) are less than
1405 the specified concentration thresholds (50 and 100 $\mu\text{g}/\text{m}^3$, respectively) for
1406 contamination source-building separation distances as small as 0 ft. For other
1407 compounds evaluated, soil vapor concentrations above risk-based soil vapor
1408 concentrations only occurred for separation distances smaller than 3 ft (0.9 m).
 - 1409 b. For the clean soil method (Method B), the 95th percentile vertical clean soil
1410 thickness for benzene vapor attenuation is approximately 5.4 ft (1.6 m).
 - 1411 c. The analysis indicates for dissolved sources there is a low probability of
1412 exceeding risk-based concentrations for small separation distances.
- 1413 3. For LNAPL sources and UST sites:

- 1414 a. For the vertical distance method, approximately 95 percent of the benzene soil
1415 vapor concentrations are less than the thresholds for a source-building separation
1416 distance of approximately 15 ft (4.6 m). For other compounds evaluated, soil
1417 vapor concentrations above risk-based soil vapor concentrations occurred at
1418 smaller separation distances.
- 1419 b. For the clean soil method, the 95th percentile vertical clean soil thickness for
1420 benzene vapor attenuation is approximately 13.5 ft (4.1 m).
- 1421 4. For LNAPL sources and all facility types considered (UST, petroleum refinery, fuel
1422 terminal, and petro-chemical sites), the findings are:
- 1423 a. For the vertical distance method, over 95 percent of the benzene soil vapor
1424 concentrations are less than the thresholds for a source-building separation
1425 distance of approximately 30 ft (9.1 m). For other compounds evaluated, soil
1426 vapor concentrations above risk-based soil vapor concentrations occurred at
1427 smaller separation distances.
- 1428 b. For the clean soil method, the 95th percentile vertical clean soil thickness for
1429 benzene vapor attenuation is approximately 16.4 ft (5.0 m).
- 1430 5. The data indicate benzene is the risk driver, with greater occurrences of exceedances
1431 of risk-based vapor concentrations for larger contamination source-building
1432 separation distances compared with other compounds evaluated.
- 1433 6. The data indicate a weak correlation between benzene concentrations in groundwater
1434 and soil vapor from deeper distances, but for the clean soil method, a trend was
1435 observed where clean soil thicknesses for benzene vapor attenuation increased when
1436 the dissolved benzene concentrations were above approximately 5 mg/L.
- 1437 7. Surface cover type appears to have a weak effect on oxygen availability and PHC
1438 vapor transport, and depending on the data set used, either sites with pavement or
1439 building surface covers had lower probabilities of benzene concentrations less than
1440 $100 \mu\text{g}/\text{m}^3$ for a given source-separation building separation, although these findings
1441 are uncertain given the size of the data set and variable results.
- 1442 8. Because the vertical distance method evaluation includes soil vapor concentration
1443 data from below buildings at 33 UST sites, the results are considered sufficiently
1444 robust with respect to including the potential influence of surface cover.

1445 The findings of this study have important implications for improved and more efficient
1446 screening methods for PHC compounds based on the observed attenuation in PHC vapor
1447 concentrations and an exclusion distance approach. Inclusionary criteria or conditions not
1448 analyzed in this database, and where more detailed PVI assessment is considered warranted,
1449 include non-UST facilities, high organic-rich soils (e.g., peat), large building foundations (e.g.,
1450 associated with apartment complexes or commercial/industrial buildings), and significant
1451 subsurface preferential pathways. Future research may indicate that certain ethanol contents in

1452 gasoline may also warrant inclusion and PVI assessments because of their tendency to generate
1453 methane that can interfere with the biodegradation of PHCs.

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

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

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Table 2. Select Three-Dimensional Abreu and Johnson (2005) Model Simulation Results from U.S. EPA (2012b)

Source Hydrocarbon Vapor Concentration (mg/L)	Vapor Intrusion Attenuation Factor	
	Single Soil Layer	Two Soil Layers (Capping Scenario)
200	6.7×10^{-5}	6.8×10^{-4}
2	N/A	7.1×10^{-15}

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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} .

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

Location	Sites	Location	Sites
United States			
California	7	Ohio	4
Maine	13	South Carolina	1
Maryland	1	Utah	15
Minnesota	22	United States unknown	1
New Jersey	3		
Other Countries			
Canada	2	Australia	1
Total Sites = 70			

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Table 4. Summary of Information in PVI Database

Site Name	City	Country	State or Province	Contamination Source	Vapor Source Type	Soil Type	Site Type	Building Use					Foundation Type			Media Sampled		
								Number Buildings	Residential	Smaller Commercial	Larger Commercial	Building Footprint (ft. ²)	Basement	Slab on Grade	Crawlspace or Dirt Floor	Groundwater	Soil Vapor	Subslab Vapor
Alameda Naval Air Station	Alameda	USA	CA	G	LNAPL	Coarse	UST	1		0		538		0		0	0	0
Coachella	Coachella	USA	CA	G	LNAPL	Coarse	Terminal										0	
Huntington Beach	Huntington Beach	USA	CA	G	LNAPL	Coarse	UST										0	0
Mission Valley Terminal	San Diego	USA	CA	G, D, J, E	LNAPL	Coarse/Fine	Terminal	2		0	0	1,500–7,200		0		0	0	0
Newport Beach	Newport Beach	USA	CA	G	LNAPL/Dis	Coarse	UST										0	
Port Hueneme	Port Hueneme	USA	CA	G	LNAPL/Dis	Coarse	UST									0	0	0
Former Chevron Station #9-5669	South San Francisco	USA	CA	G	LNAPL/Dis	Coarse	UST									0	0	0
Dave's Amoco	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
NYM	N/A	USA	MN	G*	Dis	Coarse	UST									0	0	0
Jacobsen Residence	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST									0	0	0
Larsons 66	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
D&E Sales	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
Moen Oil	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
Johnsons Auto	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
Midtown Service	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST									0	0	0
John's Garage	N/A	USA	MN	G*	LNAPL/Dis	N/A	UST									0		

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

Site Name	City	Country	State or Province	Contamination Source	Vapor Source Type	Soil Type	Site Type	Building Use					Foundation Type			Media Sampled		
								Number Buildings	Residential	Smaller Commercial	Larger Commercial	Building Footprint (ft. ²)	Basement	Slab on Grade	Crawlspace or Dirt Floor	Groundwater	Soil Vapor	Subslab Vapor
Buchannon Nursing Home	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Red & White Service	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Side Lake Store	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Ossippe Store	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
AC Oil	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Schmunks	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Kennys Oil	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST								0	0		0
Settes Garage	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST									0		
Tilson Auto	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST									0		
Rogers Mobile	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST								0	0		0
Rub-a-Dub	N/A	USA	MN	G*	LNAPL/Dis	Coarse	UST								0	0		0
Long Shot Trucking	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST								0	0		
Eggens Oil	N/A	USA	MN	G*	LNAPL/Dis	Fine	UST								0	0		0
Chillum site	Maryland	USA	MD	G	LNAPL/Dis	Coarse	UST								0	0		
Reuben's Market	Milo	USA	ME	G	LNAPL/Dis	Coarse/Fine	UST	1		0		N/A		0	0	0	0	0
Cumberland Farm 1803	Sandford	USA	ME	G	LNAPL	Coarse	UST	1	0			N/A	0		0	0	0	

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

Site Name	City	Country	State or Province	Contami-nation Source	Vapor Source Type	Soil Type	Site Type	Building Use					Foundation Type			Media Sampled			
								Number Buildings	Residential	Smaller Commercial	Larger Commercial	Building Footprint (ft. ²)	Basement	Slab on Grade	Crawlspace or Dirt Floor	Groundwater	Soil Vapor	Subslab Vapor	Soil
Cumberland Farm 1817	Berwick	USA	ME	G	LNAPL/Dis	V.Coarse	UST									0	0		
Twin Bridge Market	Leeds	USA	ME	G	LNAPL/Dis	Coarse	UST									0	0		0
Cumberland Farm 1806	South Portland	USA	ME	G	LNAPL	Coarse	UST									0	0		0
Cumberland Farm 1805	Portland	USA	ME	G	LNAPL/Dis	V.Coarse/Coarse	UST	1			0	3,900		0		0	0	0 e	0
Cumberland Farm 1839	Portland	USA	ME	G	LNAPL/Dis	Coarse/Fine	UST									0	0		
Cumberland Farm 1822	Saco	USA	ME	G	LNAPL/Dis	Coarse	UST	1								0	0	0	
7-Eleven	Lewiston	USA	ME	G	LNAPL/Dis	Coarse/Fine	UST	2	0	0		1,500–2,000	0	0		0	0	0 e	
Cumberland Farm 1836	North Windham	USA	ME	G	LNAPL/Dis	Coarse	UST	1			0	5,000		0		0	0	0	
Cumberland Farm 1829	Augusta	USA	ME	G	Dis	V.Coarse	UST									0	0		
BP Paulsboro	Paulsboro	USA	NJ	G	LNAPL	Coarse	Terminal	1	0			N/A	0			0	0	0	0
Hulme Street	Mount Holly	USA	NJ	G	Dis	Coarse	UST	3	0			400	0		0	0	0	0	0
Stafford	Stafford	USA	NJ	G	LNAPL/Dis	Coarse	UST	5	0			600–800	0			0	0	0	0
BP Akron	Akron	USA	OH	G	LNAPL/Dis	Coarse	UST										0		0

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

Site Name	City	Country	State or Province	Contami-nation Source	Vapor Source Type	Soil Type	Site Type	Building Use					Foundation Type			Media Sampled		
								Number Buildings	Residential	Smaller Commercial	Larger Commercial	Building Footprint (ft. ²)	Basement	Slab on Grade	Crawlspace or Dirt Floor	Groundwater	Soil Vapor	Subslab Vapor
BP Columbiana	Columbiana	USA	OH	G	LNAPL	Fine	Terminal									0	0	
BP Conneaut	Conneaut	USA	OH	G	LNAPL	Coarse	UST									0	0	
BP Kent	Kent	USA	OH	G	LNAPL	V.Coarse	UST									0	0	
Beaufort	Beaufort	USA	SC	G	LNAPL	Fine	UST							0	0			
Bountiful Bicycle	Bountiful	USA	UT	G	LNAPL	Fine	UST										0	
Gas & Go #7	North Salt Lake	USA	UT	G	LNAPL/Dis	Fine	UST							0	0			
Gold Cross Ambulance	Salt Lake City	USA	UT	G	Dis	Fine	UST	2	0		0	1,500-10,000		0		0	0	0
Hal's Chevron	Green River	USA	UT	G	LNAPL/Dis	Fine	UST	2		0		625-2,500	0			0	0	0
Handi Mart	Midvale	USA	UT	G	LNAPL	Coarse	UST									0	0	
#102 Chevron	Jacksons	USA	UT	G	Dis	Coarse	UST	4	0	0		N/A	0	0		0	0	
Logan Food Mart	Logan	USA	UT	G	Dis	Fine	UST	1		0		N/A		0			0	
Price Rental Property	Price	USA	UT	G	LNAPL	Coarse	UST	1		0		N/A						
Salina Cash Saver	Salina	USA	UT	G	LNAPL	Coarse	UST	1			0	2,700		0			0	0
Jenkins Oil	Santa Clara	USA	UT	G	LNAPL/Dis	Fine	UST	1		0		1,350		0		0	0	
Wheel-In Market	Salt Lake City	USA	UT	G	LNAPL	Fine	UST	1		0		N/A		0		0	0	
Teasdale Country Store	Teasdale	USA	UT	G	LNAPL	Coarse	UST	1		0		N/A	0			0	0	

(continued)

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

Site Name	City	Country	State or Province	Contamination Source	Vapor Source Type	Soil Type	Site Type	Building Use				Foundation Type			Media Sampled				
								Number Buildings	Residential	Smaller Commercial	Larger Commercial	Building Footprint (ft. ²)	Basement	Slab on Grade	Crawlspace or Dirt Floor	Groundwater	Soil Vapor	Subslab Vapor	Soil
Tesoro #40	Salt Lake	USA	UT	G	Dis	Fine	UST	2	0			2,200	0 1/2			0		0	
7-Eleven #23387	Murray	USA	UT	G	LNAPL	Fine	UST									0	0		
Refinery Site	Hooven	USA	-	G,D	LNAPL	Coarse	Refinery									0	0		
Chatterton Research Site	Delta	Canada	British Columbia	BTX	LNAPL	Coarse	Refinery	1	0			610		0		0	0	0	
Ottawa	Ottawa	Canada	Ontario	G,D	Dis	Fine	UST									0	0		
North Battleford	North Battleford	Canada	Saskatchewan	G	LNAPL/Dis	Coarse	UST	1	0					0	0	0	0	0	0
Perth	Perth	Australia	Western Australia	K	LNAPL	Coarse	Refinery	1			0	2,700		0					

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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Table 5. Soil Vapor Analyses in PVI Database

Site Name	City	Benzene	Toluene	Ethylbenzene	Xylenes	Naphthalene	2,2,4-Trimethylpentane	Hexane	Heptane	MTBE	1,3-Butadiene	TPH	TPH Method	MADEP TPH Fractions	Oxygen	Carbon	Methane
Alameda Naval Air Station	Alameda	2	0	0	0	0	0	0	0	0	0	12	Iso-pentane	0	12	12	8
Coachella	Coachella	27	0	0	0	0	0	0	0	0	0	0	N/A	0	26	25	26
Huntington Beach	Huntington Beach	26	0	0	0	0	0	0	0	0	0	0	N/A	0	26	26	26
Mission Valley Terminal	San Diego	84	0	0	0	0	0	0	0	0	0	84	TPHg 8260	0	24	22	0
Newport Beach	Newport Beach	20	0	0	0	0	0	0	0	0	0	0	N/A	0	20	20	20
Port Hueneme	Port Hueneme	0	0	0	0	0	0	0	0	0	0	62	GC/FID	0	55	47	0
Former Chevron Station #9-5669	South San Francisco	27	18	18	18	0	0	0	0	0	0	9	Modified TO-3 GC/FID	0	18	18	9
Dave's Amoco	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
NYM	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Jacobsen Residence	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Larsons 66	N/A	4	4	4	4	0	0	3	4	0	0	4	TPH as Gas	0	0	0	0
D&E Sales	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Moen Oil	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Johnsons Auto	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Midtown Service	N/A	10	0	0	0	0	0	10	10	0	0	10	TPH as Gas	0	0	0	0
John's Garage	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Buchannon Nursing Home	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Red & White Service	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Side Lake Store	N/A	5	2	2	2	0	0	5	5	0	0	5	TPH as Gas	0	0	0	0
Ossippe Store	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0

(continued)

May 3, 2012

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

Site Name	City	Benzene	Toluene	Ethylbenzene	Xylenes	Naphthalene	2,2,4-Trimethylpentane	Hexane	Heptane	MTBE	1,3-Butadiene	TPH	TPH Method	MADEP TPH Fractions	Oxygen	Carbon	Methane
Ossippe Store	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
AC Oil	N/A	4	0	0	0	0	0	0	0	0	0	4	TPH as Gas	0	0	0	0
Schmunks	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Kennys Oil	N/A	4	0	0	0	0	0	0	0	0	0	4	TPH as Gas	0	0	0	0
Settes Garage	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Tilson Auto	N/A	3	0	0	0	0	0	0	0	0	0	3	TPH as Gas	0	0	0	0
Rogers Mobile	N/A	3	3	3	3	0	0	0	0	0	0	3	TPH as Gas	0	0	0	0
Rub-a-Dub	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Long Shot Trucking	N/A	4	2	2	2	0	0	0	0	0	0	4	TPH as Gas	0	0	0	0
Eggens Oil	N/A	3	1	3	3	0	0	0	0	0	0	3	TPH as Gas	0	0	0	0
Chillum site	Maryland	18	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0
Reuben's Market	Milo	7	7	7	7	7	0	0	0	7	7	7	MADEP APH	7	7	7	7
Cumberland Farm 1803	Sandford	3	3	3	3	3	0	0	0	3	3	3	MADEP APH	3	5	5	5
Cumberland Farm 1817	Berwick	6	6	6	6	6	0	0	0	5	6	6	MADEP APH	6	6	6	4
Twin Bridge Market	Leeds	4	4	4	4	4	0	0	0	4	4	4	MADEP APH	4	4	4	4
Cumberland Farm 1806	South Portland	1	1	1	1	1	0	0	0	1	1	1	MADEP APH	1	1	1	1
Cumberland Farm 1805	Portland	28	28	28	28	28	0	0	0	28	28	28	MADEP APH	28	28	28	28
Cumberland Farm 1839	Portland	9	9	9	9	9	0	0	0	9	9	9	MADEP APH	9	9	9	9
Cumberland Farm 1822	Saco	2	2	2	2	2	0	0	0	2	2	2	MADEP APH	2	2	2	2
7-Eleven	Lewiston	17	17	17	17	17	0	0	0	17	17	17	MADEP APH	17	17	17	17
Cumberland Farm 1836	North Windham	5	5	5	5	5	0	0	0	5	5	5	MADEP APH	5	5	5	4
Cumberland Farm 1829	Augusta	5	4	5	5	5	0	0	0	5	5	5	MADEP APH	5	5	5	5

(continued)

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

Site Name	City	Benzene	Toluene	Ethylbenzene	Xylenes	Naphthalene	224-Trimethylpentane	Hexane	Heptane	MTBE	1,3-Butadiene	TPH	TPH Method	MADEP TPH Fractions	Oxygen	Carbon	Methane
BP Paulsboro	Paulsboro	11	11	11	11	0	0	0	0	0	0	7	GRO (8015)	0	18	18	7
Hulme Street	Mount Holly	8	8	8	8	0	6	0	0	0	0	0	N/A	0	2	1	0
Stafford	Stafford	14	14	14	14	0	14	12	12	12	0	0	N/A	0	4	0	0
BP Akron	Akron	9	0	0	0	0	0	0	0	0	0	9	GRO (8015)	0	9	9	0
BP Columbiana	Columbiana	4	0	0	0	0	0	0	0	0	0	4	GRO (8015)	0	4	4	0
BP Conneaut	Conneaut	3	0	0	0	0	0	0	0	0	0	3	GRO (8015)	0	3	3	0
BP Kent	Kent	4	0	0	0	0	0	0	0	0	0	4	GRO (8015)	0	4	4	0
Beaufort	Beaufort	9	6	3	6	0	0	0	0	0	0	7	Select C6-9 all & aro cmpd's	0	9	9	0
Bountiful Bicycle	Bountiful	14	14	14	14	8	0	6	6	0	0	14	TO-15	0	6	7	0
Gas & Go #7	North Salt Lake	15	15	15	15	15	0	0	0	0	0	15	TPH (relative to MW=100 TMB)	0	15	15	15
Gold Cross Ambulance	Salt Lake City	5	0	0	0	0	0	0	0	0	0	5	TO-15	0	0	0	0
Hal's Chevron	Green River	127	14	14	14	0	0	0	0	0	0	127	Modified TO-3 GC/FID	0	68	66	31
Handi Mart	Midvale	0	0	0	0	0	0	0	0	0	0	3	N/A	0	3	3	0
#102 Chevron	Jacksons	55	44	44	56	42	0	0	0	0	0	56	Modified TO-3 GC/FID	0	56	56	56
Logan Food Mart	Logan	1	0	0	0	0	0	0	0	0	0	0	N/A	0	0	0	0
Price Rental Property	Price	1	1	1	1	0	0	0	0	0	0	0	N/A	0	0	0	0
Salina Cash Saver	Salina	14	14	14	14	14	0	0	0	0	0	14	GRO as TMB	0	14	14	0
Jenkins Oil	Santa Clara	63	63	63	63	63	0	50	50	23	0	63	TO-15 GRO at MW=100	0	63	62	63
Wheel-In Market	Salt Lake City	1	0	0	0	0	0	0	0	0	0	1	TO-15	0	0	0	0
Teasdale Country Store	Teasdale	3	0	0	0	0	0	0	0	0	0	3	N/A	0	2	2	0
Tesoro #40	Salt Lake	4	4	4	4	4	4	4	4	0	0	4	TO-15 (C5-11)	0	2	2	0

(continued)

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

Site Name	City	Benzene	Toluene	Ethylbenzene	Xylenes	Naphthalene	224-Trimethylpentane	Hexane	Heptane	MTBE	1,3-Butadiene	TPH	TPH Method	MADEP TPH Fractions	Oxygen	Carbon	Methane
7-Eleven #23387	Murray	5	5	5	5	3	0	0	0	0	0	5	Modified TO-3 GC/FID	0	5	5	5
Refinery Site	Unknown	53	0	0	0	0	10	0	0	0	0	53	N/A	0	31	31	0
Chatterton Research Site	Delta	63	0	0	0	0	0	0	0	0	0	0	N/A	0	24	0	0
Ottawa	Ottawa	0	0	0	0	0	0	0	0	0	0	7	Gastector	0	7	7	0
North Battleford	North Battleford	9	9	9	9	0	9	5	0	0	0	9	TO-15 C6-10	0	9	9	5
Perth	Perth	1	0	0	0	0	0	0	0	0	0	13	0	0	17	8	0
Number Sites with Data		65	37	37	37	18	5	21	20	13	11	59	N/A	11	41	39	23
Total Number Analyses		879	362	362	377	236	43	147	143	121	87	772	0	87	645	594	357

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

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Table 6. Potential LNAPL Hydrocarbon Indicators

Type	Indicator	Measures and Screening Values
Adopted for this study		
Direct	Current or historic presence of LNAPL in groundwater or soil	Laboratory and/or field observations, sheens, results of paint filter, dye and shake tests
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 ₂ and CO ₂ profiles	PHC vapor and CO ₂ concentrations in soil gas that show no decrease (or O ₂ 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 ³ suggest LNAPL because dissolved plumes are primarily composed of soluble aromatic hydrocarbons (Lahvis et al., In prep.)

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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

Chemical	Toxicity Endpoint	Risk-Based Indoor Air Concentration ($\mu\text{g}/\text{m}^3$) ¹	Source
Benzene	Carcinogenic	2.9 (1×10^{-5} ILCR); 0.29 (1×10^{-6} ILCR)	U.S. EPA IRIS ²
Toluene	Non-carcinogenic	5,000 (RfC)	U.S. EPA IRIS
Ethylbenzene	Non-carcinogenic	1,000 (RfC)	U.S. EPA IRIS
Xylenes	Non-carcinogenic	100 (RfC)	U.S. EPA IRIS
Naphthalene	Non-carcinogenic	3 (RfC)	U.S. EPA IRIS
n-Hexane	Non-carcinogenic	700 (RfC)	U.S. EPA IRIS
MADEP Aliphatic C5-8	Non-carcinogenic	200	MADEP (2003)
MADEP Aliphatic C9-18	Non-carcinogenic	200	MADEP (2003)
MADEP Aromatic C9-18	Non-carcinogenic	50	MADEP (2003)

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.

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Table 8. Summary of Results for Vertical Distance Method

	Dissolved Source	LNAPL Source—UST Sites	LNAPL—All Sites
Oxygen	Most O ₂ conc. > 4%, and no O ₂ < 1%	Many data points with O ₂ < 4%, and O ₂ < 1% to 6 ft (1.8 m) separation	Many data points with O ₂ < 4%, and O ₂ < 1% to 11-ft (3.4-m) separation, greater O ₂ depletion than UST only
Benzene (100 $\mu\text{g}/\text{m}^3$ threshold)	P _{KM} > 97% for 0 ft separation increasing to 99% at 5 ft (1.5 m)	P _{KM} > 61% for 0 ft separation increasing to ~ 95% for 15-ft (4.6-m) separation	P _{KM} > 48% for 0-ft separation increasing to > 90% at 15 ft (4.6 m) and ~ 95% at 30 ft (9.1 m)
Benzene (50 $\mu\text{g}/\text{m}^3$ threshold)	P _{KM} > 94% to 95% for 0 ft to 5 ft (1.5 m)	P _{KM} > 57% for 0 ft separation increasing to ~ 93% for 15-ft (4.6-m) separation	P _{KM} > 46% for 0 ft separation increasing to > 90% at 15 ft (4.6 m) and ~ 95% at 30 ft (9.1 m)
Xylenes	One vapor concentration > RBC _v for separation distance of 3 ft (0.9 m)	>10 vapor concentrations > RBC _v for separation distance up to 11 ft (3.4 m)	>10 vapor concentrations > RBC _v for separation distance up to 12 ft (3.7 m)
Hexane	All vapor concentrations < RBC _v 0 ft	Five vapor concentrations > RBC _v for separation distance up to 4 ft (1.2 m)	N/A
C5-8 Aliphatic	Two vapor concentrations > RBC _v for separation distance up to 3 ft (0.9 m)	Five vapor concentrations > RBC _v for separation distance up to 3 ft (0.9 m)	N/A
C9-12 Aliphatic	All vapor concentrations < RBC _v 0 ft	Eight vapor concentrations > RBC _v for separation distance up to 2 ft (0.6 m)	N/A
C9-10 Aromatic	All vapor concentrations < RBC _v 0 ft	Four vapor concentrations > RBC _v for separation distance up to 2 ft (0.6 m)	N/A

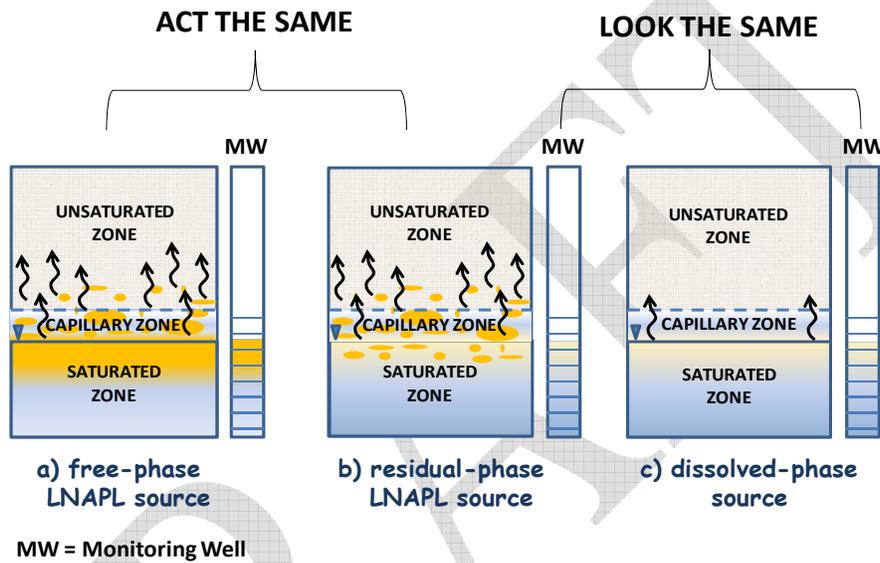
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.

1713 ¹ P_{KM} = Probability estimated using Kaplan-Meier method for exceeding threshold.

1714 **Table 9. Summary of Results for Clean Soil (Davis) Method**

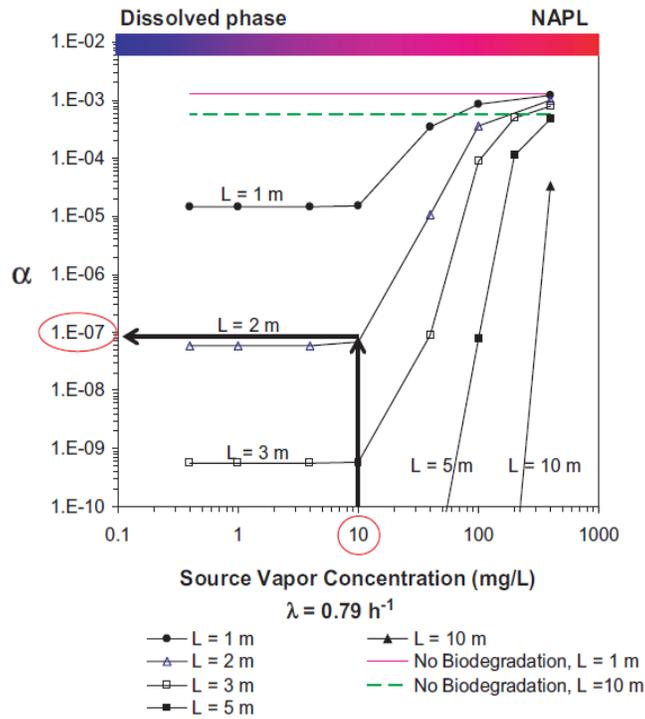
Source Scenario and Facility Type	Number Sites	Number Data Points	95th Percentile Clean Soil Thickness	
			Method A	Method B
Dissolved	47	170	10.0 ft (3.0 m)	5.4 ft (1.6 m)
LNAPL (UST only)	53	172	13.9 ft (4.2 m)	13.5 ft (4.1 m)
LNAPL (all facilities)	60	216	20.0 ft (6.1 m)	16.2 ft (4.9 m)

1715 Note: The above statistics include site data when no benzene groundwater concentration was available.



1716 **Figure 1. Conceptual Model Illustrating the Potential for Vapor Intrusion for a) Free-Phase**
 1717 **LNAPL Source, b) Residual-Phase LNAPL Source, and c) Dissolved-Phase Source.**
 1718 **(source Lahvis et al., In prep.; used with permission).**
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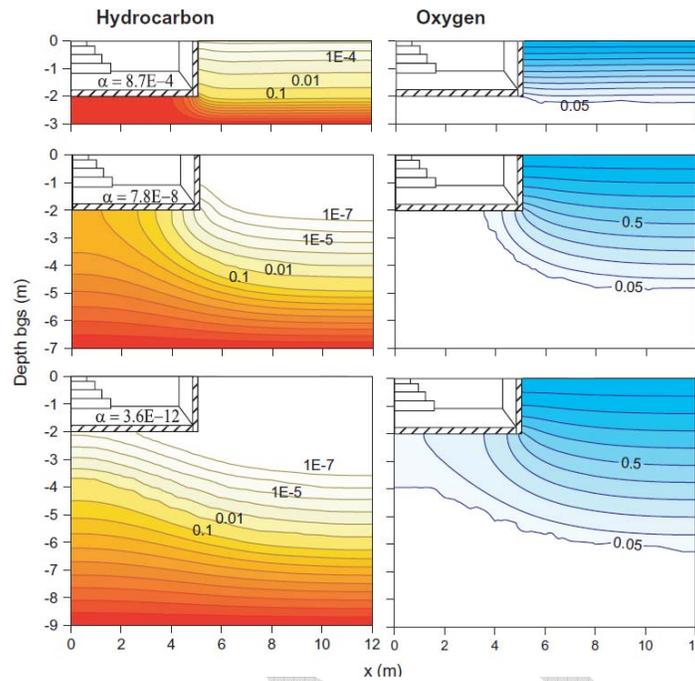
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Figure 2. Vapor Intrusion Attenuation Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model for a Range of Source Total Hydrocarbon (benzene) Vapor Concentrations and Separation Distances for a Residential House Scenario (from Abreu et al., 2009).

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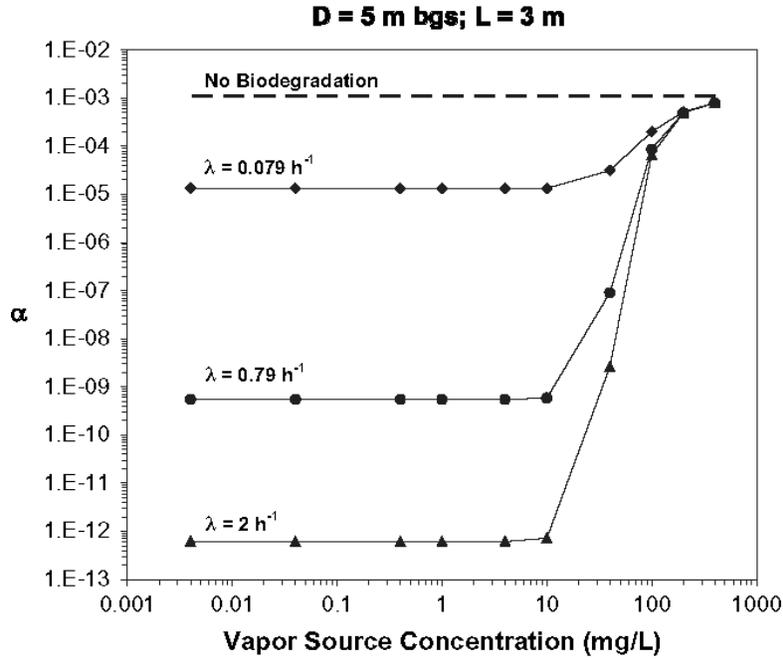
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Figure 3. Effect of Source Depth on Soil Gas Distribution and Vapor Intrusion Attenuation Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model for a Source Total Hydrocarbon (Benzene) Vapor Concentration of 100 mg/L and Biodegradation 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).

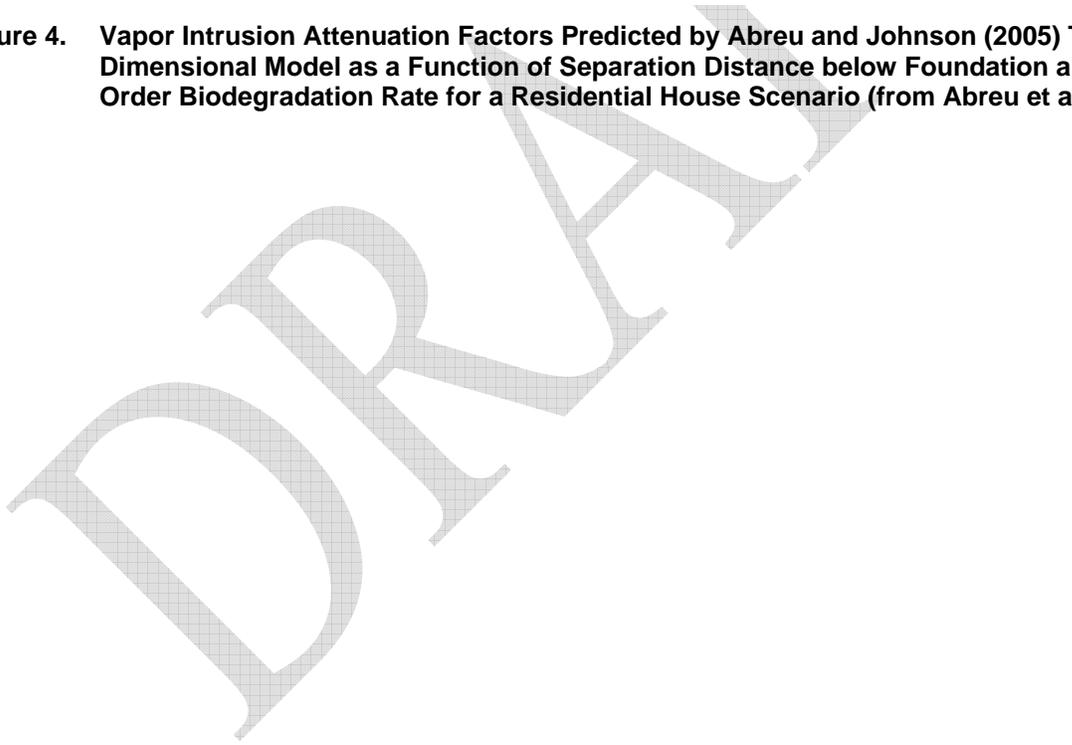
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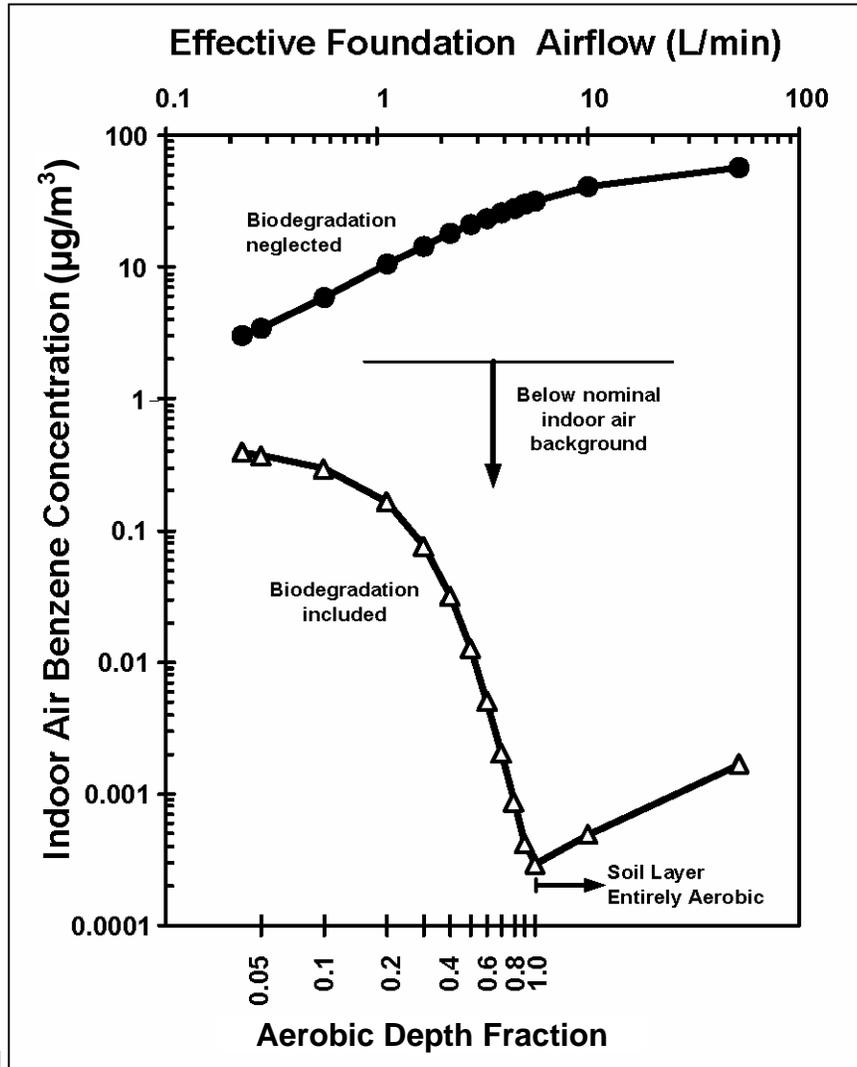
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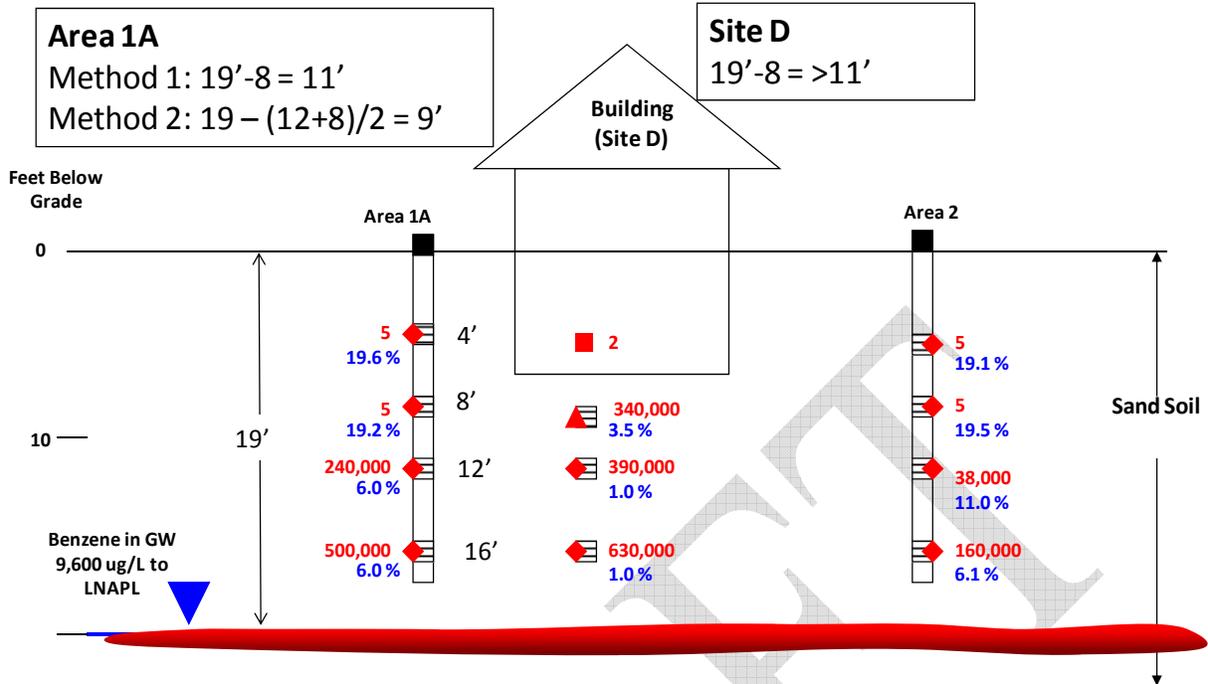
Figure 4. Vapor Intrusion Attenuation Factors Predicted by Abreu and Johnson (2005) Three-Dimensional Model as a Function of Separation Distance below Foundation and First-Order Biodegradation Rate for a Residential House Scenario (from Abreu et al., 2009).





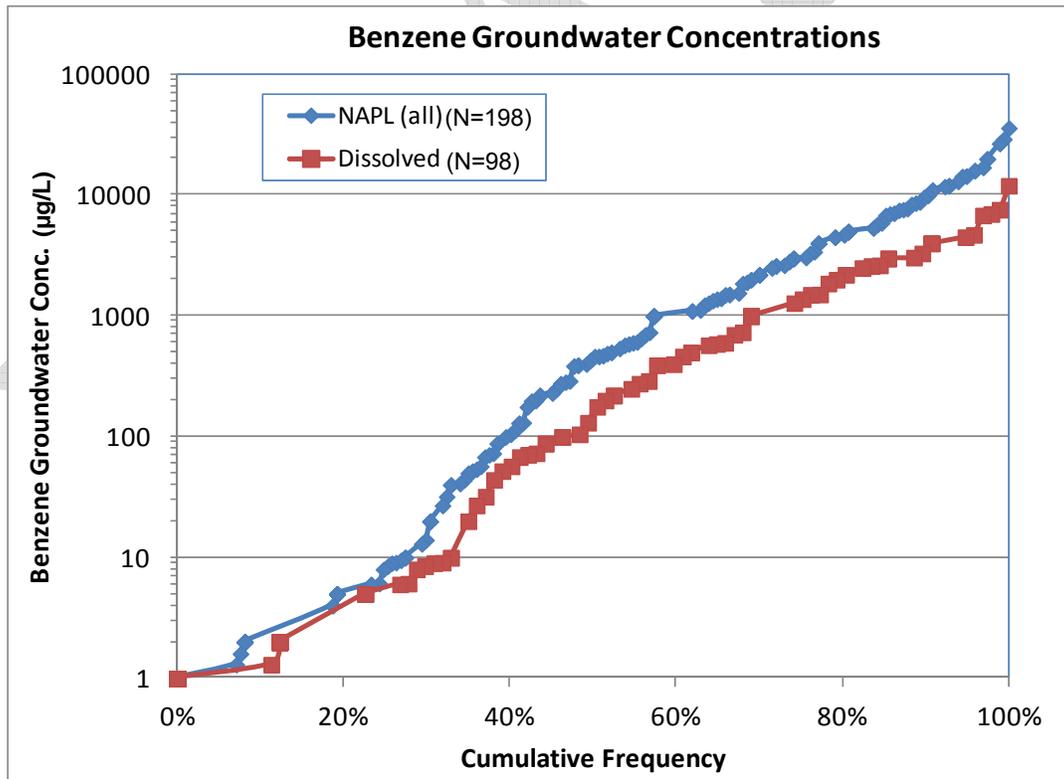
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Figure 5. Estimates of Indoor Air Benzene Concentrations Using BioVapor Model for Varied Effective Airflow through the Basement Foundation. Foundation Effective Airflow Statistics: 5th percentile = 0.3 L/min, 50th percentile = 3 L/min, 95th percentile = 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 DeVaul, 2010).



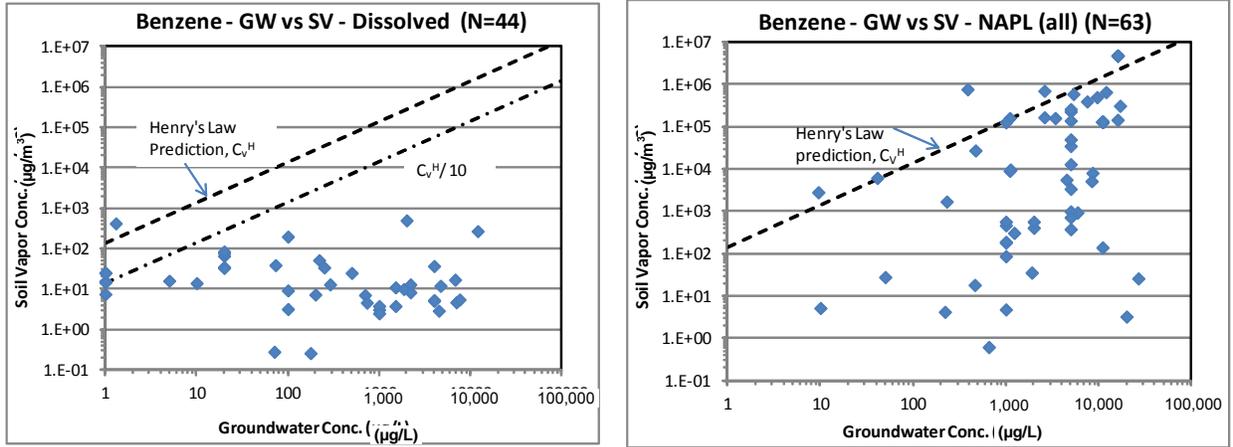
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Figure 6. Example Calculation of Clean Soil Distances.



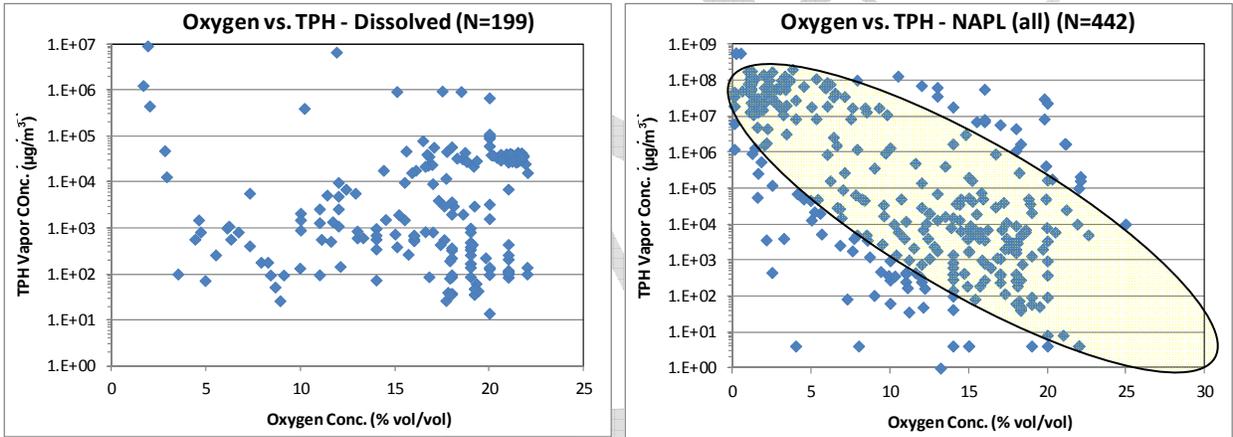
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Figure 7. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites).



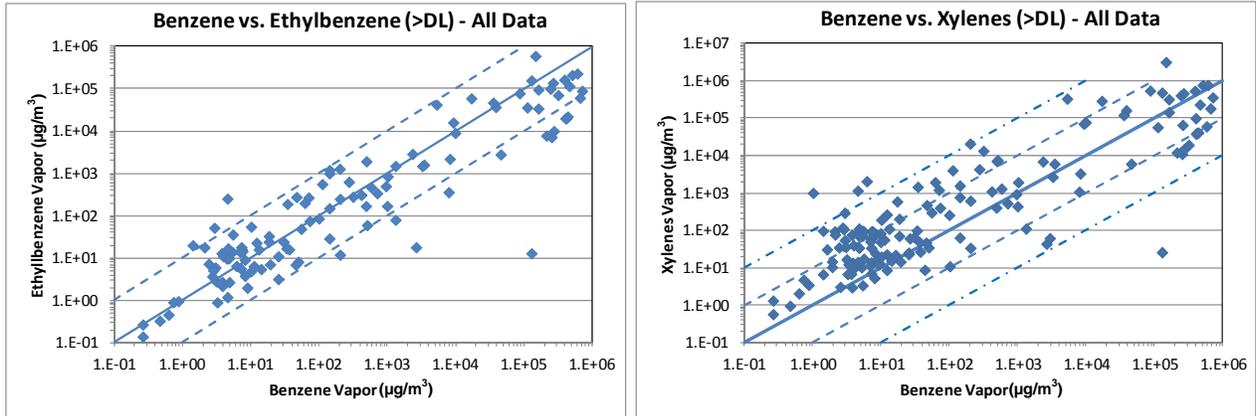
1752 **Figure 8. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for**
 1753 **Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites).**
 1754 **Only detectable benzene vapor concentrations shown.**

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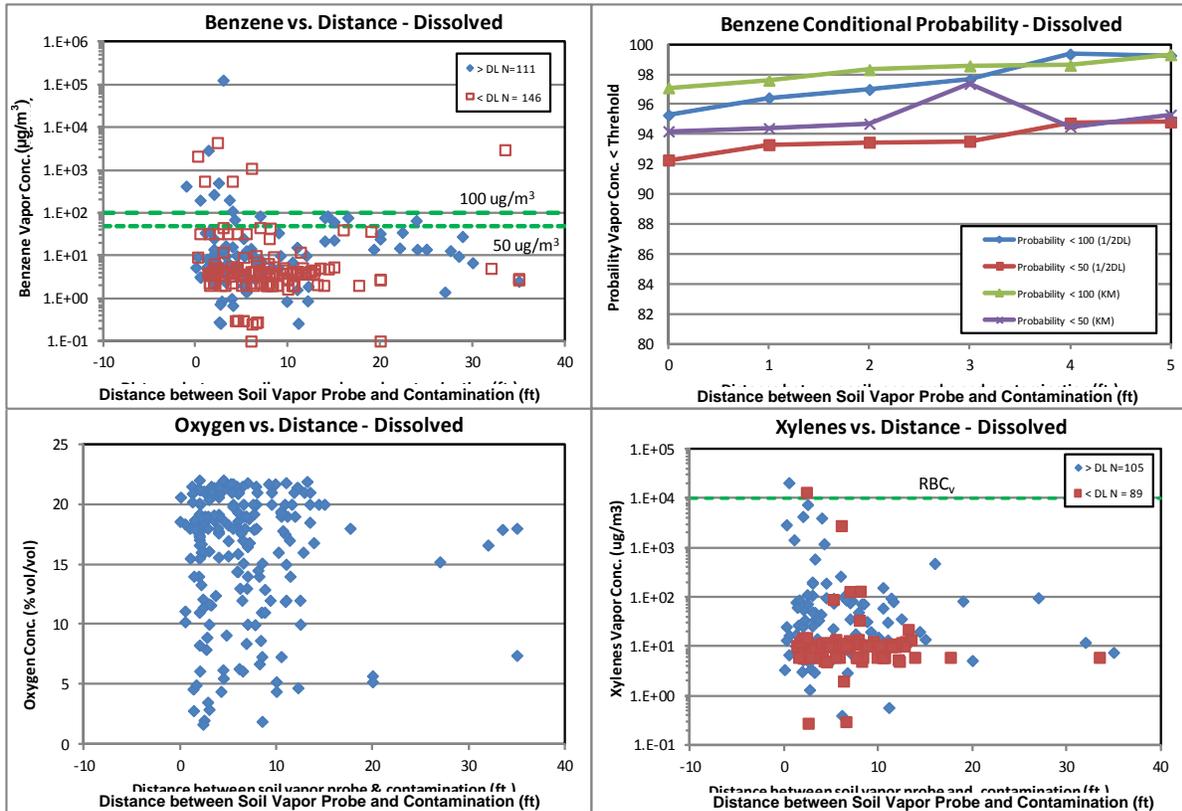
1756 **Figure 9. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for**
 1757 **Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites).**
 1758 **Data points shown are where both TPH vapor and oxygen concentrations were above**
 1759 **detection limits. Shaded ellipse encompasses data that generally support the aerobic**
 1760 **mineralization paradigm.**

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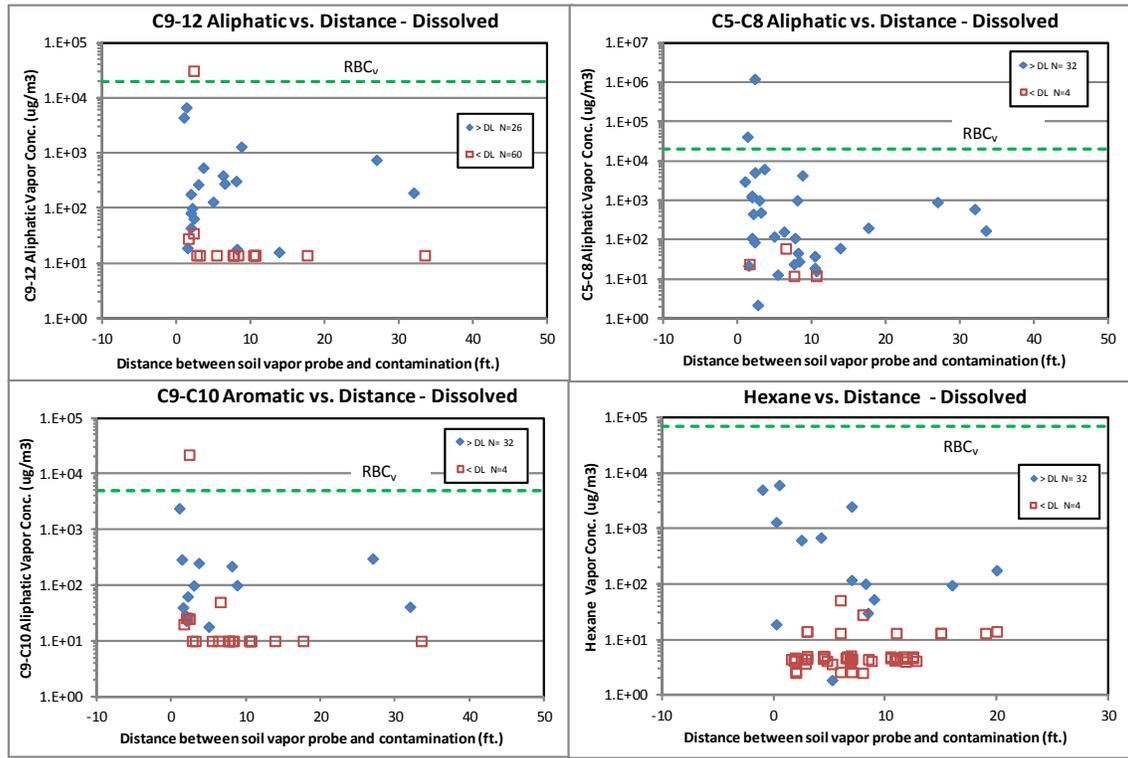
Figure 10. Relation between Benzene and Ethylbenzene and Benzene and Xylenes Vapor Concentrations. Data points shown are where both compounds were above detection limits.



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

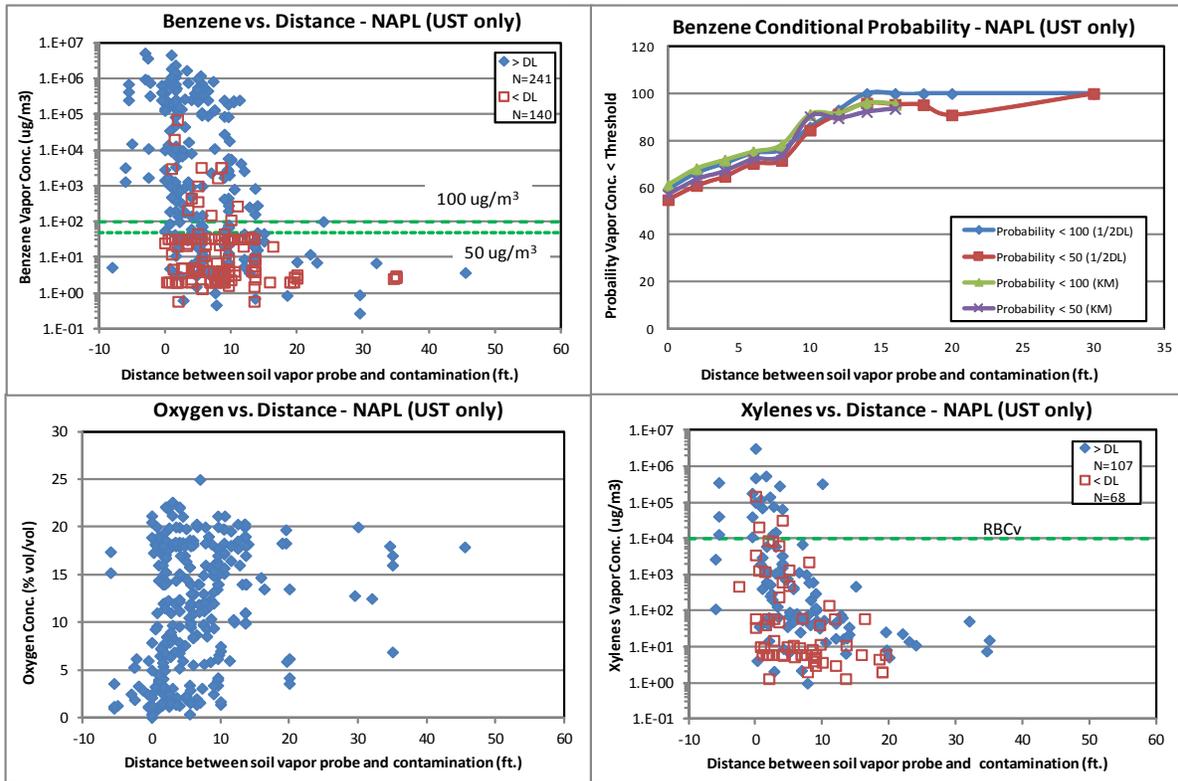
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Figure 12. Vertical Distance Method–PHC Fraction and Hexane Data for Dissolved Sites.

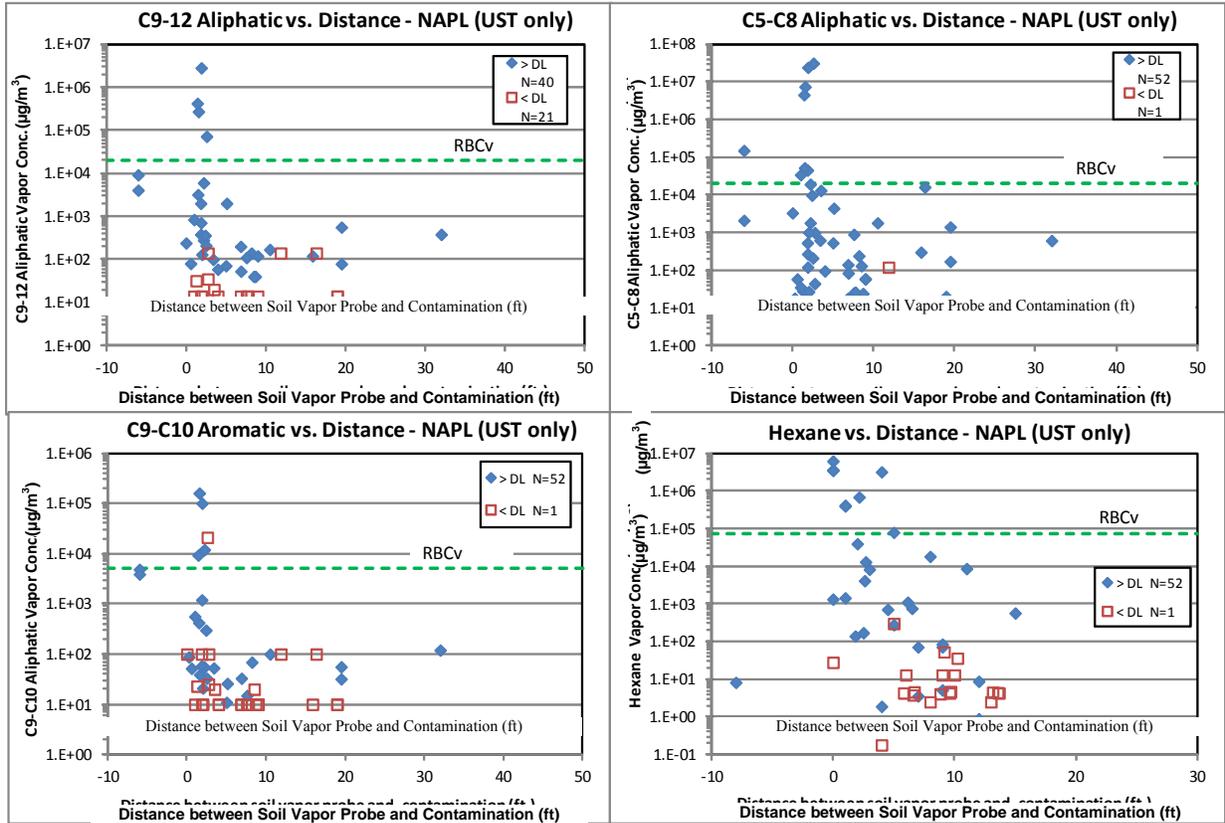


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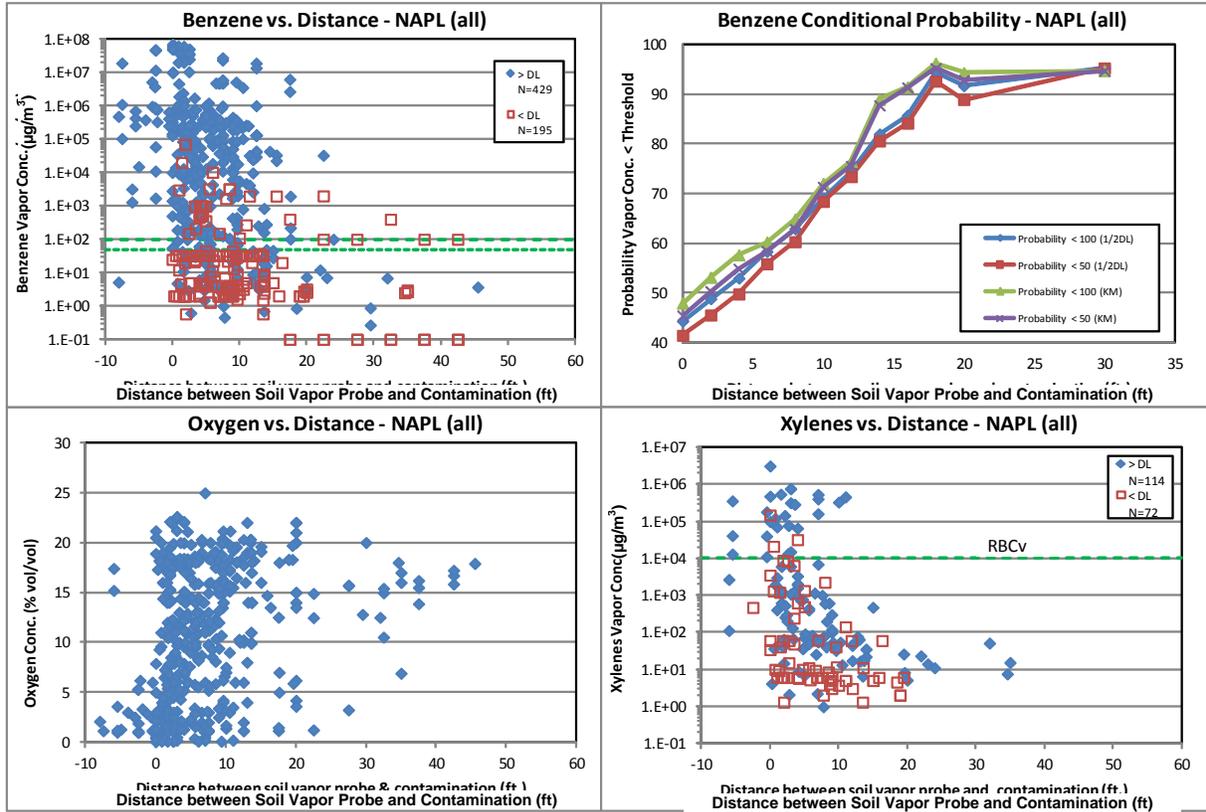
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Figure 13. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (UST only) Sites (KM = Kaplan-Meier).



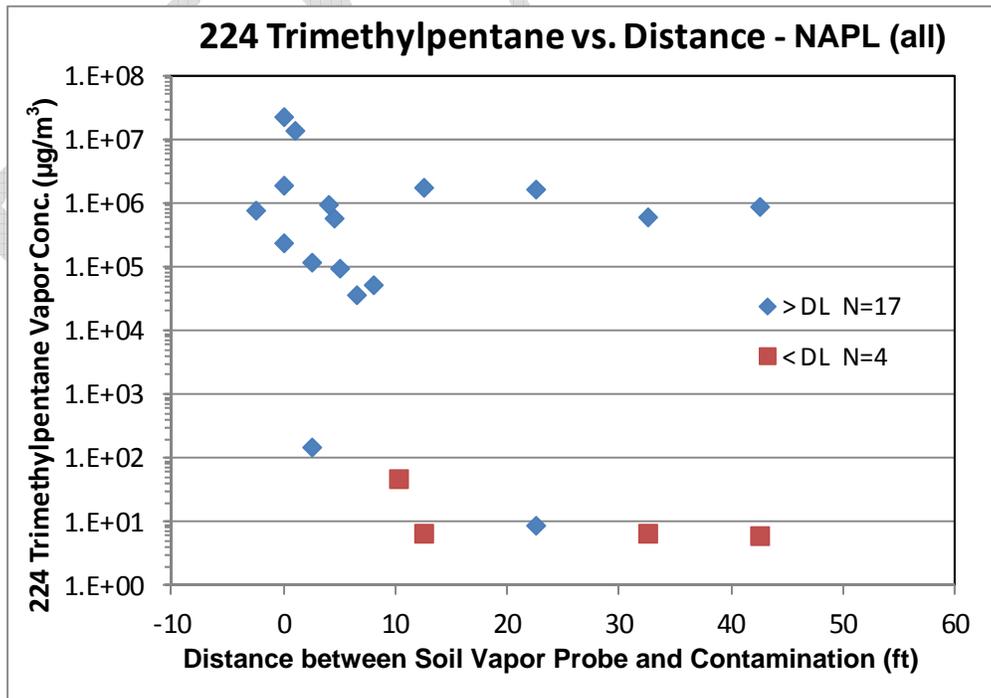
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Figure 14. Vertical Distance Method–PHC Fraction and Hexane Data for LNAPL (UST only) Sites.



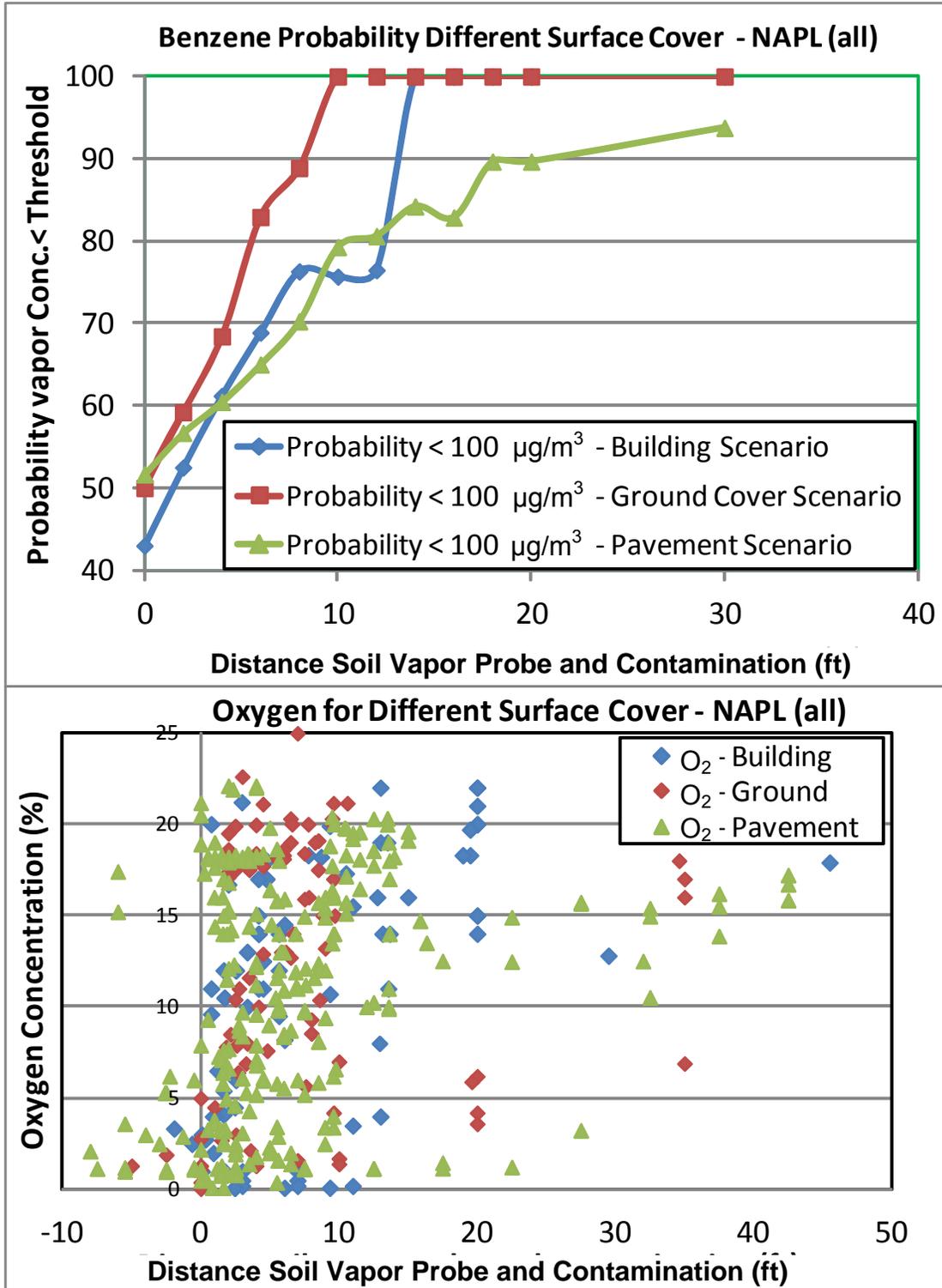
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Figure 15. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (all sites) Sites (KM = Kaplan-Meier).



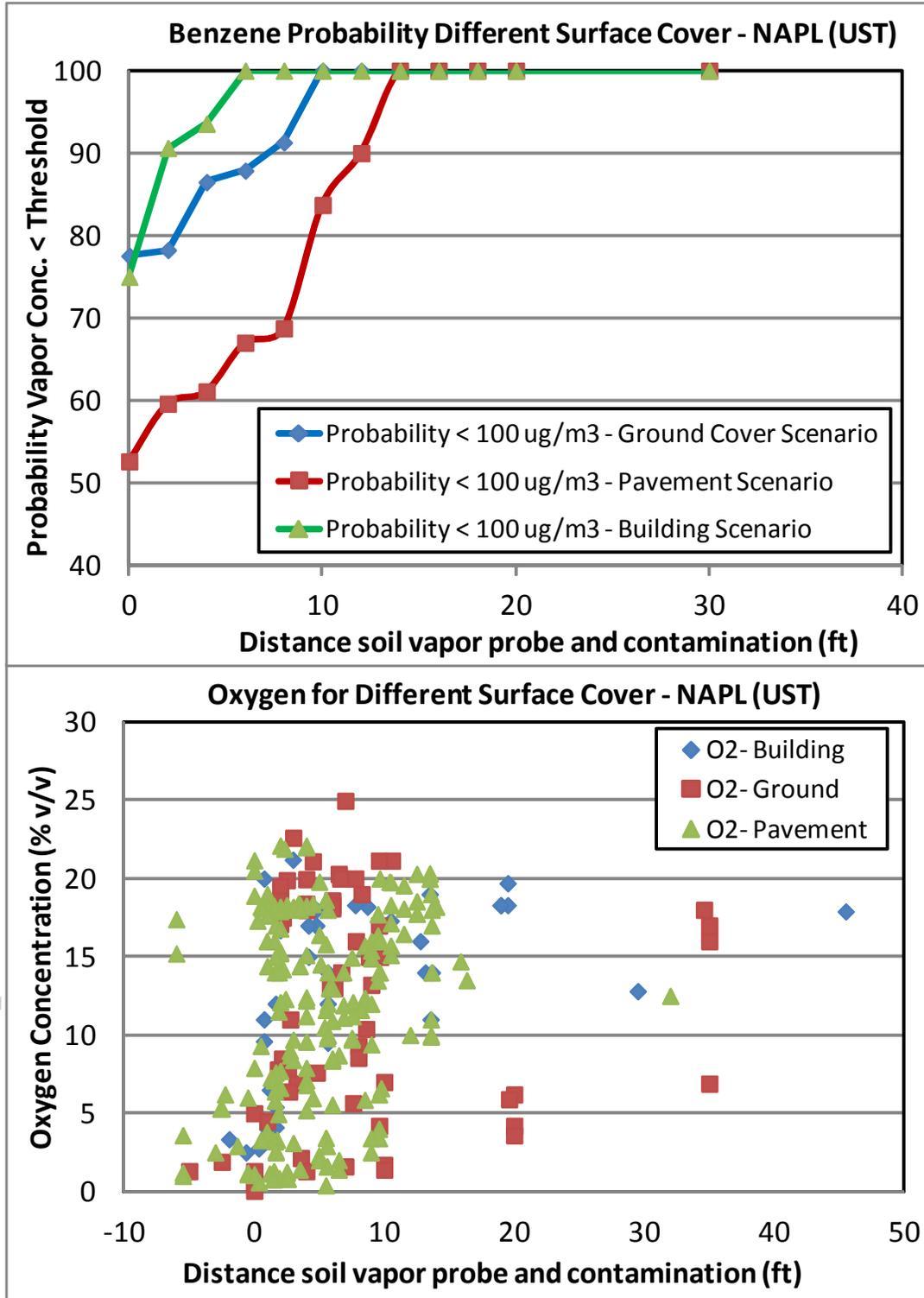
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Figure 16. Vertical Distance Method–2,2,4-Trimethylpentane Data for LNAPL Sites (all sites).



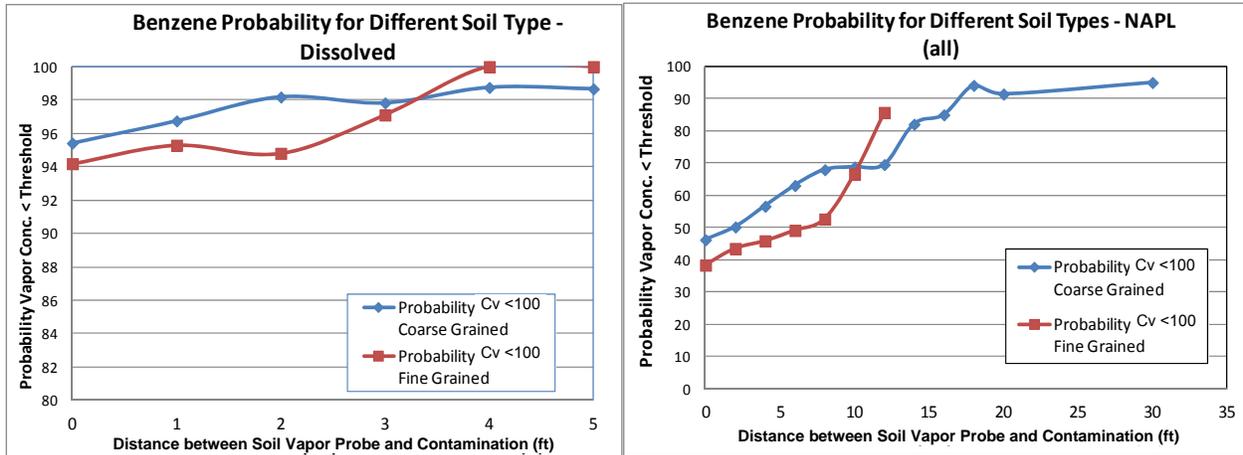
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Figure 17. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (all sites). Below detection limit concentrations replaced with half the detection limit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



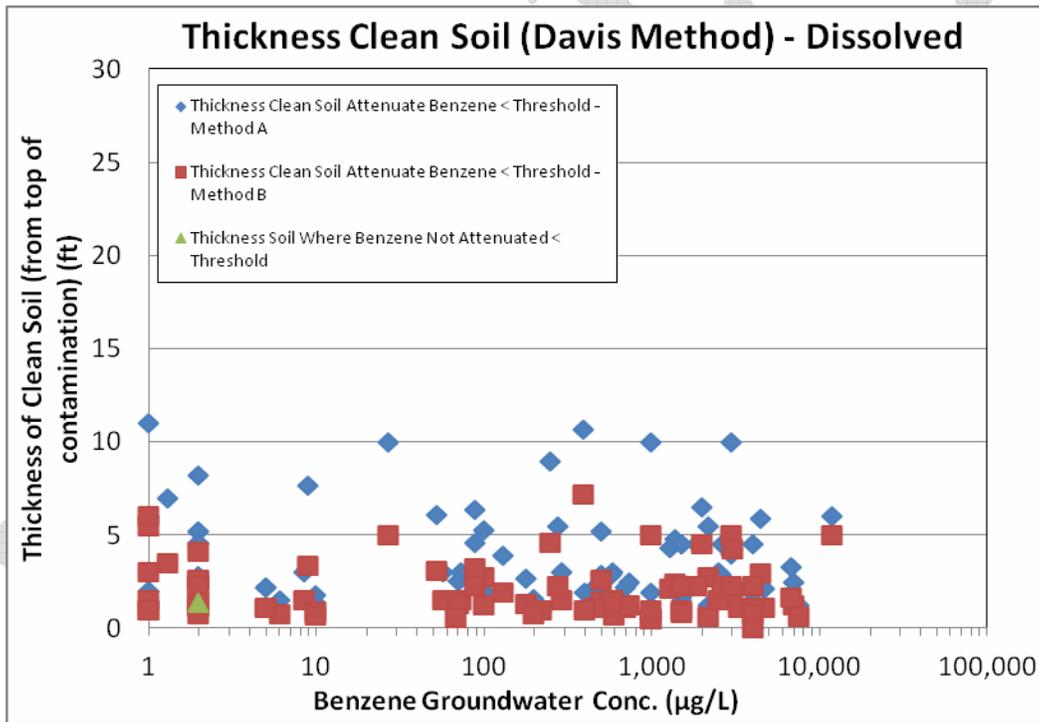
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Figure 18. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (UST sites). Below detection limit concentrations replaced with half the detection limit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



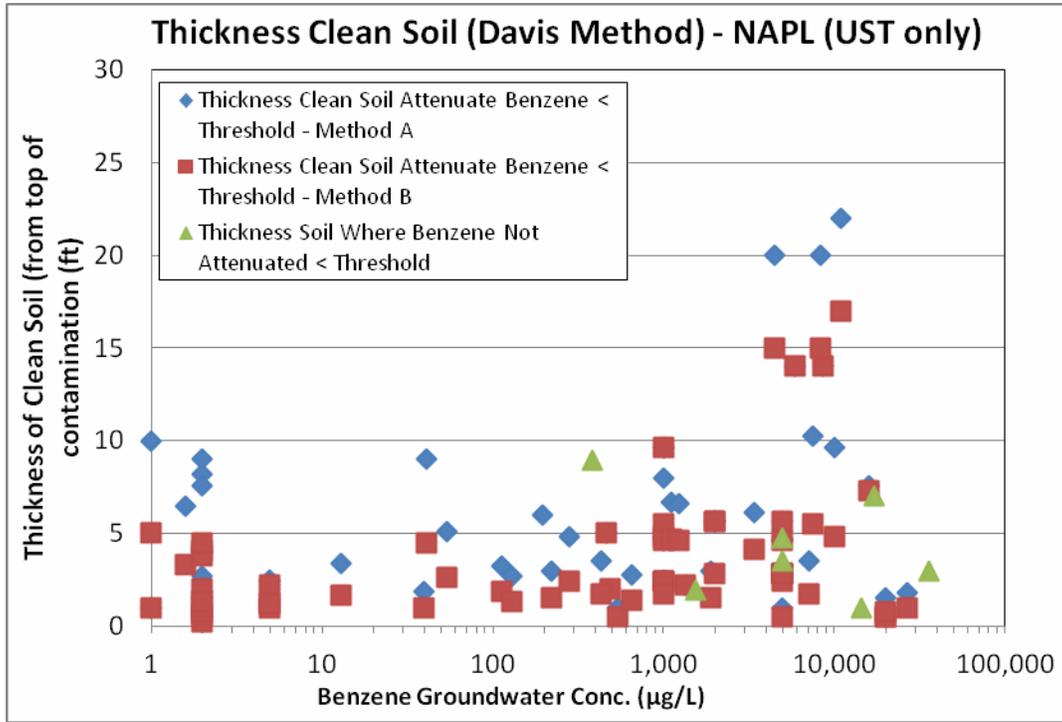
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Figure 19. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold for Different Soil Types (coarse and fine grained). Below detection limit concentrations replaced with half the detection limit for analysis.



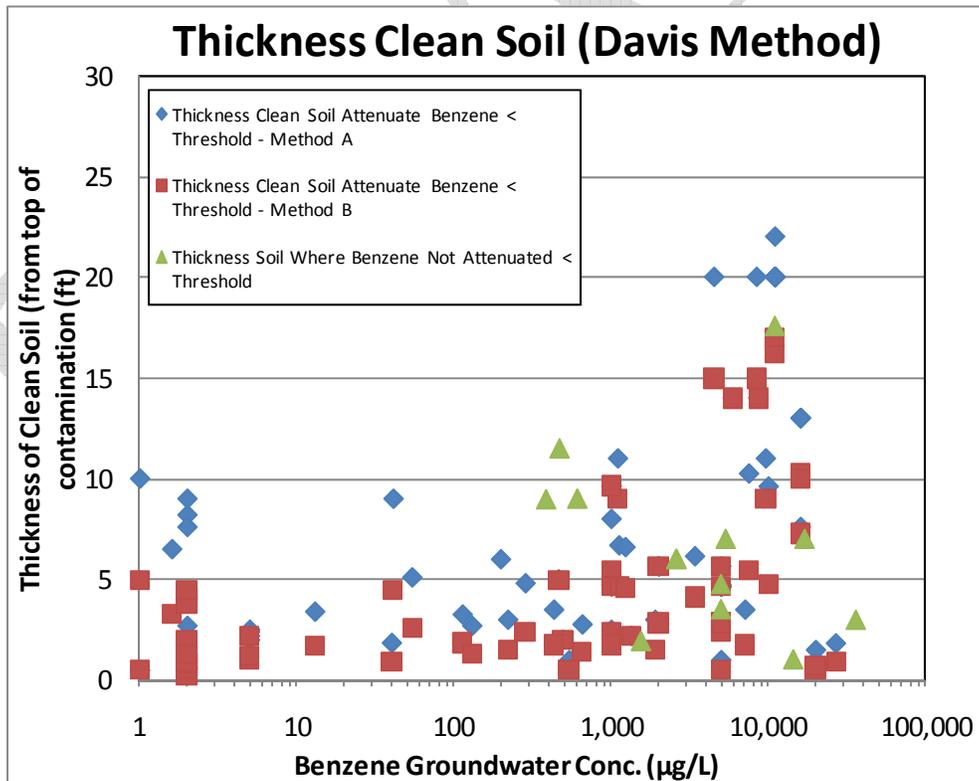
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Figure 20. Results of Clean Soil (Davis) Method for Dissolved-Source Sites. 47 sites, N = 170.



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



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

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Appendix A. PVI Database Data Dictionary

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

Field Name	Type	Size	Description
Table: Building Distances			
building_id	Long Integer	4	Link to Buildings table
location_id	Long Integer	4	Link to Locations table
horz_dist_to_bldg	Double	8	Horizontal distance, sample location to building (na for indoor samples)
horz_dist_to_bldg_unit	Text	20	Horizontal distance unit
horz_dist_comment	Text	255	Comment about building-to-location link
time_stamp	Date	8	Date/time record was created
Table: Buildings			
building_id	Long Integer	4	Building identifier (aka, subsite)
orig_bldg_id	Text	50	ID number for building (from original source)
site_id	Long Integer	4	Link to Sites table
bldg_name	Text	60	Name of building
bldg_type	Text	50	Physical description of building (links to It_Building_Types)
bldg_use	Text	50	Use of building (residential, commercial, industrial, school, etc.)
footprint_area	Double	8	Area of the building footprint
footprint_area_unit	Text	20	Unit of measurement for footprint_area
foundation_type	Text	50	Building foundation types (lookup values in It_Foundation_Types)
fnd_depth_to_base	Double	8	Depth to base of foundation (below ground surface)
fnd_depth_to_base_unit	Text	20	Unit of measurement for depth to base of foundation
bldg_comment	Memo	0	Comment field
time_stamp	Date	8	Date/time record was created
Table: Data Provider			
data_provider_id	Long Integer	4	Unique ID for data provider
data_provider	Text	60	Name of company or agency responsible for completion & submittal of any part of electronic data deliverables
data_contact_name	Text	30	Name of contact associated with data_provider
data_contact_address1	Text	40	Contact street address and/or box number
data_contact_address2	Text	40	Site address, part two. Box number or other info.
data_contact_city	Text	20	City
data_contact_state	Text	2	Postal abbreviation for State
data_contact_zipcode	Text	10	Zip code
data_contact_email	Text	60	Contact e-mail address
data_contact_phone	Text	60	Contact phone number
time_stamp	Date	8	Date/time record was created

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 3 D 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

Field Name	Type	Size	Description
samp_loc_name	Text	255	More specific name of sampling location; can vary by depth
sample_depth	Double	8	Sample depth, below land surface
sample_depth_unit	Text	20	Unit of measurement for sample depth
loc_type	Text	50	Location type (indoor air, outdoor air, probe, bulk soil, or well)
loc_int/ext	Text	20	Interior or exterior location
loc_desc	Text	255	Additional location description (e.g., floor; room use)
vz_soil_text_code	Text	10	Soil texture code (links to It_Soil_Textures)
vz_alt_soil_desc	Text	255	Soil description (more specific than vz_soil_txt_code)
vz_alt_soil_grade	Text	255	Site soil gradation (V.Coarse, Coarse, Fine)
vz_porosity	Double	8	Vadose zone porosity
vz_porosity_unit	Text	20	Unit of measurement for vadose zone porosity
loc_comment	Memo	0	Comment/notes about latitude, longitude, vertical elevation (collection method, post processing, etc.)
time_stamp	Date	8	Date/time record was created
Table: It_Building_Types			
bldg_type	Text	50	Physical description of building
Table: It_Countries			
country	Text	5	Country short name
country_name	Text	25	County name
Table: It_Foundation_Types			
foundation_type	Text	50	Building foundation types (lookup for Buildings table)
Table: It_Hydrogeologic_Settings			
hydro_setting_desc	Text	255	General Hydrogeologic setting description
Table: It_Parameters			
parameter_id	Long Integer	4	Unique ID for each measurement parameter
parameter_abbrev	Text	10	Abbreviation for measured parameter (e.g., MEK, BP)
parameter_name	Text	50	Measured parameter (e.g., 2-butanone, barometric pressure)
cas_number	Text	15	Chemical Abstract System number (where applicable)
parameter_class	Text	50	Parameter class or grouping
organic_yn	Text	1	"Y" for organic chemicals, "N" for inorganic chemicals
HLC25	Double	8	Henry's Law Constant at 25 degrees C (unitless)
DeltaH	Double	8	Enthalpy of vaporization, normal boiling point (cal/mol)
Tc	Double	8	Critical temperature (degrees Kelvin)
Tb	Double	8	Normal boiling point (degrees Kelvin)
comment	Text	255	Comment on parameter
sort_name	Text	50	Parameter name used for sorting
Table: It_Sample_Media			
media	Text	50	Sample media type

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

Field Name	Type	Size	Description
test_result_comment	Memo	0	Comment field
fixed_gas_method	Text	255	Method for fixed gases
time_stamp	Date	8	Date/time record was created
Table: Samples			
sample_id	Long Integer	4	Unique ID for each sample
sample_location_id	Long Integer	4	Location ID where sample was taken at 3 D level (including depth z)
original_sample_id	Text	40	Sample ID in original source
sample_medium	Text	20	Measured medium. (links to It_Sample_Media)
sample_start_date	Date	8	Date sample collection began in (MM/DD/YYYY) format
sample_comment	Memo	0	Comments related to the sample
time_stamp	Date	8	Date/time record was created
Headspace_yn	Text	1	Soil sample only: is this a headspace measurement? (Y, N)
gw_temp	Double	8	Ground water samples only: GW temperature at the time of sampling
gw_temp_units	Text	10	Ground water samples only: Units for GW temperature (i.e. °C)
ground_cover	Text	50	Soil Gas samples only: Ground cover (paved, grassy, etc.)
leak_test_yn	Text	1	Soil Gas samples only: Has the vapor probe been leak tested? (Y, N)
vz_moisture_content	Double	8	Vadose zone moisture content (measured value)
vz_moisture_content_unit	Text	20	Unit of measurement for vadose zone moisture content
Soil_TPH_paired_result_value	Double	8	Paired soil TPH results (Links by 3D location and sample Date)
Soil_TPH_paired_result_unit	Text	15	Units for paired Soil TPH result (and result_error_delta)
Table: Sites			
site_id	Long Integer	4	Unique ID for site
data_provider_id	Long Integer	4	Company, agency, or individual submitting VI data. Links to the Data_Provider table.
original_site_id	Text	45	Site identifier in original source
site_city	Text	20	City of site
site_state_abbrev	Text	4	State abbreviation for State of site (links to It_States)
site_country	Text	50	Country name (links to It_Countries)
site_hydrology	Text	255	Hydrogeologic Setting (links to It_Hydrogeologic_Settings)
site_vapor_src_type	Text	50	Type of contamination (e.g., gasoline)
site_vapor_src_origin	Text	255	Origin of the vapor source (UST, spill, landfill, etc.)
public_yn	Text	1	Can this information be made available to the public? (Y=yes, N=no)
time_stamp	Date	8	Date/time record was created

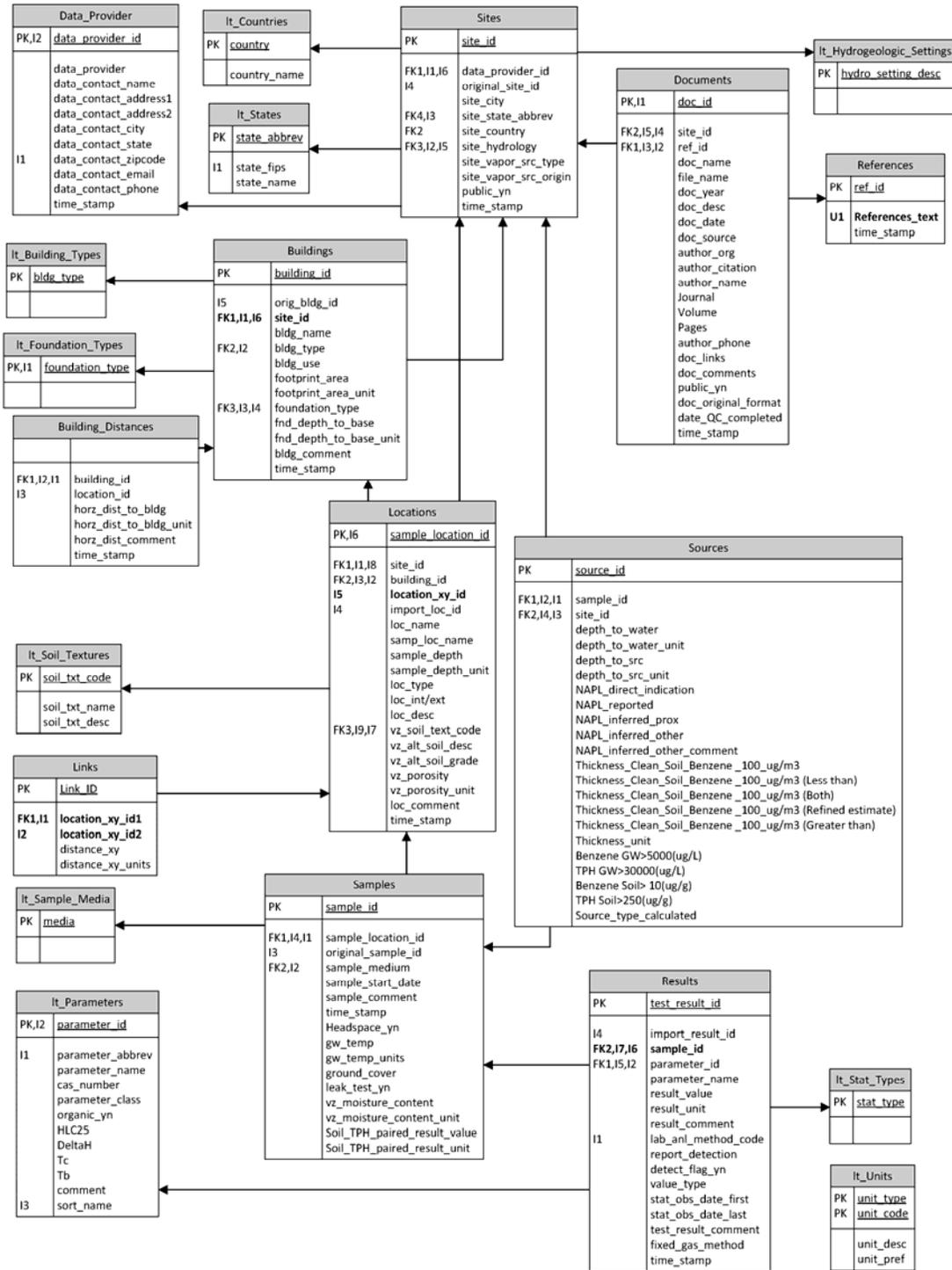
Field Name	Type	Size	Description
Table: Sources			
source_id	Long Integer	4	Unique ID for sources
sample_id	Long Integer	4	Link to Sample table
site_id	Long Integer	4	Link to Sites table
depth_to_water	Double	8	Depth to water table (below land surface) at time of sampling
depth_to_water_unit	Text	20	Unit of measurement for depth to water
depth_to_src	Double	8	Depth to vapor source at time of sampling (= GW depth for GW samples)
depth_to_src_unit	Text	20	Unit of measurement for depth to src
NAPL_direct_indication	Boolean	1	NAPL based on direct indication
NAPL_reported	Boolean	1	NAPL based on report
NAPL_inferred_prox	Boolean	1	NAPL inferred from proximity
NAPL_inferred_other	Boolean	1	NAPL inferred from other references
NAPL_inferred_other_comment	Text	255	Comments on NAPL inferred from other references
Thickness_Clean_Soil_Benzene_100_ug/m3	Double	8	Method 1: Thickness Clean Soil Benzene 100 ug/m ³ Criteria
Thickness_Clean_Soil_Benzene_100_ug/m3 (Less than)	Double	8	Method 1: Thickness Clean Soil Benzene 100 ug/m ³ Criteria (less than)
Thickness_Clean_Soil_Benzene_100_ug/m3 (Both)	Double	8	Method 1: Thickness Clean Soil Benzene 100 ug/m ³ Criteria (both)
Thickness_Clean_Soil_Benzene_100_ug/m3 (Refined estimate)	Double	8	Method 2: Thickness Clean Soil Benzene 100 ug/m ³ Criteria (Refined)
Thickness_Clean_Soil_Benzene_100_ug/m3 (Greater than)	Double	8	Thickness Clean Soil Benzene 100 ug/m ³ Criteria (greater than)
Thickness_unit	Text	20	Unit of measurement for thickness
Benzene GW>5000(ug/L)	Boolean	1	Calculated Benzene GW indicator by 3D and date linkages
TPH GW>30000(ug/L)	Boolean	1	Calculated TPH GW indicator by 3D and date linkages
Benzene Soil> 10(ug/g)	Boolean	1	Calculated Benzene Soil indicator by 3D and date linkages
TPH Soil>250(ug/g)	Boolean	1	Calculated TPH Soil indicator by 3D and date linkages
Source_type_calculated	Text	255	Source type (NAPL or Dissolved)

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Appendix B. PVI Database Entity Relationship Diagram

PVI Database Diagram (draft)
April 17, 2012



1807

MATRIX OF PEER REVIEW COMMENTS: *Draft* Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
EnviroGroup				Comment on General Charge Question	[In reference to] <i>the scientific appropriateness of the database for OUST's purposes</i> - The database is appropriate for application to USTs, but very weak in evaluation of diesel and high-ethanol fuels.	The limited number of diesel sites is not viewed as a significant limitation because the 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.
EnviroGroup				Comment on General Charge Question	[In reference to] <i>whether the reported analyses are based on sound scientific principles, methods, and practices and are appropriate and complete for OUST's purposes</i> - The analyses and methods are appropriate for OUST's purposes, but some areas of incomplete analysis are present as described below.	Additional analyses have been conducted to address these concerns
EnviroGroup				Comment on General Charge Question	[In reference to] <i>whether the reported conclusions are adequately supported by the data and analyses</i> . 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.	Additional analyses have been conducted for non-UST, diesel and petroleum additives.
EnviroGroup		1			Yes	No revision warranted.
EnviroGroup		2			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.	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.
EnviroGroup		3			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.	Additional analyses have been conducted for MtBE 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.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
EnviroGroup		4			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.	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.
EnviroGroup		5			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).	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.
EnviroGroup		6			Yes.	No revision warranted
EnviroGroup		7			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.	A number of Australian sites, including several in arid climates, were added to the database. Between these and existing data from some Utah sites, we believe that low soil moisture effects are adequately addressed, as discussed in greater detail in the revised report. Additional information on oxygenated fuels has been added to the report (see above). The impervious surface cover analysis and discussion was expanded for non-UST sites.
EnviroGroup		8			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 its 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.	MtBE, naphthalene and trimethylbenzenes analyses added.
EnviroGroup		9			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: 1) Cowart, J. & Breyer, L. 2005. Vapor Intrusion at a Diesel LNAPL Site. USEPA Annual RCRA Hazardous Waste Conference. Poster Session. Denver, Colorado. 2) Cowart, J. & Breyer, L. 2004. Attenuation Factors for Hydrocarbons Associated with a Diesel Spill. Vapor Intrusion Attenuation Workshop. 14th Annual West Coast Conference on Soils, Sediments, and Water. March 15-18, 2004, San Diego, California.	Cowart and Breyer site (Mandan) added to database

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
EnviroGroup		2.4	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.	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.
EnviroGroup		2.5	491-504		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.	The screening criteria is revised to include discussion on the importance of the potential effect of low permeability shallow soils on soil vapor transport.
EnviroGroup		2.5	512-517		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.	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.
EnviroGroup		3	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.	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 for 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)
EnviroGroup		3.1	600-615		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.	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.
EnviroGroup		6.2	828-829		Database Structure: Information on the release date and ethanol content of the fuel would also be important to include.	This information is not available
EnviroGroup		6.2	834-836		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.	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)
EnviroGroup		6.3	874-875		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.	There is limited documentation on ethanol content in fuels. Not feasible to add a release date.
EnviroGroup		6.3	876-878		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.	Added to text "Thus, the applicability of the database to large buildings may be limited."
EnviroGroup	Tables		1701-1704	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.	These two sites fall within th 95% probability. There was rapid attenuation of benzene vapour concentrations at these sites.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
EnviroGroup		7.1.3	968-970		Proximity to Fuel Storage/Dispensing Facilities: 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.	The point is not to comment on lateral distance but simply a distance that would be appropriate for screening of sites. Text simplified.
EnviroGroup	Figures		1747	Figure 6	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.	Legend added. Area 1A adequately describes method, Area 2 does not need to be discussed.
EnviroGroup		8.1	1140-1143		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.	Agreed. This point is made in report discussion and conclusions.
EnviroGroup		8.1	1158-1161		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.	Methane analysis added.
EnviroGroup		8.2.1	1214-1215		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.	Agreed. This point is made in report discussion and conclusions.
EnviroGroup		8.2.1	1218-1219		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)?	Comment addressed in footnote #3.
EnviroGroup		8.2.2	1233-1235		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 "yielded similar results" based on Figure 17.	Revised.
EnviroGroup		8.2.3	1257-1261		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.	Statement added on case study results by Luo et al (2010) where layered system may have influenced observed attenuation.
EnviroGroup	Figures		1791	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.	Added: The evaluation of data trends is limited by absence of fine-grained data beyond 14 ft separation distance
EnviroGroup		8.3	1271-1277	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).	No revision warranted - this is stated.
EnviroGroup		9.2	1338-1339		The exclusion of fractured rock unsaturated zones should be reiterated in the conclusions.	Revised.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
EnviroGroup		9.3	1351-1354		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?)	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.
EnviroGroup		9.5	1375-1381		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.	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.)
EnviroGroup		10	1390-1453	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?	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 "bright line" 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.
McAlary				General Comment	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.	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
McAlary				General Comment	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.	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.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary				General Comment	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.	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.
McAlary				General Comment	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.	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.
McAlary				General Comment	Considering the extent of the comments and the significance of the omissions, this reviewer recommends a major revision.	Major revisions made.
McAlary				Comment on General Charge Question	[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.	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.
McAlary				Comment on General Charge Question	[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.	No revision warranted

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary				Comment on General Charge Question	[In reference to] whether the reported conclusions are adequately supported by the data and analyses - The data is not highly reliable, as stated above.	Data reliability framework has been added
McAlary	1				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.	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.
McAlary	2				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.	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.
McAlary	3				Yes, the assessment implications, described above.	No revision warranted.
McAlary	4				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 pre-emptive mitigation would be appropriate in either case. That's not specifically stated anywhere, which is another reason why this document is incomplete.	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.
McAlary	5				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.	No revision made. The different number of data points per site is 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.
McAlary	6				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.	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.
McAlary	7				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.	No response warranted.
McAlary	8				No.	No response warranted.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		9			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 Ettinger (2010)	Data from the first paper already in the database. Data from the second report is added.
McAlary		10			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.	Introductions provides additional clarification on purpose of the two documents.
McAlary		Table of Contents	100	Source Zone Identification Methods	Add O2/CH4, FID, soil staining, odor, and Radon as evidenced by mineral precipitates	Soil staining, odours and CH4 added. Radon not considered standardized approach for source zones.
McAlary		Table of Contents	105 & 110	Exploratory Data	Not everyone uses the term Exploratory Data	Exploratory data analysis is defined in the document and executed as defined. No revision made as it is not an incorrect term per se.
McAlary		Table of Contents	108	Soil Vapor Concentration Thresholds	Move to in between 7.1.2 Soil Concentration Data and 7.1.3 Proximity to Fuel Storage Dispensing Facilities	No revision made
McAlary		Table of Contents	120 & 121	Exclusion Distance Assessment Framework & Lateral Exclusion Distances	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.	No revision - this recommendation goes beyond scope of this report
McAlary		Table of Contents	176		How many ND values had elevated reporting limits? These should not be considered "clean."	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.
McAlary		Table of Contents	179-180		Oxygen below detection almost never happens.	The report includes an enhanced discussion on measurements methods and data quality.
McAlary			1 219-220		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.	The main focus is item #2 but item #1 is indirectly addressed. The rationale for not addressing #3 is provided in the text.
McAlary		1.1	234		Compared to chlorinated compounds; therefore screening PHCs using the same methodology as CI VOCs is overly conservative and risks waste of resources.	Text added "compared to chlorinated hydrocarbons; therefore, screening for PHCs using the same methodology as chlorinated hydrocarbons is overly conservative"

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		1.1	238-240		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 "Methane"] 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 "DeVaul, 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	336		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

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		2.2	363-370	Refers to Section 2.2 in its entirety (Lines 343-379)	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.	No change made - restructuring not considered necessary, see response to comments on lines 344-362 (Column G, Row 85)
McAlary		2.2	375-376		[Add] and supply (i.e., flux balance);	Added: "and supply (i.e., flux balance)"
McAlary		2.2	378		[In reference to "properties"] porosity and moisture content (not sure which other properties matter)	Added: "e.g., soil porosity and moisture"
McAlary		2.2	374-379		Need to say how each of these must be characterized as part of a PVI screening process! What is an acceptable level of uncertainty?	No change made - Given that this is CSM discussion, recommendation of which parameters must be characterized is not considered warranted.
McAlary		2.3	381-394		Far better to add a table and show all this with numbers.	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.
McAlary		2.3	388		Explain [lower biodegradation rates]	Reference to lower biodegradation rates deleted
McAlary		2.3	403		Replace "study" with studies and define "meta analyses and database evaluations"	Revised as "case studies and database evaluations"
McAlary		2.3		General Comment on Section	Expand on LNAPL sources. Distinguish between vadose zone and smear zone, high and low water table.	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.
McAlary		2.4	409-445		Compare and contrast this to the list in lines 374-379. Why have both?	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.
McAlary		2.4	414		[Replace "type" with] "concentration, oxygen supply and oxygen demand"	Revision maded
McAlary		2.4	416		Define [preferential pathway]	Added: such as coarse-grained utility backfill
McAlary		2.4	416-418		Need ΔP in addition to high gas K	No revision made - diffusion may also be important
McAlary		2.4	419-431		What about wet clay (outside building) and dry, dessicated and fractured clay beneath the building?	Revised to include clay layer
McAlary		2.4	426		Add "in the range of ___ to ___" after "measured rates"	Rates added
McAlary		2.4	433		Create new sentence after "zones"	Revision made
McAlary		2.4	436		[In reference to "most likely"] Vague.	Revision made
McAlary		2.4	439-441		Some amount of data is pretty critical.	No revision warranted
McAlary		2.4		General Comment on Section	There needs to be some guidance on "how do you know" whether any of these conditions are present. i.e., number, spacing, frequency of data, collection methods, decision criteria, etc.	No revision warranted for this section of the report
McAlary		2.4	444		What about anerobic conditions? Particularly under buildings?	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.
McAlary		2.4	444-445		CH4 flux vs O2 flux. When does CH4 win? Effect of barometric inversions.	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 condusive for aerobic biodegradation to reduce concentrations below levels of concern before reaching receptors.
McAlary		2.5	452		Add McAlary et al 2011, Michaelski et al 2010	McAlary et al 2011 added

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		2.5.1	464		At what depths?	Added "compared to similar depths below the building"
McAlary		2.5.2	477		[In reference to "benzene, toluene, and xylene"] And nothing else?	Correct
McAlary		2.5.3	488		Not near the saw-cut expansion joints during times of positive ΔP	Revision made
McAlary		2.5.4	490 & 491		Change "unknown" to "confidential"	Revision made
McAlary		2.5.4	499		["the observed behavior"] vague	Added: "and elevated shallow PHC concentrations"
McAlary		2.5.4	504		Add "for _____" after "these reasons"	Added "for the observed soil vapor behavior"
McAlary		2.5.5	508		[In reference to "sharp rise"] I've also seen sites (Michaelski et al 2010) where vapor concentrations increase during periods of low water table. Explain why both can occur.	Added: "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)".
McAlary		2.5.6	517		[In reference to sentence ending with "greater solubility"] Do you mean slower degradation rates?	Revision made: "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)"
McAlary		2.5.6		General Comment on Section	So why was this one building worse? Does that factor also need to be characterized?	Revision made: "No PVI was detected at a nearby slab-at-grade building above residual LNAPL or other buildings above a dissolved groundwater source." Context provided to indicate why conditions worse.
McAlary		2.5.7		General Comment on Section	Expand soil type, source depth, building size, etc	No additional data available.
McAlary		2.5.8	529		[In reference to "up to 500 m (1,640 ft) from the release"] i.e. beyond the NAPL distribution.	Available information suggests that 500 m from location of release, and not NAPL (which likely extends significant distance from the release)
McAlary		2.5.8	529-530		Surely, there's more than just PID data.	No additional data available.
McAlary		3.0	532-538		One sentence does not a paragraph make. [Combine with next paragraph at 539-547]	Revision made.
McAlary		3.0	541		Why just these three [benzene, toluene, and xylene]? Ethylbenzene? MTBE? 124 TMB?	BTX replaced with petroleum hydrocarbon vapors
McAlary		3.0	551-552		Vague wording.	Added "through prediction of distances over which PHC vapor concentration attenuation occurs for varying site conditions"
McAlary		3.0	557		[Remove the word "subsequent." Add "The model has been used in several studies (A&J 2005, A et al 2009, US EPA 2012)." In its place. Next sentence starts with "Three-dimensional"]	Revised
McAlary		3.0	558		Replace "studies" with "scenarios"	Revised
McAlary		3.1.1	572		[Replace "cycling is a relevant condition" with] fluctuations occur (very common)	No revision considered warranted. The text acknowledges this is relevant condition and additional emphasis ("very") not warranted.
McAlary		3.1.1	575-577		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.	No revision made - out of context for this section
McAlary		3.1.1	583		[In reference to 10 mg/L] Does that include methane? It should.	No revision made - this is in reference to dissolved sites. Elevated methane concentrations were only measured at a few NAPL sites.
McAlary		3.1.1		General Comment on Section	Simulators likely overestimate PVI potential? Can't say this without considering CH4.	Added: "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."
McAlary		3.1.1	590		Compare to Michaelski et al 2010	No revision made - out of context for this section

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		3.1.1	594-597		This is a good example of vague wording being clarified with a quantitative statement. Please do the same where comment "vague" is used elsewhere	No revision made - Text is "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." The word "significant" is given context through a specific example with quantitative comparison. The use of the word "approximate" is considered appropriate given the accuracy of model simulations.
McAlary		3.1.2	613-615		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?	No revision made - out of context for this section
McAlary		3.1.3		General Comment on Section	What if saturation was near 100% for a month (wet spring)? See McAlary et al 2011.	Added paragraph: "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)."
McAlary		3.1.4		635	Replace "unknown" with "confidential"	Revision made
McAlary		3.1.4	637-639		This indicates that it is essential to document the geology and soil moisture profile as part of a PVI screening process.	No revision made - out of context for this section
McAlary		3.2	642		Insert "1-D" after "results for a"	Revision made
McAlary		3.2	655		What's the value for the non-degradation scenario?	Attenuation factors for non-degrading case added
McAlary		3.3	673		Replace "source" with "deep soil"	Revision made
McAlary		3.3	676		Are you assuming building acts like an accordion? i.e., Q soil in = Q soil out?	No revision made - addressed in next paragraph
McAlary		3.3	679		[In reference to "conceptually easier"] Why?	Added - "because of common usage soil gas advection rate or Q_{soil} parameter in modeling studies"
McAlary		3.3	680-681		[with ref to converted] How?	Added - "through consideration of density of air and oxygen content of air"
McAlary		3.3		General Comment on Section	Qsoil in = Qsoil out? Justify (net neutral building with ΔP cycles from wind gusts, etc)	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.
McAlary		3.4	687-688		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.	Disagree with comment in that given 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: "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)."
McAlary		3.4	695-696		I'm not aware of any good data to show the surface capping effect and the model input were not validated, only estimated.	Agree that there is limited data for capping scenario. No revision made.
McAlary		3.4	697-700		Need to follow through with protocols for site characterization.	No revision made
McAlary		4.0		712	How many of these [25 sites] were sampled from temporary probes vs slurry-sealed probes?	Added: "A rigorous quality assurance/quality control program was followed for data collection including installation of properly sealed permanent probes and leak tracer tests."
McAlary		4.0	722-723		Can you check again and add now?	No revision made, beyond scope of this work to add data.
McAlary		4.0		732	How many ug/m^3 ?	Revision made - thresholds in ug/m^3 added

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		4.0		General Comment on Section	Add papers by McAlary and Michaelski.	McAlary paper and Oklahoma site added. Michaelski site data already included
McAlary		5.0		General Comment on Section	Re-sequence and groom.	Revision made - see below
McAlary		5.0	738-741		Three ideas [should be], three sentences.	Revision made - see below
McAlary		5.0	738-747		[Reviewer suggests this re-sequencing] Most states exclude sites from the need for VI assessments if they are more than a specified distance from the source of a 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"	Revision made.
McAlary		5.0	754		It isn't "free," really. Better to stick with one term: NAPL.	This is NJDEP terminology. Quotations added
McAlary		6.1	805		Is this ["Davis" database] publically available? If so, where?	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.	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.	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.	Information on QA/QC added
McAlary		6.2	864		How much, exactly?	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.	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).	Added: "(all statistics with respect to number of sites with data is provided in Table 5)"
McAlary		6.3	890-893		Sealed vs temporary probes? Fixed vs mobile labs?	Information on QA/QC added
McAlary		7.1.2	963-964		And soil gas samples were within what distance of this evidence?	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.	No revision made.
McAlary		7.2	994-995		["And other factors"] Vague.	Revised to be more specific
McAlary		7.2.2	1031-1031		Based on how many rounds of water level monitoring, on average?	Added: "where multiple monitoring events were available (on average, there was about two events per site)."
McAlary		7.2.3	1035-1036		It isn't "unimpacted" and it isn't "clean." These terms are misleading. Better to say "soil with no NAPL."	Text added: i.e., soil without NAPL
McAlary		7.2.3	1039-1042		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)	No revision made - this recommendation is beyond the scope of this report
McAlary		7.2.3	1047		Show this with a figure.	No revision made - this is shown (Figure 6)

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary		7.2.3	1051-1054		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?	Added: The method provides for a conservative estimate of the attenuation distance because for any shallow concentration above 40 µg/m ³ , the full distance to this vapor sample location is used.
McAlary		7.2.3	1055		Because?	Added: "because a minimum distance is required for concentration attenuation to occur."
McAlary		7.2.3	1059-1061		Exactly why a semi-log plot would be a better choice.	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/m ³ , the full distance to this vapor sample location is used
McAlary		7.2.3	1069-1073		Move this paragraph to line 1056	Revision made
McAlary		7.3	1075		Need to add a "topic sentence"	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.
McAlary		7.3	1094-1105		Combine paragraphs.	Revision made.
McAlary		7.3	1097		Add "spatial and temporal" before "variability"	Revision made.
McAlary		7.3	1099 & 1102		[In reference to "95th" and "90th"] Why not use the same?	Revised to be the same.
McAlary		7.3		General Comment	Radon studies could also be used to support 0.01. You should say that a steady-state model is best compared to a 50th percentile empirical α . Then defend why you looked at 90 or 95th percentile values (RAGS) generally recommends that when there is enough data).	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.
McAlary		7.3	1109		[In reference to "exposure amortization"] Not everyone will know this term, so define.	Added: (e.g., calculation of average exposure rate from a less than continuous or lifetime exposure)
McAlary		7.3	1109-115		Seems weakly supported.	Added: "and for consistency with previous database evaluations by Davis (2009) and Lahvis et al. (In prep.)." 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.
McAlary		7.3		General Comment	You defend $\alpha \sim 0.01$ as reasonably conservative, then don't use that for the one chemical that is your primary focus. Seems odd.	See above
McAlary		8.1	1120		[In reference to "a proportion"] Why not be specific and say 25% or whatever? There are many instances when the wording is vague.	Revision made: replace statement on on proportion has low concentration with "but the difference in the distribution between LNAPL and dissolved sites is smaller than expected".
McAlary		8.1	1118-1124		Elevated reporting limits?	No, not the reason
McAlary		8.1	1127		[In reference to "there is no apparent correlation for dissolved-source data"] Why is this? Is it because of some processes? Or data quality?	Added: "The reason for the lack of correlation for dissolved-source data and relatively consistent, low soil vapor concentrations is inferred to be biodegradation."
McAlary		8.1	1127		[In reference to "weak"] Just say $r^2 = \underline{\hspace{1cm}}$	Regression coefficient (R ² =0.08) added
McAlary		8.1	1132		Add "from the measured groundwater concentration" after "partitioning"	Revision made
McAlary		8.1	1129-1134		This is reasonably attributable to biodegradation	Revision made
McAlary		8.1	1138		[In reference to "predicted concentrations by Henry's Law"] Why not just be specific: "groundwater concentration multiplied by Henry's Constant"	Revision made
McAlary		8.1	1138-1139		[Starting with "which is consistent" to the end of the sentence] Good. But the previous paragraph needs a "tie-in" sentence like this too.	No revision made.

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McAlary		8.1	1144-1157		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.	Revision made.
McAlary		8.1	1144-1145		[In reference to "has been hypothesized as"] This wording sounds too academic.	Revision made.
McAlary		8.1	1146		[after "low oxygen"] add concentrations where there are	Revision made.
McAlary		8.1	1147		[after (near atmospheric)] add concentrations where there are	Revision made.
McAlary		8.1	1148		[In reference to "high natural oxygen demand"] Define what this means. Were there any such sites in the database?	Revision made.
McAlary		8.1	1150-1151		[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?	There may some limitation associated with portable equipment.
McAlary		8.1	1151		[Figure 9] Plot as both linear-linear and log-log scales.	Revision made
McAlary		8.1	1152-1154		Do these data points pass the quality screen? If so, why?	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 1×10^6 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-O ₂ consumption ratio based on stoichiometric considerations, this suggests a hydrocarbon level at which significant oxygen consumption should be resolvable of about $(280 \times (2 / 21) \times 0.3 = 8 \text{ g/m}^3$ or 8×10^6 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 (6% 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...)

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary (continued from preceding comment)						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 Hal'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.
McAlary		8.1	1158-1163		I personally believe methane is more common at LNAPL sites and is an important sink for oxygen. This doesn't do it justice.	Data added
McAlary		8.1	1168		Also not clear why this matters.	Rationale added.
McAlary		8.1	1170-1174		Very hard to follow as worded.	Revised
McAlary		8.1	1174		[In reference to "a probability"] of what? [In reference to "95"] why 95?	95 is based on regulatory precedence
McAlary		8.2.1	1180		[In reference to "only PHC fraction and hexane data"] Have these sites been adequately characterized to use in the database?	Yes these sites have been adequately characterized.
McAlary		8.2.1	1195-1196		[In reference to "(possibly because groundwater is a poor predictor of soil vapor concentrations.)"] This also has implications for the scope of a PVI investigation.	Agreed. This is addressed in discussion and conclusions.
McAlary		8.2.1	1212		[In reference to "relatively small"] Be specific.	Revision made to be more specific.
McAlary		8.2.1	1212-1215		[sentence starting at For LNAPL] I'm having a hard time following the distinction. Why not simply use 2 categories: 1) dissolved source, and 2) NAPL source?	Clarified, there are 3 categories 1. Dissolved, 2) UST, 3) non-UST.
McAlary		8.2.1	1220		Add a tie-in sentence.	Added.
McAlary		8.2.1	1221-1222		[In reference to "greater" and "larger"] be specific.	Revised.
McAlary		8.2.2	1228		[In reference to "building concrete foundations"] Are there any data below buildings in cold climates where the stack effect might result in a depressurized basement? If not, be careful what you say about oxygen shadows below buildings.	The stack effect is not considered the primary factor in causing an oxygen shadow. Instead the source vapor concentrations, the source-separation geology (i.e., soil air permeability, moisture content, source strength, and soil air permeability) all contribute to the potential for an oxygen shadow being under a building.
McAlary		8.2.2	1234-1235		[between 5 and 20 percent greater for the ground cover scenario, compared with the pavement and building scenarios, which yielded similar results.] Not clear how this supports line 1292.	Revised
McAlary		8.2.2	1241-1242		[the probabilities for benzene concentrations less than 100 ug/m ³ were similar for the ground cover and building scenarios.] Not clear how this supports line 1292.	Revised.
McAlary		8.2.2	1250		[In reference to Table 4] Table 4 doesn't specifically include a column for vertical profile below building floor.	No revision made
McAlary		8.2.2		General Comment	What do modeling studies show? If data and models do not agree, what does that tell us?	Modeling summary section enhanced to address comment.
McAlary		8.2.3	1259-1261		[it is not possible to identify if soil type has an influence on benzene soil vapor concentrations and probabilities of exceedances.] This has implications for PVI assessment. If temporary probes were used in fine-grained soils, you'd need to do more to defend the data quality anyway.	In almost cases permanent probes were used.
McAlary		8.3	1263-1265		You've said this already.	Section shortened.
McAlary		8.3	1268, 1276, 1281-1283		[In reference to "there is no trend," "an attenuation distance could not be provided," and 1281-1283] What is the significance of this? Too many statements that appear to be potentially significant with no clarification of whether they are or not. This weakens the whole analysis.	This section re-structured and clarified.
McAlary		8.3	1271-1283		Combine?	No revision made - separate analysis warranted.
McAlary		9.1	1291-1292		[depending on site conditions] Vague.	Example site conditions added.

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McAlary		9.1	1294		["large buildings or a capping effect based on geologic conditions."] Your analysis (8.2.2) did not support this statement very well or maybe just wasn't very clearly worded.	Revised.
McAlary		9.1	1299-1302		This has implications for PVI assessment scope.	Agreed.
McAlary		9.2	1309		[overly conservative] By how much?	Not possible to quantify by how much.
McAlary		9.2	1311		[too far apart.] How far is too far? This has implications for the site characterization too.	Revised to indicate 5-10 ft.
McAlary		9.2	1312-1319		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.	Additional discussion on oxygen shadow added.
McAlary		9.2	1320-1324		Pretty vague and unconvincing.	Text revised.
McAlary		9.2	1326-1330		You shouldn't just assume the reader is familiar with these topics and gloss over them.	Revised.
McAlary		9.2	1331		[In reference to "uncertainty"] Specifically, what is uncertain?	Revised to remove reference to uncertainty.
McAlary		9.2	1333		Is it methanogenesis and associated oxygen demand?	Reference to methogenesis added.
McAlary		9.2	1334-1335		[In reference to "not necessarily"] Vague.	Revised, clearer definition provided.
McAlary		9.2	1339		Need to make sure these conditions are carried through.	Agreed
McAlary		9.3	1344-1345		[In reference to "PVI is unlikely to occur unless a dissolved source is very close to a building foundation."] Except for preferential pathways, fractured rock, naturally high foc, large footprint buildings?	Not considered warranted for dissolved sites.
McAlary		9.3	1352-1354		Poorly worded and hard to follow.	Revised
McAlary		9.4	1358-1361		[In reference to "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."] 2 ideas, [needs] 2 sentences.	Revised
McAlary		9.4	1360		[In reference to "uncertainty"] 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.	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.
McAlary		9.4	1367		[In reference to "for LNAPL" sources"] Only for LNAPL? Wouldn't you need to show dissolved	Yes - these factors have not been demonstrated for dissolved sources as PVI case studies indicate LNAPL is of primary concern.
McAlary		9.4	1371		[In reference to "significant"] What specifically makes a preferential pathway significant?	Revised.
McAlary		9.4	1371-1373		Seems I've read this several times, but each time, it is just a passing comment.	Disagree, appropriate emphasis given. Word methanogenesis added.
McAlary		9.5	1379-1380		[In reference to "uncertainty associated with delineating a PHC source near existing or future buildings"] Describe exactly what makes this uncertain. Is it data density? Data quality? Poor knowledge of the processes?	Revised to indicate why, i.e., practical limitations associated with site investigation.
McAlary		9.5	1380		[In reference to "larger"] by how much?	Not possible to indicate by how much
McAlary		9.6		General Comment on Section	Virtually all of section 9 is either vague or redundant. I would suggest a complete rewrite. It needs to answer several basic questions, see "Global Comments."	Revised.
McAlary		10.0	1391		[In reference to "typically high"] Vague. [replace with] "overly"	Revised.
McAlary		10.0	1393		[In reference to "screening evaluation methods"] To me, a "screening evaluation method" 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.	Revised to indicate screening approach
McAlary		10.0	1396		[In reference to "characterizing PVI"] Not really. The impression I get is that all of the sites were simply assumed to be well-characterized.	Revised to "evaluating" instead of "characterizing"

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McAlary		10.0	1399-1401		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.
McAlary		10.0	1403-1408		Specify whether this includes preferential pathways, fractured rock, large buildings, etc, etc etc.	This analysis was not conducted, comment out of context
McAlary		10.0	1412		[after "concentrations"] insert ""except"	No revision made - correct as is.
McAlary		10.0	1414-1420		Excluding preferential pathways, fractured rock, etc, etc etc.	Yes. This is addressed in concluding paragraph.
McAlary		10.0	1421		[In reference to "UST"] Would it matter if this category was dropped from this group? It's confusing to have 3 categories and the UST LNAPL shows up in 2 of them.	Important to have three categories
McAlary		10.0	1430		[In reference to "benzene is the risk driver."] By 10x? By 100x? By 1000x? Can't the others be ignored?	Statement that risk driver is sufficient. This statement not intended to preclude assessment for other compounds. No revision considered warranted.
McAlary		10.0	1434		[In reference to "distances"] Intervals? Depths?	Revised.
McAlary		10.0	1434-1436		[In reference to "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."] And therefore, what?	Revised.
McAlary		10.0	1437-1441		Seems like a stretch. Can you really say this?	Revised. See previous sections.
McAlary		10.0	1439		[In reference to "lower" and "less".] Double-negative.	Revised.
McAlary		10.0	1442		[In reference to "8."] Not a separate point.	Revised.
McAlary		10.0	1446		[In reference to "screening methods"] Why not include recommendations right here?	Screening framework provided.
McAlary		10.0	1452-1453		[In reference to "because of their tendency to generate methane that can interfere with the biodegradation of PHCs."] Makes it sound as if other hydrocarbons are not methanogenic and that's not true.	Revised.
McAlary	Tables			Table 1	(Oklahoma Refinery (McAlary et al 2011) and Ohio Refinery (Michaelski et al 2010)) These two have very detailed data sets and should be considered because they show important aspects of temporal variability that has not been adequately addressed.	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.
McAlary	Tables			Table 3	[In reference to Total Sites=70] How many are "research" sites? (i.e. 100s of times more samples) [Add] "Oklahoma" [increase Ohio count] to 5 from 4	Number of samples analyzed is provided in Table 5. Oklahoma site added. No revision needed for Ohio count.
McAlary	Tables			Table 5	Probe type? (temporary or implant) Lab type? (Mobile or fixed) Name of sample collection firm? Name of lab?	Probe type addressed in data quality table. Lab type, name of firm and name of lab is information that is not considered warranted to add to report, but some of this information is available in supporting documents assembled by RTI
McAlary	Tables			Table 5	[In reference to the zero values for Oxygen, Carbon Dioxide, and Methane for the bottom 13 sites listed] How much do you really know if they didn't measure these? [add] "dioxide" [to table tab after carbon]	"dioxide" added after carbon
McAlary	Tables			Table 6	This has implications for the site characterization. The document should specify whether and to what extent these data are necessary before a PVI assessment is adequate.	Beyond scope of this report.
McAlary	Tables			Table 8	[In reference to "95% at 30ft (9.1m)" for both Benzene concentrations] Confirms most existing guidance on exclusion distances.	No revision warranted.
McAlary	Tables			Table 8	Naphthalene? MTBE? TMBs?	Naphthalene, MTBE, and TMB added to discussion and figures.
McAlary	Tables			Table 9	[In reference to "act the same" and "look the same"] Need more verbage to describe what "acting" and "looking" means.	Revised.
McAlary	Figures			Figure 6	Add legend to specify what red and blue numbers are (TPH and oxygen? benzene and oxygen?)	Legend added
McAlary	Figures			Figure 7	Why not also plot soil vapor concentrations? By itself, this plot is intuitively obvious (detection limit to saturation limit, what else would you expect?)	This is shown on Figure 8. The point of Figure 7 is to show the difference between dissolved and NAPL sites.

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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 r 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 over interprets 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/m ³ TPH with 20% O ₂ ?	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?	MtBE, 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?	MtBE, naphthalene, TMBs added. No TBA data.
McAlary	Figures			Figure 15	Error bars?	See above comment
McAlary	Figures			Figure 16	RBCv	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 O ₂ 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=_____. Sequence should match Figure 17.	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 O ₂ values approaching atmospheric seems very unlikely.	The available data have been plotted.
McAlary	Figures			Figure 19	Error bars?	See above comment

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
McAlary	Figures			Figure 20	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?	In general, there should 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.
McAlary	Figures			Figure 22	[In reference to title add] -NAPL (All)	Revised
Widdowson	1				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.	We appreciate the positive review of document structure and organization. We did not add a glossary in this draft as terms like "attenuation factor" are well used and understood in the VI practitioner community. Acronyms are defined on first use within the text. 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. (see comment #47 above)
Widdowson	2				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 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.	No revision necessary.
Widdowson	3				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.	Revisions made: "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" and "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."

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Widdowson	4				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.	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.
Widdowson	5				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.	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.
Widdowson	6				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.	An appendix on K-M is not considered warranted but additional information added: "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."
Widdowson	7				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.	Discussion on temporal variability on water table height added to discussion.
Widdowson	8				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.	Revised to address this concern

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Widdowson		9			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.	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.
Widdowson		10			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.	Beyond scope of this report to specify best practices, but the need for such practices is emphasized.

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,*

seasonal and climatological effects, preferential transport pathways, type of petroleum fuel, surface cover) been adequately considered?

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 its 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.

Cowart, J. & Breyer, L. 2005. Vapor Intrusion at a Diesel LNAPL Site. USEPA Annual RCRA Hazardous Waste Conference. Poster Session. Denver, Colorado.

Cowart, J. & Breyer, L. 2004. Attenuation Factors for Hydrocarbons Associated with a Diesel Spill. Vapor Intrusion Attenuation Workshop. 14th Annual West Coast Conference on Soils, Sediments, and Water. March 15-18, 2004, San Diego, California.

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.

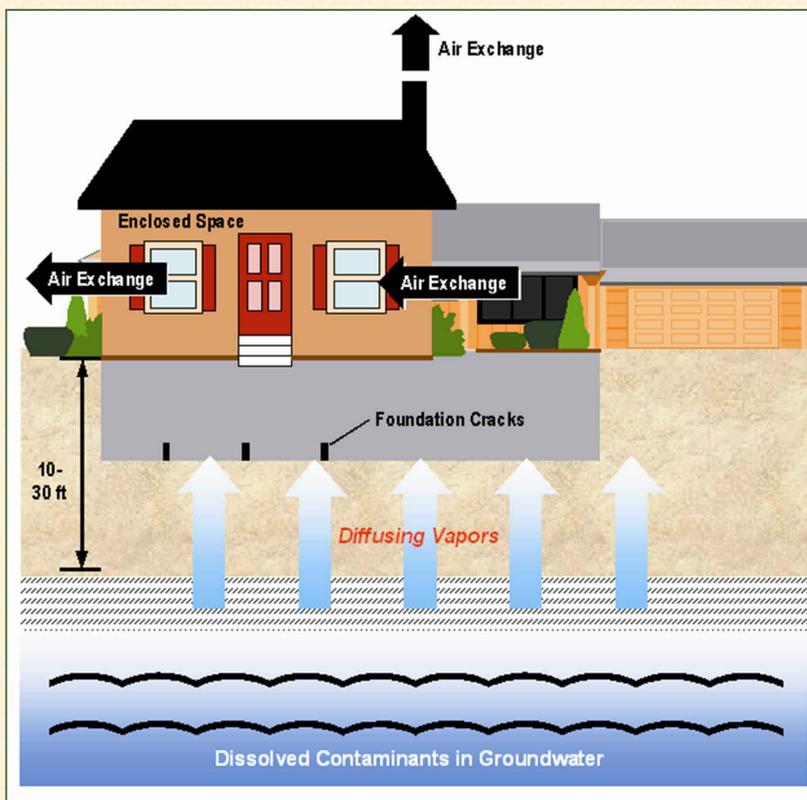
3. **Section 2.5 – UST Site, Stafford, New Jersey, lines 512-517:** This case study suggests that vapor intrusion from MTBE and 2,2,4-TMP might be more likely than benzene due to their higher solubility and possibly lower attenuation. This example should prompt further evaluation of MTBE in the database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

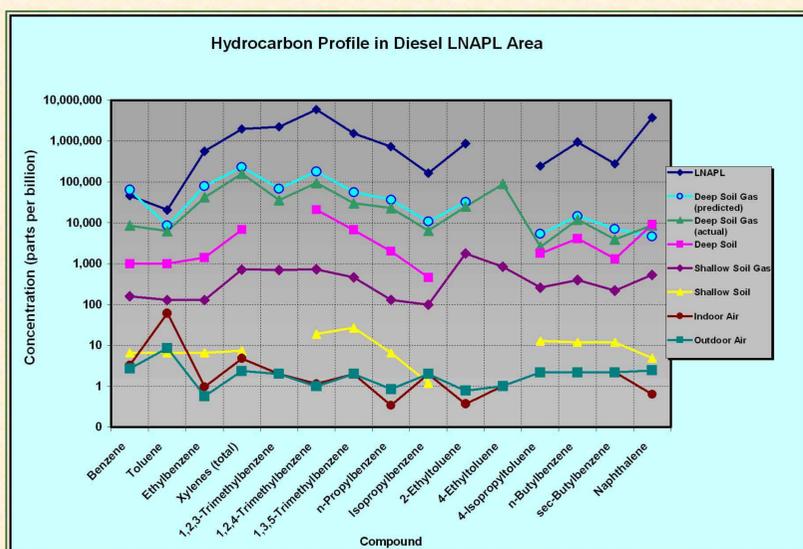
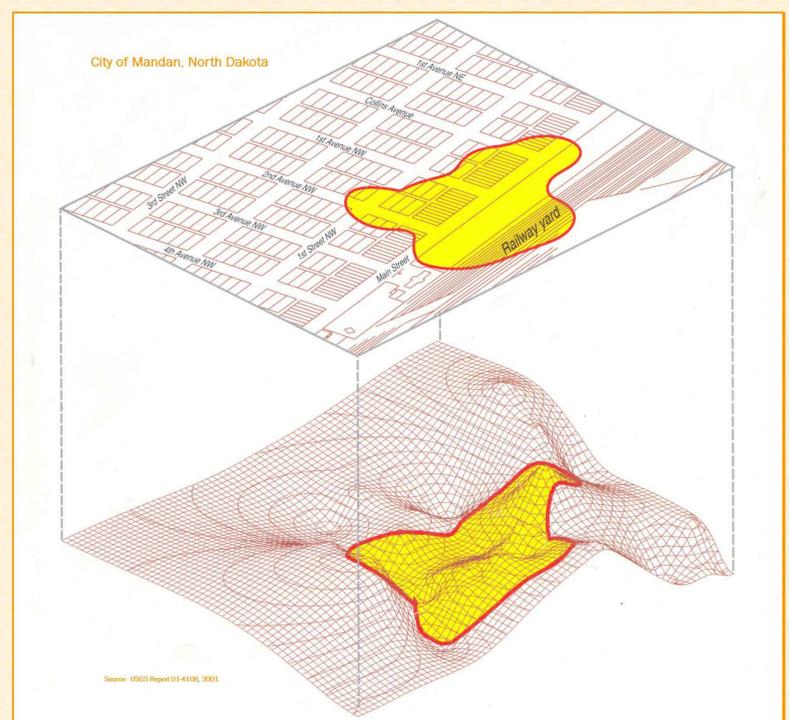
Principal Investigators: James B. Cowart, P.E. and Lindsay Breyer, CIH



- Vapor intrusion evaluates the migration of volatile contaminants from a subsurface Source (groundwater, LNAPL or soil), through a Pathway (vadose zone), to a Receptor (indoor resident or worker), creating an Exposure (adult or child inhalation), which may exceed Risk criteria (carcinogen or non-carcinogen), above Background conditions.
- Since 1997 Walsh Environmental has assessed and remediated vapor intrusion at some of the largest and most complex RCRA sites:
 - ◆ Headquarters CDOT Materials Testing Laboratory, Denver, Colorado (TCA, DCM, TCE, DCE)
 - ◆ 4800 Dry Creek Road, Littleton, Colorado (TCE, PCE)
 - ◆ Mandan, North Dakota (Diesel LNAPL)

• 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 11-17 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.

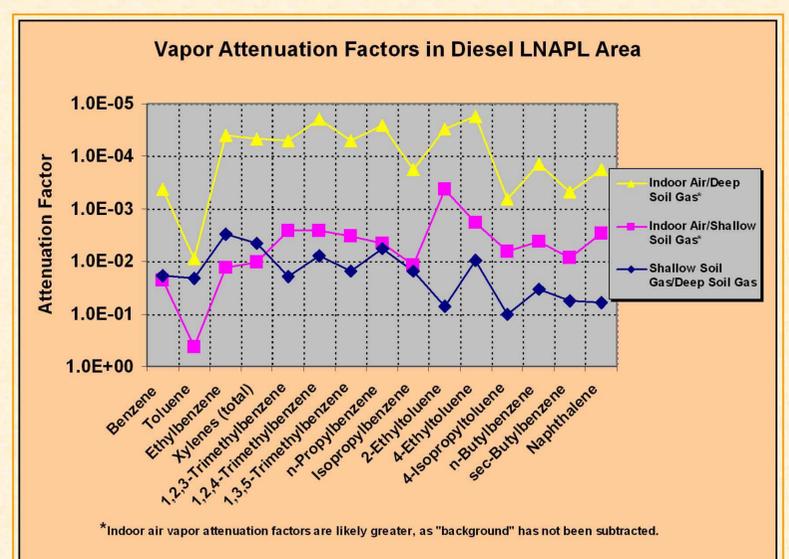


- Hydrocarbons were profiled in Diesel LNAPL, soils and soil-gas (deep & shallow), and indoor/outdoor air media.
- Media were analyzed for Volatile and Semi-volatile Organic Compounds, Diesel Range Organics, C2-C10 Hydrocarbons, and Fixed Gases. 15 compounds were identified as Preliminary Contaminants of Concern (PCOCs).
- 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 PCOC vapors ranged generally as follows:

- ◆ Deep soil gas 10,000 to 100,000 ppb.
- ◆ Shallow soil gas 100 to 1,000 ppb.
- ◆ Indoor air and outdoor air 0.5 to 5.0 ppb, 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 basement level) were 10-500 times less concentrated than deep soil-gas (i.e., attenuation factor 1×10^{-1} to 5×10^{-2}).
- ◆ Indoor air concentrations were typically 100-1,000 times less concentrated than shallow soil-gas (i.e., attenuation factor 1×10^{-2} to 1×10^{-3}).
- ◆ Cumulative vapor intrusion attenuation factors (deep soil-gas to indoor air) were generally 1×10^{-3} to 5×10^{-4} , and likely were greater if "background" hydrocarbons had been subtracted.



*Indoor air vapor attenuation factors are likely greater, as "background" has not been subtracted.

Attenuation Factors for Hydrocarbons Associated With a Diesel Spill *by Lindsay Breyer, CIH and James B. Cowart, PE*

Presented at:

Vapor Intrusion Attenuation Workshop
14th Annual West Coast Conference on Soils, Sediments, and Water
March 15-18, 2004, San Diego, California

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-isopropyltoluene, 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 course 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

Analysis	Soil	Groundwater	Soil Gas	Indoor/Outdoor Air
Volatile Organic Compounds (VOCs)	EPA 8260B	EPA 8260B	EPA TO-15	EPA TO-15
Semivolatile Organic Compounds (SVOCs)	EPA 8270C	EPA 8270C	EPA TO-13 ¹	EPA TO-13 ¹
Diesel Range Organics (DRO)	EPA 8015M	EPA 8015M	EPA TO-13 Mod.	EPA TO-13 Mod.
C2 to C10 Hydrocarbons	NA	NA	EPA TO-3	EPA TO-3
Fixed Gases ²	NA	NA	ASTM D1946	ASTM D1946

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 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

Compound	Locations Above LNAPL			Locations Outside LNAPL But Above Contaminated Soil		
	LNAPL to Deep Soil Gas	Deep Soil Gas to Shallow Soil Gas	Shallow Soil Gas to Indoor Air	Deep Soil to Deep Soil Gas	Deep Soil Gas to Shallow Soil Gas	Shallow Soil Gas to Indoor Air
1,2,4-Trimethylbenzene	0.0127	0.0077	0.0026	8.34	0.0270	0.0026
1,3,5-Trimethylbenzene	0.0194	0.0153	0.0023	7.24	0.0338	0.0013
4-Isopropyltoluene	NA	0.1000	0.0044	4.49	0.0879	0.0018
Benzene	NA	0.0186	0.0231	157	0.0022	0.4789
Ethylbenzene	0.0631	0.0031	0.0130	51.0	0.0077	0.0139
Isopropylbenzene	0.0281	0.0155	0.0070	22.6	0.0407	0.0052
Naphthalene	0.0033	0.0609	0.0020	4.12	0.0480	0.0018
n-Butylbenzene	NA	0.0333	0.0015	6.64	0.0421	0.0018
n-Propylbenzene	0.0242	0.0057	0.0045	17.6	0.0224	0.0043
sec-Butylbenzene	0.0132	0.0564	0.0015	3.02	0.0662	0.0048
Toluene	NA	0.0206	0.4256	NA	0.0762	0.6791
Xylenes (total)	0.0572	0.0045	0.0103	59.7	0.0150	0.0085
1,2,3-Trimethylbenzene	NA	0.0194	0.0023	NA	0.0279	0.0022
2-Ethyltoluene	NA	0.0720	0.0004	NA	0.0317	0.0015
4-Ethyltoluene	NA	0.0094	0.0019	NA	0.0274	0.0022
Methane	NA	0.0870	0.0018	NA	0.0512	0.0068
Average	0.0276	0.0331	0.0315	31.1	0.0379	0.0761
Minimum	0.0033	0.0031	0.0004	3.02	0.0022	0.0013
Maximum	0.0631	0.1000	0.4256	157	0.0879	0.6791

Table 3. Monitoring Results for Locations Above LNAPL

Compound	Average LNAPL ug/L n=2	Deep Soil ug/kg n=1	Shallow Soil ug/kg n=1	Deep Soil Gas ug/m ³ n=1	Shallow Soil Gas ug/m ³ n=1	Average Indoor Air ug/m ³ n=6	Average Outdoor Air ug/m ³ n=3	"Background" Indoor Air ug/m ³ n=1
1,2,4-Trimethylbenzene	7,500,000	21000	19	95,000	730	1.9	0.51	2.8
1,3,5-Trimethylbenzene	1,545,000	6700	27	30,000	460	1.0	<2	0.71
4-Isopropyltoluene	NA	1800	13	2,600	260	1.1	<2.2	2.2
Benzene	<200,000	1000	6.6	8,600	160	3.7	2.7	2.7
Ethylbenzene	666,000	1400	6.6	42,000	130	1.7	0.57	1.3
Isopropylbenzene	228,000	460	1.2	6,400	99	0.69	<2	0.76
Naphthalene	2,655,000	9100	4.9	8,700	530	1.0	<2.6	<2.6
n-Butylbenzene	NA	4100	12	12,000	400	0.59	<2.2	0.78
n-Propylbenzene	952,000	2000	6.6	23,000	130	0.58	0.28	1.2
sec-Butylbenzene	296,000	1300	12	3,900	220	0.33	<2.2	0.56
Toluene	<200,000	1000	6.6	6,300	130	55.3	8.6	79
Xylenes (total)	2,780,000	6800	7.4	159,000	720	7.4	2.4	5.1
1,2,3-Trimethylbenzene	NA	NA	NA	36,000	700	1.6	<2	1.9
2-Ethyltoluene	NA	NA	NA	25,000	1,800	0.76	0.18	0.9
4-Ethyltoluene	NA	NA	NA	89,000	840	1.6	0.53	2
Methane	NA	NA	NA	23%	2.00%	0.0036%	0.0056%	0.0003%
Averages exclude non-detects								

Table 4. Monitoring Data for Locations Outside LNAPL, Above Soil Contamination

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

Table 5. Detection of Diesel-Related Compounds in Various Media

Compound	Soil*	Groundwater	Deep Soil Gas	Shallow Soil Gas	Indoor Air	Background Indoor Air	Outdoor Air
Benzene	X	X	X	X	X	X	X
Toluene	X	X	X	X	X	X	X
Ethylbenzene	X	X	X	X	X	X	X
Xylenes (total)	X	X	X	X	X	X	X
1,2,3-Trimethylbenzene	NA	NA	X	X	X	X	
1,2,4-Trimethylbenzene	X	X	X	X	X	X	X
1,3,5-Trimethylbenzene	X	X	X	X	X	X	
n-Propylbenzene	X	X	X	X	X	X	X
Isopropylbenzene	X	X	X	X	X	X	
2-Ethyltoluene	NA	NA	X	X	X	X	X
4-Ethyltoluene	NA	NA	X	X	X	X	X
n-Butylbenzene	X		X	X	X	X	
Sec-butylbenzene	X	X	X	X	X	X	
p-Isopropyltoluene	X	X	X	X	X	X	
Naphthalene	X	X	X	X	X		
2-Methylnaphthalene	X	X	NA	NA	NA	NA	NA
Acenaphthene	X	X	X	X			
Fluorene	X	X					
Phenanthrene	X	X					
Anthracene	X						
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.

Principal Engineer, Environmental Resources Management - South, Inc., Miami, Florida, 1985 to 1993.

Senior Engineer, Environmental Science and Engineering, Gainesville and Miami, Florida, 1974 to 1985.

Graduate Student, Rochester Institute of Technology, New York and University of Florida, Florida, 1971 to 1974.

Captain, U.S. Army Signal Corps, Engineering and Management, 1967 to 1971.

INDOOR AIR/ VAPOR INTRUSION INVESTIGATION & MITIGATION PROJECTS

VAPOR INTRUSTION 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION MITIGATION DESIGN, COMMERCIAL BUILDING, LYNDBURST, 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION 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 INTRUSTION 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.

DEVELOPMENT OF NPDES GUIDELINES FOR THE U.S. EPA, 1975-1985

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.

PESTICIDE WASTEWATER TREATMENT STUDY, NORTH CAROLINA, FOR THE US EPA, 1980-1982

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 I 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 I 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 Technologies 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, Plaintiffs, 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

- Kurtz, J. and Cowart, Jim. 2011. Application of Indoor Air Mitigation System Influent/Effluent to Mitigation System Termination at the CDOT MTL Site, Denver, Colorado. 21st Annual West Coast Conference on Soils, Sediments, and Water. Association of Environmental and Health Sciences. March, 2011, San Diego, California.
- Kurtz, J. and Cowart, Jim. 2010. Correlation and Applications of Indoor Air Mitigation System Influent from the CDOT MTL Site, Denver, Colorado. Vapor Intrusion 2010, Air and Waste Management Association, Chicago, Illinois.
- Cowart, Jim, Kurtz, J.P., and Breyer, L.M. 2010. Vapor Intrusion Flux of Methane and VOCs at Commercial Buildings Overlying a Landfill. 7th Battelle Conference on Remediation. May, 2010, Monterey, California.
- Cowart, Jim. & Breyer, L. 2009. Vapor Intrusion Mitigation: Design and Operation at Large Commercial Buildings. 19th Annual West Coast Conference on Soils, Sediments, and Water. Association of Environmental and Health Sciences. March 9-12, 2009, San Diego, California.
- Breyer, L. & Cowart, Jim. 2009. Vapor Intrusion and Methane: Criteria for Worker and Occupant Protection. 19th Annual West Coast Conference on Soils, Sediments, and Water. Association of Environmental and Health Sciences. March 9-12, 2009, San Diego, California.
- Cowart, Jim. & Ash, Julie. 2008. Ecological Approach Used to Remediate Former Mining Site. U.S. Environmental Protection Agency Technology News and Trends. July, 2008.
- Cowart, Jim. 2007. Environmental Reclamation at the Burlington Mine, Jamestown, Colorado. Presentation for the Boulder Creek Watershed Initiative Environmental Forum Series, Boulder Public Library, Colorado.
- 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.
- Cowart, J. & Breyer, L. 2005. Vapor Intrusion at a Diesel LNAPL Site. USEPA Annual RCRA Hazardous Waste Conference. Poster Session. Denver, Colorado.
- Cowart, J. & Breyer, L. 2004. Attenuation Factors for Hydrocarbons Associated with a Diesel Spill. Vapor Intrusion Attenuation Workshop. 14th Annual West Coast Conference on Soils, Sediments, and Water. March 15-18, 2004, San Diego, California.
- Cowart, J. & Kurtz, J. 2004. Measured Versus Model-Predicted Vapor Intrusion Attenuation at a Site in Littleton, Colorado. Vapor Intrusion Attenuation Workshop. 14th Annual West Coast Conference on Soils, Sediments, and Water. March 15-18, 2004, San Diego, California.
- Cowart, James B. et. al. 2004. Burlington Mine Site Voluntary Cleanup: Innovative Design for Mine Site Reclamation. American Society of Civil Engineers-Colorado Section, 2004 Biennial Geotechnical Seminar.
- Cowart, J.B. & Levin, M. 2004. 3-D Mine Mapping Drives Cleanup Design and Closure, Burlington Fluorspar Mine Site, Jamestown, Colorado. Tailings and Mine Waste '04. Balkema Publishers, London.
- Cowart, J.B. & Milne, J. 2004. Remediation of 25 Million Gallons of Acidic Groundwater, Nacimiento Copper Mine Site, Cuba, New Mexico. Tailings and Mine Waste '04. Balkema Publishers, London.
- Cowart, James B. et. al. 2004. Burlington Mine Site Voluntary Cleanup: An Ecologically-Based Approach to Mine Site Remediation. Newsletter of the Colorado Riparian Association, Volume 15, Number 2, Summer 2004.
- Cowart, J. PE, A Barnard, CIH, CSP, and L Breyer, CIH. 2002. "Risks to Indoor Air Quality from Volatile Organic Compounds in Groundwater." Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Monterey, California, June 30 - July 5, 2002.
- Cowart, James B., et. al. 2000. Volatile Organic Compounds in Indoor Air from Ground Water Sources. 16th International Conference on Contaminated Soils and Water. Amherst, Massachusetts.
- Cowart, James B., et. al. 2000. Design and Performance of Indoor Air VOC Mitigation Systems. 16th International Conference on Contaminated Soils and Water. Amherst, Massachusetts.
- U.S. Environmental Protection Agency. 1983. Methods for Non-conventional Pesticide Analysis of Industrial and Municipal Wastewater. Washington, D.C. EPA 440/1-83/079c. James Cowart, Project Manager.
- U.S. Environmental Protection Agency. 1982. Development Document for Effluent Limitations Guidelines for Expanded Best Practicable Control Technology, Best Conventional Pollutant Control Technology, Best Available Technology, New Source Performance Technology, and Pretreatment Technology in the Pesticide Chemicals Industry. Washington, D.C. EPA 440/1-82/079-b. James Cowart, Project Manager.

- Cowart, J. & Jett, G. 1980. State of the Art: Wastewater Treatment in the Pesticide Industry. Water and Wastewater Equipment Manufacturers. Eighth Annual Industrial Pollution Conference. Houston, Texas.
- U.S. Environmental Protection Agency. 1976. Development Document for Interim Final Effluent Limitations Guidelines for the Pesticides Chemicals Industry. Washington, D.C. EPA 440/1-75-060d. James Cowart, Project Manager.
- U.S. Environmental Protection Agency. 1975. Development Document for Effluent Limitations Guidelines and New Source Performance Standards. Miscellaneous Foods and Beverages Point Source Category. Washington, D.C. PB95-133252. James Cowart, Project Manager, Malt Beverage, Wine, Distilled Spirits, Soft Drink, Pectin and Hydrolyzed Vegetable Protein industries.

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? 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

Date

Printed Name

James B.

Affiliation/Organization

Cowart

Check here if any explanation is attached

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'

DAVID J. FOLKES, P.E.
ENVIROGROUP LIMITED
CURRICULUM VITAE
October 2011

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.

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 reviewer of vapor intrusion guidance documents for New Jersey DEP, California DTSC, Washington DOE, Minnesota DEP, Illinois EPA, Wyoming DEQ, and Colorado OPS.
- 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).
- 2011 Invited Chair, Battelle International Symposium on Bioremediation and Sustainable Environmental Technologies, vapor intrusion mitigation session, Reno Nevada, June 27-30, 2011.
- 2010 Invited speaker, American Industrial Hygiene Conference and Exhibition, on use of aerated floor systems for vapor intrusion mitigation, Denver, Colorado, May 24, 2010.
- 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.
- 2009 Invited speaker, EPA Region 3 Forum on Vapor Intrusion, on new developments in vapor intrusion mitigation, Philadelphia, PA, January 12-13, 2009.
- 2008 Invited external peer reviewer, California EPA, DTSC *Vapor Intrusion Mitigation Advisory*, December 2008.
- 2008 Invited speaker, Society for Risk Analysis Annual Meeting, on variances in state approaches to vapor intrusion guidance, Boston, MA, December 2008.
- 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, New England Waste Management Officials Association and Brown University, on mitigation of commercial buildings, Westford MA and Brown University, Providence RI, September 2008.
- 2008 Invited speaker, American Industrial Hygiene Conference and Expo, on vapor intrusion mitigation, Minneapolis, MN, June 2008.
- 2008 Invited speaker, Air Force Center for Environmental Excellence, on vapor intrusion mitigation, San Antonio, TX, March 2008.
- 2008 Invited reviewer, vapor intrusion portions of the ASHRAE *Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., February 2008 Draft.

- 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.
- 2008 Invited speaker, Colorado Hazardous Waste Management Society, on the *ASTM Standard Practice for Assessment of Vapor Intrusion into Structures on Property Involved in Real Estate Transactions*, Denver, January 2008.
- 2007 Invited reviewer, Colorado *Petroleum Hydrocarbon Vapor Intrusion Guidance Document*, published December 11, 2007, Colorado Department of Labor and Employment, Division of Oil and Public Safety, Remediation Section.
- 2007 Invited speaker, ACI 2nd Annual Conference on Chemical Products Liability Litigation, on evaluation of vapor intrusion claims, Chicago, IL, November 2007.
- 2007 Invited speaker, National Brownfields Association Brownfields Conference, on the Vapor Intrusion Assessment Tiered Process under the ASTM Vapor Intrusion Standard, Chicago, IL, October 2007.
- 2007 Invited session chair, AWMA Vapor Intrusion Conference on Vapor Intrusion, Providence, RI September 26-28, 2007.
- 2007 Invited speaker, State Bar of California Environmental Law Section 12th Annual Spring Roundtable on Contaminated Sites, on evaluating and managing vapor intrusion risks, Long Beach, CA, June 8-10, 2007.
- 2006 Invited speaker, University Consortium 2006 Focus Meeting, Subsurface Vapor Migration, State of the Science and Research Needs, on Use of Indoor Air Data for Vapor Intrusion Evaluations, Denver, CO, November 2006.
- 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, Air and Waste Management Association, Seminar on Vapor Intrusion, Vapor Intrusion Control Strategies at Large Commercial/Industrial Sites, Philadelphia, January 2006.
- 2006 Invited speaker, Northeast Waste Management Officials Association (Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, New Jersey), vapor intrusion training session, Chelmsford, MA, April 2006
- 2006 Invited speaker, RTM Brownfields seminar, vapor intrusion case history, Washington D.C., March 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 Invited speaker, Severn Trent Laboratories seminars on Technical Guidance for Indoor Air Vapor Intrusion, Los Angeles CA and Oakland CA, February 2005.
- 2005 Invited speaker, New Jersey Department of Environmental Protection, Vapor Intrusion – Real World Observations and Lessons Learned, Trenton, NJ, August 2005.
- 2005 Invited speaker, Brownfields 2005, vapor intrusion case history, Denver, CO, November 3, 2005.
- 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
- 2002 invited speaker, EPA indoor air vapor intrusion guidance training seminars, San Francisco (2002), Dallas (2003) and Atlanta (2003).
- 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.
- 1999 invited speaker, Lead Industries Association, 21st Annual Lead Occupational Health and Environmental Protection Conference, Whitefish, Montana.
- 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

- 1993 faculty member, CLE International Seminar on Hazardous Waste Cleanup, Denver, Colorado, May 20-21, 1993
- 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
- 1991 invited speaker, 1991 Rocky Mountain Energy Conference, Environmental Implementation Issues, Practical Strategies for the Oil and Gas Industry, 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"
- 1986 invited speaker, Rocky Mountain Underground Storage Tank Conference, on "Subsurface Migration of Petroleum Hydrocarbons", Denver, July 1986
- 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, Fredericton, 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
- 1983 - 1985 Senior Geotechnical Engineer/Office Manager, D.R. Piteau and Associates, Inc.
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 **Mt Holly, New Jersey**, including soil vapor and indoor air testing. The results of tests and lines of evidence evaluation indicated that and 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 of 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

project.

Expert witness for defendant, class action lawsuit regarding potential for vapor intrusion due to PCE in groundwater in residential areas downgradient 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 downgradient 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.

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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”

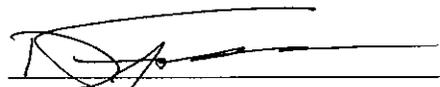
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- Did you contribute to the development of the document under peer review, or were you consulted during its development, or did you offer comments or suggestions to any drafts or versions of the document during its development? No Yes
- Do you know 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

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- (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.


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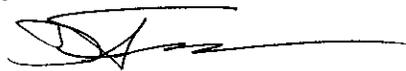
4/18/12
Date

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see reverse

DAVID FOLKES
Printed Name

ENVIROGROUP LIMITED
Affiliation/Organization

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.

A handwritten signature in black ink, consisting of a stylized, cursive name followed by a horizontal line.

EnviroGroup Limited

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 Monitoring & Remediation*, V. 30, No. 3, p. 107-112.
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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"

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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:

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Signature: [Handwritten Signature] Date: 4/18/12

Printed Name: Jeffrey P. Kurtz

Affiliation/Organization: Enviro Group Limited

[] Check here if any explanation is attached

GENERAL COMMENTS

Draft Report: Evaluation of Empirical Data and Modeling Studies to Support Soil Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Compounds 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 pre-emptive 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., $X \pm Y$), 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.

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— add
 O₂/CH₄
 FID
 Soil Staining
 Odor
 Redox as evidenced by mineral precipitates

not everyone uses this term

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.

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212 N = 216.67
213
214

*low many
NO
values
had
elevated
reporting?
limits?
These
should
not
be
considered
"clean".*

*oxygen levels detection almost
never happens!*

215 **1. Introduction**

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

*This has at least 3 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?*

225 **1.1 Background**

226 In support of its general guidance development effort for the VI exposure pathway, U.S.
227 EPA has compiled an empirical database of paired measurements of subsurface media
228 (groundwater, soil gas) and indoor air concentrations, which consists primarily of data for
229 chlorinated solvent chemicals, with very limited data for PHC compounds (approximately
230 3 percent of the database) (U.S. EPA, 2012a). The study discussed in this document is
231 exclusively directed at PHCs and only analyzes subsurface media (soil gas, soil, and
232 groundwater) concentrations and other supporting data for PHCs. The rationale for this focus on
233 subsurface PHC measurements is that PHC vapors can rapidly biodegrade in the presence of
234 oxygen and attenuate to much lower concentrations in soil gas (U.S. EPA, 2011).

If seems like the focus is only on item #2.

chlorinated compounds; therefore screening PHCs using the same methodology as

235 Because the bioattenuation process is well documented and widespread (U.S. EPA,
236 2011), the analysis of subsurface soil gas data from sites provides an opportunity for developing
237 improved and more realistic screening evaluation methods for PHC compounds based on the
238 observed attenuation. These data can be used to identify “an exclusion distance,” defined in this
239 report as the contamination source-separation distance at which the potential for PVI is deemed
240 negligible. This exclusion distance, and much of the underlying data on which it is based,
241 primarily stems from the work of Robin Davis, a regulator with the Utah Department of
242 Environment’s UST program (see Davis, 2009, 2010, 2011a, and 2011b).

CI VOCs is overly conservative and risks waste of resources.

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

combine

250 In addition, several similar parallel efforts are in progress in this country (Lahvis et al., In
251 prep.; Peargin and Kolhatkar, 2011), and Australia (Wright, 2011, 2012) using somewhat
252 different data sets than the one used in this document. Regarding these complementary database
253 evaluations, the benzene data from sites in the United States and Canada are identical for this

elaborate on how and why this is useful, how it fits into a screening program and how it improves on the existing status quo

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.

254 database study and the Lahvis et al. (In prep.) effort. The main differences between Lahvis et al.
 255 (In prep.) and this U.S. EPA study are that:

- 256 1. The Lahvis et al. (In prep.) study includes data from sites in Wright’s (2011)
 257 Australian database, whereas the U.S. EPA database does not¹.
- 258 2. The U.S. EPA database includes a more extensive evaluation of a range of chemicals,
 259 including aromatic and aliphatic hydrocarbon fractions, whereas the focus of Lahvis
 260 et al. (In prep.) is benzene vapor attenuation.

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

263 **1.2 Goals and Objectives**

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

these are two different things. Need to make sure you address both of them

- 268 1. Sites with a relatively high potential for a complete PVI pathway² and possible
 269 unacceptable risks.
- 270 2. Sites with a relatively high potential for an incomplete PVI pathway.
- 271 3. Sites with an unknown potential for a complete PVI pathway and risk, thus requiring
 272 further assessment.

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

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

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!

- 281 To develop and support the exclusion distances, the objectives of this study were to:
- 282 • Assemble an empirical database from petroleum release sites where the PVI pathway
 283 has been evaluated via primarily soil gas and groundwater measurements;
 - 284 • Consolidate and independently check existing databases and enter and check newly
 285 available data;

labs can quantify to parts per trillion. That's not necessary or appropriate.

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.

Calore RBSLs!

- 286 • Analyze the database and available case studies to determine when and under what
287 conditions there is the potential for a complete PVI pathway at a site;
- 288 • Review published modeling studies on PHC vapor transport and intrusion as a
289 supporting line-of-evidence; and
- 290 • Identify methods and criteria that can be used to exclude (and include) petroleum
291 release sites from further PVI investigation and concern.

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

292 **1.3 Document Organization**

293 This report is organized as follows:

- 294 • Section 2 describes the conceptual site model (CSM) for aerobic biodegradation of
295 PHC vapors and select case studies where PVI has been documented.
- 296 • Section 3 provides a review of select modeling studies of the biodegradation of PHCs
297 in the subsurface.
- 298 • Section 4 provides a review of empirical database studies of PHC vapor attenuation.
- 299 • Section 5 provides a review of exclusion distances for PVI in existing state VI
300 guidance.
- 301 • Section 6 describes the PVI database development, structure, and content.
- 302 • Section 7 describes the PVI database analysis approach and methods.
- 303 • Section 8 describes the PVI database analysis results.
- 304 • Section 9 provides a discussion of the results and comparisons with other studies.
- 305 • Section 10 provides conclusions drawn based on this study.

306 **2. Conceptual Site Model and Select Case Studies**

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

311 **2.1 Aerobic Biodegradation Processes**

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

need to also discuss methanogenesis, CH4 impact on O2 demand, potential for explosion, etc., partially light, non aqueous phase liquids or

319 Volatilization of PHCs will occur from both LNAPL and dissolved (groundwater)
320 hydrocarbon sources. Methane and carbon dioxide gas may be generated through microbial

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This should not be ³ under this heading. create a new section, and cover the anaerobic processes more completely.

are there no other citations for rates?

321 breakdown of PHC compounds in anaerobic source zones. Fuel oxygenates, such as ethanol and
322 methyl tert-butyl ether (MTBE), can also be present in the vapor phase in the unsaturated zone
323 proximate to LNAPL source zones.

need a tie-in sentence - how is this relevant?

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

vague: use more specific terms, 1000-fold reduction over 1m or so

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

if this doesn't get published, why not spell out the flux balance concept here?

is advection important? is it just one process? or many?

343 **2.2 Factors Influencing Aerobic Biodegradation**

vague

344 Biodegradation of petroleum hydrocarbons has been reported in more than 70 years of
345 publications (ZoBell, 1946; Atlas, 1981; Leahy and Colwell, 1990), including PHC liquids and
346 gases; straight, branched, and ring-structure PHC compounds with single and multiple carbon
347 bonds; by many microbial species, including 30+ genera of bacteria, 25+ genera of fungi, and
348 several algae (although not every chemical is degraded by every microbial species); in marine,
349 freshwater, sediment, and soils environments; and in direct metabolism and co-metabolism (co-
350 oxidation). Microbial degradation of petroleum produces biomass, intermediate products
351 (alcohols, aldehydes, organic acids), and the ultimate mineralization products carbon dioxide
352 (CO₂) and water (H₂O). In general, relatively fast acclimation times are observed, absent other
353 limits, by population enrichment (fast biomass growth) and/or plasmid transfer. Acclimation
354 times tend to be shorter with prior chemical exposure. Environmental conditions under which
355 petroleum biodegradation has been observed range from 0° to 70°C, salinity up to 25 parts per
356 thousand sodium chloride (NaCl), and pH from 6 to 10, although optimum conditions can be
357 narrower. Aerobic biodegradation is the primary mechanism in the unsaturated zone, but
358 anaerobic biodegradation near source zones may also occur through other electron acceptors
359 present (nitrate, sulfate, etc.) (strict or facilitative), or under fermentative or methanogenic
360 conditions (DeVaul et al., 1997; Madigan et al., 2010). There have been extensive compilations
361 of rates of aerobic degradation specific to vadose zone aerobic soils (e.g., DeVaul et al., 1997;
362 Hers et al., 2000; Ririe et al., 2002; Davis et al., 2009; DeVaul, 2011).

Lots of information here, and no discussion of whether any of these factors need to be measured

Does Larson + Humber address rates? (1996)

(and if so, how?), or if not, why not.

May 3, 2012

Contractor Draft - Do not Distribute or Cite

This section needs to be restructured. Currently there are 3 paragraphs. The first talks about everything, without saying what matters, the second says nothing matters, and the third says what REALLY matters, without saying what is needed to provide enough data on these factors.

363 The U.S. Air Force Bioventing Initiative study of 125 sites indicated that environmental
364 factors, such as soil moisture, nutrients, and pH, did not significantly influence biodegradation
365 activity and respiration rates, except for one site located in the Mohave Desert with very dry soils
366 (moisture content of 2 percent), although some biological activity did still occur at this moisture
367 content (Leeson and Hinchee, 1996). Biological activity is limited when the moisture content is
368 at or below the permanent wilting point (Zwick et al., 1995; Holden et al., 1997), which is
369 expected to be rare in most geological and climatic environments (note that the empirical
370 database for this project includes sites in dry areas).

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

- 374 • Vapor source hydrocarbon concentration, flux, and composition (including methane);
- 375 • Oxygen demand (i.e., the oxygen required to biodegrade the available hydrocarbons
376 and any other organic matter that is present); *and supply (i.e., flux balance);*
- 377 • Distance between the vapor source and the building;
- 378 • Soil type and properties; and *porosity and moisture content (not sure which other properties matter)*
- 379 • Size and characteristics of the building and adjacent land surface.

380 2.3 Dissolved versus LNAPL Vapor Sources

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

need to say how each of these must be characterized as part of a PVI screening process. What is an acceptable level of uncertainty? explain!

395 The differences in the PHC vapor concentrations and fluxes for LNAPL and dissolved
396 vapor sources are an important distinction for defining exclusion distances (**Figure 1**).
397 Conceptually, the source type (dissolved or LNAPL) will affect the position of the aerobic
398 reaction front in the unsaturated zone relative to the oxygen source. For dissolved sources, the
399 reaction front will be located close to the hydrocarbon source (Roggemans et al., 2001; Golder
400 Associates, 2006; Abreu et al., 2009), while for LNAPL sources, the reaction front position is
401 more variable, but typically is located at greater distances from the source compared with
402 dissolved sources (Roggemans et al., 2001; Golder Associates, 2006; Abreu et al., 2009). For

403 dissolved vapor sources, case study ^{studies} meta analyses and ^{define} database evaluations reported in the
404 literature indicate no confirmed cases of PVI for a wide range of site conditions (Davis, 2009;
405 McHugh et al., 2010).

expand on LNAPL sources - distinguish between vadose zone and spread zone, high and low water table

406 **2.4 Conditions for Increased Potential for Petroleum Vapor Intrusion**

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

409 • *Direct contact between contamination (either dissolved or LNAPL) and a building*
410 *foundation.* Most documented cases of PVI are for this condition (McHugh et al.,
411 2010).

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

concentration, oxygen supply and oxygen demand

416 • *Preferential transport pathways.* If a ^{define} preferential pathway connects a contamination
417 source to a building, the chemical transport can be faster and extend farther than
418 transport through the surrounding soils.

need ΔP in addition to high gas K

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

what about wet clay (outside building) and dry, desiccated and fractured clay beneath the building?

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

vague

compare and contrast this to the last in line 374-637? why have both?

Some amount of data is pretty critical. There needs to be some guidance on "how do you know" whether

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any of these conditions are present. i.e., number, spacing frequency of data, collection methods, etc. decision criteria

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445

been an issue. Concentrations of methane above the lower explosive limit can present a flammability and explosion risk.

what about anaerobic conditions? particularly under buildings? — CH₄ flux vs O₂ flux when does CH₄ win?

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

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Confirmed occurrences of subsurface vapor intrusion to indoor air or elevated subsurface 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.

effect of barometric inversions

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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).

add McAlamy et al 2011 Michaelsh et al 2010

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

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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.

at what depths?

474
475

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

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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.

and nothing else?

483 **2.5.3 Refinery Site, Casper, Wyoming (Luo et al., 2009)**

484 Monitoring at a site in Casper, Wyoming, indicated a complete PVI pathway at a refinery
485 site with a light distillate (gasoline-range) LNAPL source. LNAPL contamination was present in
486 the unsaturated zone at depths between about 1 and 5 ft (0.3 and 1.5 m²) below a small
487 warehouse-type building with a slab-on-grade foundation. Monitoring of subslab soil gas
488 indicated oxygen was depleted (<1 percent) below the interior regions of the building, but not
489 below the edges of the building.

490 **2.5.4 Former Refinery Site (Unknown location) (Luo et al., 2010)**

491 Monitoring at a former refinery site (unknown location) with a building overlying a light
492 distillate (gasoline-range) LNAPL source indicated relatively uniform and elevated (60 to
493 160 mg/L) PHC vapor concentrations and depleted oxygen beneath and around the building
494 foundation. The building footprint area is 2,100 ft² (195 m²) with a basement depth of 5 ft (1.5
495 m) bgs. The ground surface is predominantly grass covered, except on one side of the building
496 where there is an asphalt/concrete parking lot. Soils with LNAPLs were first encountered at
497 about 30 to 35 ft (9.1 to 10.7 m) bgs; therefore, the separation distance between the building
498 foundation and contamination (LNAPL) is approximately 25 to 30 ft (7.6 to 9.1 m). Detailed soil
499 respiration and soil-air permeability test results suggest two possible reasons for the observed
500 behavior: 1) significant background oxygen uptake in surface soils and/or 2) physically limited
501 oxygen transport from the atmosphere. Soil oxygen uptake rates in shallow soil ranged from 2 to
502 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
503 to 8 ft (2.1 to 2.4 m) bgs, both with soil-air permeabilities of less than 1 × 10⁻¹⁴ m². The results
504 from Luo et al. (2010) suggest both of these reasons are plausible.

505 **2.5.5 Refinery Site, Hartford, Illinois (Illinois Department of Public Health, 2010)**

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

510 **2.5.6 UST Site, Stafford, New Jersey (Sanders and Hers, 2006)**

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

not near the saw-cut expansion joints during times of positive ΔP

vague

I've also seen sites where vapor concentrations increase during periods of low water table. EXPLAIN WHY BOTH

can occur

Michalski et al 2010

do you mean slower degradation rates? so why was this one building worse? Does that factor also need to be characterized?

519 **2.5.7 UST Site, Ogden, Utah, Mini-Mart Release (McHugh et al., 2010)**

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

} expand
soil type,
source
depth,
building
size,
etc.

523 **2.5.8 UST Site, Gunnison, Utah, Top Stop Release (McHugh et al., 2010)**

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

i.e. beyond the LNAPL distribution

531 **3. Review of Modeling Studies**

surely, there's more than just PID data

532 Numerous modeling studies of aerobic biodegradation have been conducted to evaluate
533 biodegradation processes, identify factors influencing biodegradation, compare modeled to
534 predicted hydrocarbon vapor attenuation, and estimate first-order biodegradation rates (e.g., Jury
535 et al., 1983; Lahvis and Baehr, 1999; Hers et al., 2000; Ririe et al., 2002; Grathwohl and Maier,
536 2002; Robinson and Turczynowicz, 2005; Abreu and Johnson, 2005; Abreu and Johnson, 2006;
537 DeVaul, 2007b; Abreu et al., 2009; Davis et al., 2009; DeVaul, 2011; Hers et al., 2012; U.S.
538 EPA, 2012b).

} one sentence does not make a paragraph

why only these 3? Ethylbenzene? MTBE? 124 TMB?

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

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

vague wording

553 **3.1 Abreu Three-Dimensional Model Simulations**

554 Abreu and Johnson (2005) present the theoretical basis for a three-dimensional model for
555 predicting soil vapor-to-indoor air attenuation factors incorporating subsurface processes of
556 diffusion, gas-phase advection through building depressurization, oxygen-limited first-order

557 biodecay, and uniform mixing of vapors entering a building. Subsequent three-dimensional
558 modeling studies of interest are summarized below.

The model has been used in several studies (A+J 2005, A et al 2009, USEPA 2012)

559 **3.1.1 Three-Dimensional Model Simulations—Below-Building Contamination Source and**
560 **Homogeneous Soil Conditions**

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

Fluctuations occur (very common)

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

What would be necessary and sufficient data to confirm or refute whether this condition is important for a given site? This should be part of the screening process.

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

overestimate PVI potential? Can't say this without considering CH4 simulations likely

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

Compare to Michaelski et al 2010

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

This is a good example of vague wording

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being clarified with a quantitative statement. Please do the same where comment "vague" is used elsewhere.

598 **3.1.2 Three-Dimensional Model Simulations—Lateral Migration Scenario and**
599 **Homogeneous Soil Conditions**

600 U.S. EPA (2012b) presents a modeling study of conceptual model scenarios for the VI
601 pathway where the Abreu and Johnson (2005) model was used for a range of simulation
602 scenarios, including oxygen-limited aerobic biodegradation of PHC compound vapors (using
603 benzene as a surrogate for TPH). The building assumptions in U.S. EPA (2012b) are similar to
604 those described in Abreu et al. (2009). One of the scenarios evaluated was the influence of PHC
605 source and building lateral separation distance on the predicted vapor attenuation factor. The
606 simulations were conducted for a TPH vapor concentration of 200 mg/L, a 2-m (6.6 ft) deep
607 basement, two contamination source depths (3 m and 8 m [9.8 ft and 26 ft] bgs), and a range of
608 first-order decay rates (0.018, 0.18, and 1.8 h⁻¹). The predicted vapor attenuation factors decrease
609 rapidly as the lateral distance increases. For example, the vapor attenuation factor for a shallow
610 LNAPL source that is offset approximately 15 ft (4.6 m) from the edge of the building is 1 × 10⁻⁶
611 for a decay rate of 0.018 h⁻¹ and less than 1 × 10⁻¹⁰ for a decay rate of 0.18 h⁻¹. The vapor
612 attenuation factor for a shallow below-building LNAPL source and same biodecay rate is
613 approximately 1 × 10⁻³. A key point is that there is greater attenuation, and hence lower vapor
614 attenuation factors, for the lateral compared with vertical building-contamination source
615 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 PVI screening protocol? If not, why not?

616 **3.1.3 Three-Dimensional Model Simulations—Surface Capping Scenario**

617 U.S. EPA (2012b) also presents aerobic biodegradation modeling simulations of the
618 influence of variable soil moisture and layered soil deposits, including a two-layer capping
619 scenario with a 1-m (3.3-ft) thick surface soil layer with higher moisture content (60 percent
620 saturation) underlain by a soil layer with a lower moisture content (20 percent saturation). The
621 hydrocarbon source for these simulations was located at 8-m (26-ft) depth, below a house with a
622 2-m (6.6-ft) deep basement. For a high source hydrocarbon vapor concentration (200 mg/L), the
623 attenuation factor predicted for the two-layer scenario was one order of magnitude greater than
624 the single-layer scenario (Table 2). For a lower source vapor concentration (2 mg/L), the vapor
625 attenuation factor for the two-layer scenario was 7.1 × 10⁻¹⁵. Although a single-layer simulation
626 was not performed for the lower source strength, the two-layer scenario attenuation factor is very
627 low and indicates essentially complete biodegradation, and the cap had no effect on the
628 hydrocarbon vapor attenuation below the building.

what if saturation was near 100% for a month (wet spring)?

629 **3.1.4 Comparison of Modeled to Measured Soil Vapor Concentration Data**

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

See McAlary et al 2011

Confidential

This indicates that it is essential to document the geology + soil moisture profile

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as part of a PVI screening process.

639 factor of approximately 100. The first-order rate incorporated in the Luo et al. (2010) model
 640 simulations was 0.18 h^{-1} .

641 3.2 DeVaul (2007b) Study (BioVapor Model Development)

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

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

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

664 3.3 DeVaul (2010) Study of BioVapor Application

665 DeVaul (2010) presents BioVapor model simulations where the sensitivity of the model
 666 predictions was evaluated for a residential house scenario, dissolved gasoline source
 667 concentrations, and a hydrocarbon vapor source–building separation distance of 5 ft (1.5 m). The
 668 model simulations, in part, were designed to provide insight on the applicability of the dissolved-
 669 source exclusion distance of 5 ft (1.5 m) proposed by Davis et al. (2009). The source
 670 groundwater concentrations were 1 mg/L benzene and 3 mg/L each for toluene, ethylbenzene,
 671 and xylenes, for a total benzene, toluene, and xylene source concentration of 10 mg/L. The
 672 source vapor concentrations were estimated from the Henry's Law constant and a groundwater-
 673 to-source vapor attenuation factor of 0.1, resulting in source benzene and total benzene, toluene,
 674 and xylene vapor concentrations of 12 mg/m^3 and 120 mg/m^3 , respectively. The oxygen mass
 675 transfer to below the building, a key model input parameter for the BioVapor model, was
 676 estimated from 13 studies where the soil gas advection rate and/or diffusive oxygen mass transfer
 677 rate were measured for small buildings.

deep soil

Are you assuming building
 acts like an accordion?
 i.e., $D_{\text{soil in}} = D_{\text{soil out}}$?

678 Devaul (2010) presents model-predicted indoor air concentrations as a function of the
 679 effective foundation airflow rate, which is conceptually easier to understand than the oxygen
 680 mass transfer rate (Figure 5). For modeling purposes, the foundation airflow rate is converted to
 681 an oxygen mass transfer rate. The model predicts low indoor air benzene concentrations (less
 682 than 1 µg/m³) for the range of effective foundation airflow rates considered. It is also instructive
 683 to note that the model results for recalcitrant non-degrading chemicals show an opposite trend in
 684 that the indoor air benzene concentration increases as the effective foundation airflow rate
 685 increases.

686 **3.4 Summary of Modeling Studies**

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

691 For LNAPL vapor sources, the Abreu et al. (2009) three-dimensional model simulations
 692 for a residential house scenario and homogeneous soil conditions predict that a vertical
 693 separation distance of 23 ft (7.0 m) or more is required for aerobic reaction front development
 694 within the unsaturated zone. The modeling results for smaller separation distances and an
 695 LNAPL source indicated the attenuation factor calculated by the model is sensitive to a surface
 696 capping effect. I'm not aware of any good data to show the surface capping effect and the model input were not validated.

697 The modeling results indicate further evaluation of factors potentially influencing oxygen
 698 supply and demand, such as source vapor concentration strength, building size, surface
 699 foundation and soil layer properties, and natural soil oxygen demand, is warranted for the
 700 LNAPL source scenario. I need to follow through with only estimated.

701 **4. Review of Empirical Database Studies of Petroleum Hydrocarbon**
 702 **Vapor Attenuation**

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

705 Davis (2009) obtained soil gas data from 53 geographical locations in the United States
 706 and Canada and from an analysis of 259 benzene and 210 TPH samples and then estimated that
 707 5 ft and 30 ft (1.5 m and 9.1 m) of vertical thicknesses of clean soil are required to significantly
 708 attenuate benzene and TPH vapors emanating from the dissolved-phase and LNAPL sources,
 709 respectively. Dissolved-phase sites were defined on the basis of benzene concentrations in
 710 groundwater < 1,000 µg/L. The data obtained by Davis (2009) are incorporated in this study.

711 Peargin and Kolhatkar (2011) evaluated 218 pairs of benzene soil vapor and groundwater
 712 concentration data from 25 sites. Data were categorized in bins based on 10⁻² to 10⁻⁶ excess
 713 cancer risk and assuming a soil vapor-to-indoor air attenuation factor of 0.01 (U.S. EPA, 2002).
 714 No benzene soil gas concentrations exceeding 300 µg/m³ (risk-based air concentration for 10⁻⁵
 715 cancer risk multiplied by 0.01) were observed at vertical separation distances greater than 15 ft
 716 (4.6 m). Benzene soil vapor concentrations exceeding 300 µg/m³ were only observed above

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how many of these were sampled from temporary probes vs slurry-sealed probes?

Handwritten notes and annotations:

- why?
- how? @soil = @soil out? → Justify (net neutral bldg with ΔP cycles from wind gusts, etc)
- Disagree quite strongly! You can calculate a source vapor concentration, multiply by a modeled factor and compare to RBSLs for indoor air very easily! In fact, you should correlate measured and modeled exclusion distances
- protocols for site characterization

717 groundwater sources where benzene concentrations exceeded 1,000 µg/L. The authors concluded
 718 that the data support a CSM where benzene vapor transport at concentrations exceeding target
 719 screening values can only occur where groundwater source concentrations are high, defined for
 720 this study as a dissolved benzene concentration greater than 1,000 µg/L. Some of the data
 721 analyzed by Peargin and Kolhatkar (2011) that were provided to Davis (2009) are incorporated
 722 in this study. [The remaining Peargin and Kolhatkar (2011) data were not readily accessible
 723 during the time frame of this study.] - *can you check again and add now?*

724 Wright (2011) presents data from 124 sites in Australia. There are 1,080 pairs of benzene
 725 soil vapor and groundwater concentration data; 41 percent of the data were obtained at sites with
 726 fractured rock aquifer systems and 12 percent represent data obtained below building
 727 foundations (i.e., subslab). The analysis resulted in vertical exclusion distances of 5 to 10 ft (1.5
 728 to 3.0 m) for relatively “low-strength” dissolved-phase sources (benzene < 1 mg/L and TPH
 729 < 10 mg/L), and ~30 ft (~10 m) for LNAPL and poorly characterized dissolved-phase sources
 730 (including sites with large building slabs). The lower threshold benzene and TPH soil vapor
 731 concentration for estimating the exclusion distances was based on 5 percent of the lowest
 732 Australian Health Screening Levels (Friebel and Nadebaum, 2011). None of the Australian data
 733 analyzed by Wright (2011) were incorporated in this study but are analyzed by Lahvis et al. (In
 734 prep). A preliminary analysis of the Australian data suggested that the conclusions of the
 735 empirical analysis would not change if the Australian data were included; therefore, the data
 736 were not incorporated into this study.

add papers by McAlroy + Michaelstik

how many vgl/m³?

737 **5. Review of Exclusion Distances in Existing Vapor Intrusion Guidance**

738 ~~Most regulatory approaches identify distances for determining when a PVI assessment is~~
 739 ~~not warranted—defined as “exclusion distances” in this report, although guidance on vertical and~~
 740 ~~lateral exclusion distances for PHCs based on detailed evaluations of empirical data and/or~~
 741 ~~modeling studies is a recent development.]~~ *6*

*3 ideas
∞ 3 sentences*

742 [Most states exclude sites from the need for VI assessments if they are more than a
 743 specified distance from the source of vapor contamination, which generally is the 100-ft (30-m)
 744 lateral distance, although guidance for New Hampshire, New Jersey, Connecticut, and
 745 Massachusetts includes a 15- to 30-ft (4.6- to 9.1-m) exclusion distance for aerobically
 746 biodegradable chemicals.³ The technical justification for the exclusion distance criteria is
 747 relatively limited or not provided in guidance by these jurisdictions.] *5*

*2 sentences
Re-sequence
+ groom*

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

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

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.

it isn't "free", really. Better to stick with one term: LNAPL

754 related free product contamination. As an alternative approach, NJ DEP (2012)
755 allows for an exclusion distance approach based on benzene concentrations for
756 gasoline contamination. A PVI investigation is not necessary if the vertical separation
757 distance between the water table (all references to water table are for seasonal high
758 conditions) and building slab is:

- 759 – At least 10 ft (3.0 m), for a benzene groundwater concentration $\leq 1,000$ $\mu\text{g/L}$;
- 760 – At least 5 ft (1.5 m), for a benzene groundwater concentration ≤ 100 $\mu\text{g/L}$; or
- 761 – At least 5 ft (1.5 m), for oxygen ≥ 2 percent (v/v) in the unsaturated zone, and a
762 benzene groundwater concentration $\leq 1,000$ $\mu\text{g/L}$.

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

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

773 – **Scenario 1—Unweathered LNAPL on groundwater:**

- 774 ■ A 30-ft (9.1-m) vertical bioattenuation zone between an unweathered LNAPL
775 (residual or free-phase) source and a building foundation.

776 – **Scenario 2—Unweathered LNAPL in soil:**

- 777 ■ A 30-ft (9.1 m) lateral and vertical separation distance between an
778 unweathered LNAPL (residual or free-phase) source in soil and a building
779 foundation.

780 – **Scenario 3—Dissolved phase benzene concentrations in groundwater:**

- 781 ■ With no oxygen measurements:

- 782 – A 5-ft (1.5 m) vertical separation distance between a dissolved-phase
783 benzene source < 100 µg/L and a building foundation.
- 784 – A 10-ft (3.0 m) vertical exclusion distance for a dissolved-phase benzene
785 source < 1,000 µg/L and a building foundation.
- 786 ■ With oxygen > 4 percent:
- 787 – A 5-ft (1.5 m) vertical separation distance between a dissolved-phase
788 benzene source < 1,000 µg/L and a building foundation.
- 789 – **Scenario 4—Direct measurement of soil gas concentrations:**
- 790 ■ Application of a bioattenuation (additional attenuation) factor of 1,000 times
791 to risk-based soil gas criteria (i.e., vapor sources) located within 5 ft (1.5 m) of
792 a building foundation.
- 793 • Wisconsin’s Department of Natural Resources (2010) in their guidance states that
794 where no petroleum odors are detected, PVI can be ruled out at most petroleum
795 release sites with low source concentrations where there is 5 ft (1.5 m) in the
796 horizontal and vertical direction of clean, unsaturated soil with an oxygen content
797 greater than or equal to 5 percent between the residual petroleum and the building.
798 Larger exclusion distances are specified when free product is present (30 ft [9.1 m])
799 or benzene concentrations in groundwater exceed 1 mg/L (20 ft [6.1 m]). When the
800 above distance thresholds and other criteria (e.g., no preferential pathways, no
801 fractured bedrock) are met, a PVI assessment is not required.

802 6. Database Development, Structure, and Content

803 6.1 Database Development and Checking

804 The starting point for the PVI database developed for this study is a database compiled by
805 Ms. Robin Davis of the State of Utah (the “Davis” database). Ms. Davis compiled data on PHC
806 vapor behavior from over 50 sites starting in 2003; the May 2011 version of the Davis database

807 was imported and used for this analysis. The Davis database includes information on primarily
808 groundwater and soil vapor chemistry, soil properties, and other site data.

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

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

821 6.2 Database Structure

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

827 The different data types are summarized as follows:

- 828 • **Background data:** Site location, geologic setting, contamination type, and generic
829 soil description.
- 830 • **Facility type:** UST, fuel terminal, petroleum refinery, and petrochemical plant.
- 831 • **Site conditions:** Soil type, water-filled and total porosity, and surface cover at soil
832 vapor probe (bare ground, asphaltic pavement, building).
- 833 • **Sampling data:** For each probe, vertical depth from ground surface to water table, to
834 top of contamination, and to media sampling locations. Lateral distance between soil
835 gas probe and groundwater monitoring well and between soil gas probe and UST
836 facility infrastructure (e.g., tanks, fuel dispensers) and buildings.
- 837 • **Analytical data:** Sampling date, analytical method, quality control data, and
838 chemistry data for soil, groundwater, and soil vapor. Analytes in the database are
839 fixed gases (oxygen, carbon dioxide, methane); benzene, toluene, and xylene; TPH;
840 naphthalene; MTBE; 1,3-butadiene; hexane; heptane; and aromatic and hydrocarbon
841 fractions according to methods prescribed by the State of Massachusetts.
- 842 • **Building data:** Building use (e.g., residential, commercial, institutional), foundation
843 type, and building size, for example.

Probe design, purging procedure, soil gas permeability and leak-check procedures

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without this, I have very little confidence in the data

844 As part of the data verification process, certain data quality indicators were reviewed to
 845 ensure data of known and acceptable quality. The database was processed to remove data of
 846 unacceptable quality or type, as follows: 1) analytical data obtained by unacceptable methods, or
 847 no reported methodology or evidence of quality assurance/quality control processes, to remove
 848 suspect quality data; 2) soil gas data from fractured rock systems due to the potential for
 849 preferential soil gas flow; 3) benzene concentrations in groundwater below detection level
 850 because it is not meaningful to conduct an analysis when no contamination source exists, and
 851 4) lateral spacing between groundwater monitoring well and soil gas probe (for paired data)
 852 greater than about 30 ft (9.1 m) because of variability in sources (this information was not
 853 available for all data).

This also claims that any method or evidence of QA/QC is enough, regardless of how detailed or whether it was followed.

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

That's not enough detail for me.

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

Temporary probes? low to soils? }

865 **6.3 Database Content**

How much, exactly?

866 The number of sites and site locations in the PVI database are listed in **Table 3**. The
 867 contents of the database for key fields are summarized in **Tables 4** and **5**. The majority of the
 868 sites are UST release sites, although the database also includes data from fuel terminals and
 869 petroleum refineries. Most sites were affected by gasoline releases, although a small number of
 870 sites have other types of PHC contamination (e.g., diesel, kerosene). The gasoline composition
 871 was unknown and assumed to be variable with respect to fuel oxygenate composition, given the
 872 relatively broad time span for data collection (1995 to 2011). Gasoline containing ethanol
 873 (10 percent vol/vol) was generally introduced to the United States in 2000 with a large increase
 874 in use in 2006 (U.S. EPA, 2009), so some sites in the database where recent releases occurred
 875 likely have gasoline containing ethanol.

of the two should never be used together, yet they often are.

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

why not say #/# (i.e. quantify)

880 The database is populated to varying degrees depending on the data type. It contains data
 881 for most sites and records on facility type, vertical distances, surface cover, soil type, and
 882 benzene and TPH vapor concentrations. Groundwater benzene and TPH concentration data are
 883 also available for many sites, and the database also includes data on fixed gases for a majority of
 884 the sites. For the other analytes listed above (e.g., toluene, ethylbenzene, xylenes, naphthalene),

885 the database includes data for fewer sites, although the data set for aromatic and aliphatic
886 hydrocarbons is substantial because recent data from 11 Maine sites are included. Although
887 indoor air data are included for a limited number of sites, indoor air data were not used in the
888 analysis because of the limited number of data points and the known effect of background in
889 introducing bias in soil vapor-to-indoor air attenuation factors for PHC compounds.

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

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

*sealed vs temporary probes?
fixed vs mobile labs?*

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

898 7. Database Analysis Approach and Methods

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

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

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

911 7.1 Source Zone Identification Methods (LNAPL versus Dissolved Indicators)

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

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

957 The thresholds adopted for identifying LNAPL sites are a benzene soil concentration of
 958 10 mg/kg and a TPH (gasoline) soil concentration of 250 mg/kg. The benzene concentration
 959 (10.7 mg/kg rounded down to 10 mg/kg) was estimated from the equation for soil saturation
 960 (“C_{sat}”) and the default input parameters in Exhibit 9 of the U.S. EPA Soil Screening Guidance
 961 (U.S. EPA, 1996). A TPH soil concentration of 250 mg/kg was adopted to provide for a slightly
 962 more conservative screening basis (i.e., more sites are included as dissolved sites with higher
 963 thresholds) than the ranges reported in the literature cited above. An LNAPL source site was
 964 identified on the basis of either the benzene or TPH soil concentration exceeding the threshold.

} and soilgas samples were within what distance of this evidence ?

965 **7.1.3 Proximity to Fuel Storage/Dispensing Facilities**

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

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

978 **7.2 Data Analysis Methods**

979 The data analysis consisted of three main parts:

- 980 1. Exploratory data analyses to evaluate data trends and relations between different
 981 media (e.g., groundwater versus soil gas) and analytes (e.g., hydrocarbon versus
 982 oxygen),
- 983 2. Plots of benzene and other hydrocarbon soil vapor concentrations versus the vertical
 984 separation distance of the vapor probe above the contamination source (“vertical
 985 distance method”), and
- 986 3. Estimated thickness of un-impacted soil for benzene vapors to attenuate to below a
 987 threshold (“clean soil method”). This technique required establishing rules for data
 988 interpolation.

989 The analysis focused on benzene given its importance for risk evaluations; however, it
 990 was also performed for select other compounds, including those analyzed at the Maine sites
 991 where full-spectrum hydrocarbon analyses are available (e.g., hexane, aliphatic and aromatic
 992 fractions).

} earlier, it seemed benzene was the focus. Consider moving this up front

993 Given that the database was set up to allow for filtering, the influence of site type (UST,
994 fuel terminal, petroleum refinery), soil properties, presence or absence of buildings, and other
995 factors was evaluated.

996 7.2.1 Exploratory Data Analysis

997 The exploratory data analysis involved evaluating the relations between groundwater and
998 soil vapor concentrations, and oxygen and hydrocarbon concentrations to assess whether there
999 were thresholds for minimum concentrations where aerobic biodegradation readily occurs (Davis
1000 et al., 2009; Sweeney, 2012). The rationale for this analysis is described in Section 8.1.

1001 7.2.2 Vertical Distance Method

1002 The vertical distance method involved plotting soil vapor concentration versus distance
1003 above a source and estimating either statistically the soil vapor concentrations or the probability
1004 for the soil vapor concentration to be less than a concentration threshold for variable distances
1005 above the contamination source. The conditional probabilities were estimated as follows:

$$1006 \quad P(C_v \leq C_{\text{threshold}}/z > d, \text{ Contamination } (z = 0) = \text{LNAPL or dissolved})$$

1007 where C_v is the soil vapor concentration, $C_{\text{threshold}}$ is the soil vapor concentration threshold, z is
1008 the vertical direction, d is the vertical distance from the top of the contamination to the soil gas
1009 probe, and source contamination is characterized as either an LNAPL or dissolved source.

1010 The data were sorted in a cumulative distribution of specified vertical separation
1011 distances from the source (e.g., ≥ 0 , ≥ 2 , ..., $\geq n$ ft). The conditional probabilities were calculated
1012 for two different benzene vapor concentration thresholds (50 or 100 $\mu\text{g}/\text{m}^3$ for benzene) using
1013 two different methods:

- 1014 1. Probability $P = N[C_v < C_{\text{threshold}}]/N[\text{total}]$ where $N[C_v < C_{\text{threshold}}]$ is the number of
1015 benzene vapor concentrations less than the threshold and $N[\text{total}]$ is the total number
1016 of concentration measurements; for this analysis, concentrations below the reporting
1017 limits were replaced with half the reporting limit, a common first approximation for
1018 non-detect measurements.
- 1019 2. Probability was estimated from the concentration distribution calculated by the non-
1020 parametric Kaplan-Meier method (Kaplan and Meier, 1958).

1021 Approximately 31 percent and 57 percent of benzene soil vapor concentrations associated
1022 with LNAPL and dissolved-phase sources, respectively, were non-detects, i.e., below specified
1023 reporting limits. The Kaplan-Meier method is a robust, non-parametric method for considering
1024 data below reporting limits, particularly when there are multiple reporting limits (Helsel, 2005;
1025 2006).

1026 The next step was to estimate the depth to contamination, which is important for an
1027 accurate estimation of the thickness of un-impacted soil needed for attenuation of soil vapor
1028 concentrations. For LNAPL sites, this depth was estimated from boring logs and indications of
1029 LNAPL zones (e.g., observations of product, high headspace organic vapor concentrations above

1030 500 to 1,000 parts per million [ppm], and soil chemistry data); in the absence of data, the depth
1031 to contamination was assumed to be the seasonal high water table. For dissolved sites, the depth
1032 to contamination was the depth to the water table closest to the time the soil gas data were
1033 obtained.

1034 **7.2.3 Clean Soil (Davis) Method**

1035 The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-
1036 impacted clean soil required for soil vapor benzene concentrations to attenuate to below a
1037 defined threshold, which for this analysis is 100 µg/m³. The purpose of conducting this analysis
1038 was to enable comparison to published exclusion distances based on this method previously
1039 reported by Davis (2009; 2010). A clean soil thickness was calculated except when the vertical
1040 distance between soil gas probes was greater than 10 ft (3.0 m), because there is insufficient
1041 resolution (i.e., spacing between probes) for meaningful estimation of the thickness when the
1042 vertical distance between probes is greater than about 10 ft (3.0 m). Two methods were used to
1043 estimate the clean soil thickness:

1044 • Method A: Distance to first soil gas probe with benzene C_{vapor} < 100 µg/m³ where:

- 1045 – Lower depth = D_l = Depth to top of contamination
- 1046 – Upper depth = D_u = Depth to first probe with benzene C_{vapor} ≤ 100 µg/m³
- 1047 – Distance = D_l - D_u

1048 • Method B: Interpolated distance to between a soil gas probe with benzene C_{vapor} >
1049 100 µg/m³ and a soil gas probe with C_{vapor} < 100 µg/m³ where:

- 1050 – Lower depth = D_l = Depth to top of contamination
- 1051 – Upper depth = D_u = Interpolated as halfway between the depths to a probe with
1052 benzene C_{vapor} ≤ 40 µg/m³ and C_{vapor} > 100 µg/m³; however, if the lower
1053 concentration is greater than 40 µg/m³, then D_u = depth to first probe with
1054 benzene C_{vapor} ≤ 100 µg/m³
- 1055 – Distance = D_l - D_u, subject to minimum thickness of 0.5 ft (0.2 m)

1056 For both Methods A and B, benzene concentrations below reporting limits were replaced with
1057 half the reporting limit.

1058 A lower concentration threshold was considered warranted for Method B because of the
1059 potential for the halfway distance interpolation to be non-conservative when the lower
1060 concentration is much greater than 100 µg/m³ (which is often the case) and the upper
1061 concentration is just less than 100 µg/m³. The 40 µg/m³ threshold is subjective, but when the
1062 upper benzene vapor concentration is less than this threshold, the halfway interpolation method
1063 is more accurate. Although more complicated and possibly more accurate interpolation rules
1064 could have been developed, Method B was intended as a simple, approximate method.

1065 For locations where the measured soil vapor benzene concentration does not attenuate to
1066 less than < 100 µg/m³, a clean soil thickness cannot be calculated, but a minimum clean soil

Based on how many rounds of water level monitoring, on average?

It isn't "unimpacted" and it isn't "clean". These terms are misleading. Better to say "soil with no NAPL".

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?

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) < 3m.

Exactly why a semi-log plot would be a better choice

1067 thickness (i.e., greater than) is reported as the distance between the shallowest soil gas probe and
1068 the top of contamination.

1069 *paragraph*
1070 *move this sentence to line 1056*
1071 [An example calculation of clean soil thicknesses and exclusion distances is presented in
1072 Figure 6. For the Area 1A soil gas probe profile, the Method A and B distances are 11 ft (3.4 m)
1073 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.]

1074 **7.3 Soil Vapor Concentration Thresholds**

1075 *Need to add a "topic sentence"*
1076 An important part of the analysis was defining a soil vapor concentration threshold when
1077 soil PVI would typically not be of potential concern. The concentration threshold was based on
1078 the expected attenuation in vapor concentrations between shallow soil vapor and indoor air, and
the toxicity of the chemical under consideration.

1079 The processes that affect the vapor concentration in indoor air for a shallow soil vapor
1080 source are primarily soil gas advection and ventilation and mixing of the chemical within the
1081 enclosed space (Hers et al., 2003; Johnson, 2005), although some additional biodegradation and
1082 sorption could also occur between a shallow vapor source and an indoor environment. Several
1083 modeling studies provide insight on the attenuation factor for a typical residential house. Yao et
1084 al. (2011) reported attenuation factors between 2×10^{-4} and 7×10^{-3} for a numerical modeling
1085 study. Johnson (2005) in a modeling study using the Johnson and Ettinger (1991) model
1086 calculated attenuation factors between 4.4×10^{-3} and 7.3×10^{-3} for a shallow soil vapor source
1087 and representative input parameters for a residential house. A similar study by Hers et al. (2003)
1088 included a sensitivity analysis where the maximum attenuation factor for a range of conditions
1089 was 9×10^{-3} and a relatively good comparison (within an order of magnitude) was obtained
1090 between Johnson and Ettinger model predictions and measured attenuation factors for
1091 chlorinated solvent chemicals. Although this comparison is for chlorinated solvent chemicals, it
1092 is relevant here because it identifies typical attenuation factors between shallow or subslab vapor
1093 and indoor air, irrespective of possible biodegradation processes.

1094 The U.S. EPA database of empirical vapor attenuation factors (U.S. EPA, 2012a) is
1095 another information source, although selection of a representative attenuation factor was
1096 challenging. This is because the empirical attenuation factors vary over several orders of
1097 magnitude, due to the variability in both indoor air and subslab vapor concentrations, and
1098 background sources of chemicals in indoor air.

1099 *spatial and temporal*
1100 The U.S. EPA database 50th and 95th percentiles of the subslab attenuation factor are
1101 5.0×10^{-3} and 1.8×10^{-1} , respectively, for the data set limited to indoor air concentrations above
1102 the 90th percentile literature background concentration. For the data set filtered based on subslab
1103 vapor concentrations greater than 100 times the literature background, the 50th and 90th
1104 percentiles of the subslab attenuation factor are 2.5×10^{-3} and 2.0×10^{-2} , respectively. Based on
1105 the above review, a shallow soil vapor-to-indoor air attenuation factor of 0.01 was considered a
reasonably conservative factor for the analysis.

combine
why not use the same?
Radon Studies could also be used to support 0.01.

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and should not be construed to represent any Agency determination or policy.*

*You should say that a steady-state model is best compared
to a 50th percentile empirical α . Then defend why you
looked at 90 or 95th percentile values (RAOS generally recommends
that when there is enough data)*

not everyone will know this term, so define

1106 Risk-based indoor air concentrations for a residential scenario are provided in Table 7 for
1107 the chemicals of potential concern considered in this analysis. The risk-based indoor air
1108 concentrations assume a residential scenario, continuous life-time exposure to vapors, and no
1109 exposure amortization. For chemicals other than benzene, a risk-based soil vapor concentration
1110 (RBC_v) was calculated as 100 times the risk-based air concentration. The thresholds adopted for
1111 benzene, 50 and 100 µg/m³, were based primarily on practical considerations relating to the
1112 detection limit (i.e., the frequency of non-detects increases as the benzene concentration
1113 decreases). For comparison, assuming an attenuation factor of 0.01, the calculated benzene
1114 threshold is 29 µg/m³ for an incremental lifetime cancer risk (ILCR) of 1 × 10⁻⁶, and 290 µg/m³
1115 for an ILCR of 1 × 10⁻⁵.

seems weakly supported.

You defend $\alpha \approx 0.01$ as reasonably conservative, then don't use that for the one chemical that is your primary focus. Seems odd.

1116 **8. Database Analysis Results**

1117 **8.1 Exploratory Data Analysis**

1118 The cumulative distributions of benzene concentrations in groundwater are plotted in
1119 Figure 7 for hydrocarbon sources classified as dissolved phase and LNAPL. The groundwater
1120 benzene concentrations for LNAPL sites are higher than for dissolved sites, but for a proportion
1121 of the LNAPL site data, there are relatively low benzene groundwater concentrations. This may
1122 be due to spatial variability in groundwater concentrations, highly weathered residual-phase
1123 LNAPL that is relatively depleted of benzene, variable well screen intervals relative to the water
1124 table, and vadose zone LNAPL sources.

why not be specific and say 25% or whatever?

Elevated reporting limits? just say $r^2 = \dots$

1125 The relations between benzene concentrations in groundwater and deep soil vapor probes
1126 (within 3 ft [0.9 m] of the contamination source) for dissolved and LNAPL sources are shown in
1127 Figure 8. There is no apparent correlation for dissolved-source data, but a weak proportional
1128 relation exists between groundwater and soil vapor concentrations for LNAPL source data.

There are many instances when the wording is vague

Why is this? is it because of some processes? or data quality?

1129 For dissolved-source data, the measured deep benzene vapor concentrations are, in
1130 almost all cases, at least an order of magnitude (10 times) and, in many cases 2 orders of
1131 magnitude (100 times), less than the predicted soil vapor concentration based on Henry's Law
1132 partitioning. A dimensionless Henry's Law constant of 0.14 was used for benzene, which is
1133 based on a groundwater temperature of 15°C, considered a representative value based on the
1134 groundwater temperature map in U.S. EPA (2004).

from the measured groundwater concentration

This is reasonably attributable to biodeg'n.

1135 For the LNAPL source data, the measured benzene vapor concentrations are significantly
1136 less than predicted for benzene groundwater concentrations less than approximately 1 mg/L. For
1137 concentrations greater than 1 mg/L, the benzene vapor concentrations for some data points are
1138 close to the predicted concentrations by Henry's Law (which is consistent with an LNAPL
1139 source and limited attenuation between the source and deep soil vapor sample).

good. but the previous paragraph needs a "tie-in" sentence like this too

1140 The poor correlation between groundwater and soil vapor concentrations is likely due to
1141 1) variable well screen intervals relative to the water table, 2) variable biodegradation between
1142 the groundwater and lowermost soil gas sampling location, and 3) spatial variability and
1143 differences in dissolved-phase concentrations at groundwater and soil gas sampling locations.

Why not just be specific: "groundwater concentration multiplied by Henry's Constant"

This wording sounds too academic

concentrations where there are

Plot as both linear-linear and log-log scales

1144 The relation between co-located oxygen and PHC vapor concentrations ~~has been~~ *can*
 1145 ~~hypothesized as~~ potentially providing insight on biodegradation processes and a possible lower
 1146 oxygen limit for occurrence of aerobic biodegradation. The expectation is low oxygen ~~at high~~ *concentrations*
 1147 hydrocarbon vapor concentrations and high oxygen (near atmospheric) ~~at low hydrocarbon vapor~~ *where there are*
 1148 concentrations, excluding sites where there is high natural oxygen demand. The oxygen versus
 1149 TPH vapor concentration data indicate general trends consistent with expected behavior and *define what*
 1150 notably no data indicating depleted oxygen for dissolved sources, but considerable scatter in the *this means,*
 1151 data (Figure 9). For LNAPL sources, the low oxygen concentrations (less than 2 percent) occur *Were there*
 1152 when TPH vapor concentrations exceed approximately 1 mg/L. Some data points where oxygen *any such*
 1153 and TPH vapor concentrations are both elevated may be due to the introduction of oxygen during *sites in*
 1154 sampling or analysis. Although the data suggest that aerobic biodegradation can occur at low *the database?*
 1155 oxygen concentrations (on the order of 1 to 2 percent), of greater relevance for the aerobic depth
 1156 is the oxygen flux into the soil from the atmosphere and not the lowest oxygen concentration
 1157 measured in soil.

1158 The database includes methane data for 23 sites. Methane concentrations exceeded 5
 1159 percent (lower explosive limit in air) at four sites (three UST sites and one petroleum refinery
 1160 site), but were less than 1 percent at the remaining 19 sites. There was no apparent correlation
 1161 between methane and benzene vapor concentrations in this limited data set. Three of the four
 1162 sites with elevated methane concentrations were investigated prior to 2000, so the methane at
 1163 these sites was not associated with ethanol in the gasoline leaked into the subsurface.

1164 The relations between benzene and ethylbenzene and benzene and xylenes soil vapor
 1165 concentrations are shown in Figure 10. As shown, qualitatively there is a relatively good
 1166 correlation between these two analyte pairs, although for the benzene-xylenes comparison, the
 1167 xylenes' vapor concentrations for low concentrations are generally up to two orders of
 1168 magnitude higher than the benzene concentrations.

8.2 Vertical Distance Method

1169 *I personally believe methane is more common at LNAPL sites and is an important sink for oxygen. This doesn't do it justice.*
 1170 For the vertical distance method, soil vapor concentrations (of the PHC compounds listed
 1171 below) are compared with risk-based vapor concentrations, RBC_v (risk-based indoor air
 1172 concentrations multiplied by 100), and for benzene, the probability that the soil vapor
 1173 concentration is less than a defined threshold (50 and 100 µg/m³) for varying source-separation
 1174 distances was estimated. For definition of exclusion distances, a probability greater than 95%
 1175 percent was considered a reasonable threshold.

8.2.1 All Data

1176 *Also not clear why this matters.*
 1177 The data analysis was conducted for 1) dissolved sources; 2) LNAPL sources,
 1178 incorporating data for just UST sites; and 3) LNAPL sources, incorporating data for all facility
 1179 types (UST, fuel terminal, petroleum refinery, and petro-chemical) (Figures 11 through 15).
 1180 There are only PHC fraction and hexane data for UST sites; hence, we do not include a figure for
 1181 the all-LNAPL sites category for these compounds. The following compounds were evaluated:
 1182 benzene, xylenes, hexane, 2,2,4-TMP, and Massachusetts Department of Environmental

Very hard to follow as worded of what?
It's not really clear why this paragraph is located here, it needs a better topic sentence and tie-in sentence to

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Have these sites been adequately characterized to use in the database?

clarify the relevance to the preceding and following paragraphs

define what this means, Were there any such sites in the database? If the O₂ concentration is really low, a portable meter often reads 1% or more. Is this a limitation of the equipment?

why 95?

1183 Protection (MADEP) hydrocarbon fractions (C9-10 aromatics, C5-8 aliphatics, and C9-12
1184 aliphatics).⁴

1185 For the benzene analysis, nondetects were addressed both by the common practice of
1186 substituting half the detection limit for non-detects and by using the more statistically robust
1187 Kaplan-Meier non-parametric method. The Kaplan-Meier method resulted in similar or slightly
1188 higher (0 to 7 percent) probabilities than the substitution method. The probabilities the soil vapor
1189 concentration being less than a threshold was estimated for 5 and 30 mg/L groundwater
1190 concentration thresholds for benzene and TPH, respectively, which are part of the LNAPL
1191 hydrocarbon indicators (Table 6). A sensitivity analysis was conducted where the threshold for
1192 the benzene groundwater concentration was varied between 1 and 10 mg/L, and the TPH
1193 groundwater concentration was varied between 10 and 50 mg/L. The resulting variation in
1194 probability (estimated using the substitution method) for this range was less than 0.5 percent,
1195 indicating the results are not sensitive to the concentration thresholds (possibly because
1196 groundwater is a poor predictor of soil vapor concentrations).

This also has implications for the scope of a PVI investigation

1197 The analysis results show distinct differences between the three scenarios considered
1198 (Table 8);

1199 1) For dissolved sources, greater than 97 percent and 94 percent of the benzene soil vapor
1200 concentrations are less than the specified thresholds of 50 and 100 µg/m³, respectively, for
1201 source-separation distances as small as 0 ft (Table 8 and Figures 11 and 12). Comparisons for
1202 other compounds evaluated indicate that soil vapor concentrations above risk-based soil vapor
1203 concentrations occurred only for separation distances smaller than 3 ft (0.9 m). The analysis
1204 indicates there is a low probability of exceeded risk-based thresholds for small separation
1205 distances for dissolved sources.

be specific

1206 2) For LNAPL sources, the PHC vapor concentrations were plotted against the separation
1207 distance between the soil gas probe and hydrocarbon source (Figures 13 through 15). The
1208 maximum concentrations of benzene and other hydrocarbon vapor concentrations were several
1209 orders of magnitude greater than for dissolved sources, but concentrations of benzene soil vapor
1210 concentrations decreased rapidly between 10 and 15 ft (3.0 and 4.6 m) separation distance and
1211 for other compounds at smaller separation distances, although it should be noted that the data
1212 sets for other compounds are relatively small. For LNAPL sources that are limited to UST sites,
1213 approximately 95 percent of the benzene soil vapor concentrations are less than the thresholds
1214 (50 and 100 µg/m³) at a source-separation distance of approximately 15 ft (4.6 m), which
1215 increases to approximately 30 ft (9.1 m) when all LNAPL facility types are included.

I'm having a hard time following the distinction.

1216 3) Soil vapor data for 2,2,4-TMP for LNAPL sources (all facility types) were limited
1217 (Figure 16). There were elevated 2,2,4-TMP vapor concentrations (0.01 to 10 mg/L)
1218 representing data from two sites; at one site, concentrations remained elevated for separation

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.

*use 2 categories
1) dissolved source
2) NAPL source
?*

1219 distances as great as 50 ft (15 m). The U.S. EPA IRIS database does not contain toxicity
1220 reference factors for 2,2,4-TMP. *Therefore* *number of* *(add a tie-in sentence)*

1221 The analysis results indicate benzene is the risk driver, with greater occurrences of
1222 exceedances of risk-based vapor concentrations for larger separation distances, when compared
1223 with the other compounds evaluated.

be specific because benzene has

1224 **8.2.2 Influence of Surface Cover**

1225 The potential influence of a surface cover was evaluated through comparison of the
1226 probabilities of benzene soil vapor concentrations that are less than 100 µg/m³ for varying soil-
1227 separation distances and through analysis of oxygen concentrations for three different surface
1228 covers: building concrete foundations, pavement, and bare-ground cover (**Figures 17 and 18**).
1229 The data sets evaluated were limited to LNAPL sources because oxygen is not limiting for
1230 dissolved-source sites.

are there any data below buildings in cold climates where the stack effect might result in a depressurized basement?

1231 When all the facility types were considered (which yields the largest data set), the
1232 analysis of probabilities for varying soil-separation distances indicated different results
1233 depending on surface cover. The probabilities of benzene soil vapor concentrations less than 100
1234 µg/m³ were between 5 and 20 percent greater for the ground cover scenario, compared with the
1235 pavement and building scenarios, which yielded similar results (**Figure 17**). The oxygen
1236 concentration results were generally consistent with the above probabilities, with no oxygen
1237 concentrations below 2 percent for the ground cover scenario (excluding results for zero
1238 separation distance); however, several data points indicated oxygen concentrations less than 2
1239 percent for separation distances up to 11 ft (3.4 m).

not clear how this supports line 1292

be careful what you say about oxygen shadows below buildings

1240 The above analysis was repeated for just LNAPL sources and UST sites. The results were
1241 different in that the probabilities for benzene concentrations less than 100 µg/m³ were similar for
1242 the ground cover and building scenarios, but were between 5 and 20 percent lower for the
1243 pavement scenario (**Figure 18**). The reason for this difference is not known, although it is noted
1244 that LNAPL sources and buildings will tend to be smaller at UST sites, compared with petroleum
1245 refinery or fuel terminal sites. There was a lower frequency of data points with low oxygen
1246 concentrations for UST sites, compared with the analysis where all facility types were
1247 considered.

1248 These analyses suggest surface cover type can affect oxygen availability and PHC vapor
1249 transport. However, because the vertical distance method evaluation includes soil vapor
1250 concentration data from below buildings at 33 UST sites (**Table 4**), the results are considered
1251 sufficiently robust with respect to including the potential influence of surface cover.

What do modeling studies show?

Table 4 doesn't specifically include a column for vertical profile below building floor

1252 **8.2.3 Influence of Soil Type**

1253 The potential influence of soil type is evaluated through comparison of the probabilities
1254 of benzene soil vapor concentrations less than 100 µg/m³ for varying soil-separation distances
1255 and for two general soil types: fine grained and coarse grained (**Figure 19**). The probabilities of
1256 benzene soil vapor concentrations less than 100 µg/m³ were similar for dissolved-source sites for
1257 the two soil types. For LNAPL source sites, the probabilities are between 6 and 16 percent

IF data and models do not agree, what does that tell us?

1258 greater for coarse-grained soils than those for fine-grained soils for small separation distances,
1259 but at larger separation distances, there is a reversal in the trend. Based on the analysis it is not
1260 possible to identify if soil type has an influence on benzene soil vapor concentrations and
1261 probabilities of exceedances.

this has implications for PVI assessment

1262 **8.3 Clean Soil (Davis) Method**

If temporary probes were used in fine-grained soils, you'd need to do more to defend the data quality anyway

1263 [The clean soil method (Davis, 2009; 2010) consists of an analysis of the thickness of un-
1264 impacted clean soil required for soil vapor benzene concentrations to attenuate to below a
1265 defined threshold, which for this analysis is 100 µg/m³.] As described in Section 7, two
1266 interpolation methods were used as part of the estimation process. The results of the analyses are
1267 shown in **Figures 20** through **22** and can be summarized, as follows:

- 1268 • For dissolved-source sites, there is no trend relative to dissolved benzene groundwater
1269 concentrations, and the 95th percentile clean soil thicknesses (calculated using Excel)
1270 for Methods 1 and 2 are 10 ft (3.0 m) and 5.4 ft (1.6 m), respectively.
- 1271 • For LNAPL (UST-only) source sites, there is an increase in the clean soil thicknesses
1272 for benzene groundwater concentrations greater than approximately 5 mg/L. The 95th
1273 percentile clean soil thicknesses (incorporating all the data) for Methods 1 and 2 are
1274 13.9 ft (4.2 m) and 13.5 ft (4.1 m), respectively. A small percentage of the data points
1275 represent vertical profile data where the shallowest benzene soil vapor concentration
1276 is greater than 100 µg/m³; therefore, an attenuation distance could not be calculated
1277 (green symbols on **Figures 20** through **22**).
- 1278 • For LNAPL (all sites) source sites, there is a similar trend to UST-only sites with
1279 respect to clean soil thickness versus benzene groundwater concentrations. The 95th
1280 percentile clean soil thicknesses for Methods 1 and 2 are 20.0 ft (6.1 m) and 16.2 ft
1281 (4.9 m), respectively. A small percentage of the data points represent vertical profile
1282 data where the shallowest benzene soil vapor concentration was greater than
1283 100 µg/m³.

you've said this already

what is the significance of this?

combine?

Too many statements that appear to be potentially significant with no clarification of whether they are or not. This weakens the

1284 **9. Discussion**

1285 **9.1 Conceptual Site Model and Mathematical Models**

1286 The CSM for PHC vapor behavior is the basis for the framework developed for
1287 identifying exclusion distances and inclusion criteria. At sites with dissolved PHC contamination
1288 in groundwater, aerobic biodegradation is expected to result in the attenuation of PHC vapors,
1289 such that there is limited potential for a complete PVI pathway, except for sites with very
1290 shallow contamination. For sites with shallow LNAPL contamination, there is greater potential
1291 for oxygen limitations below buildings and a complete PVI pathway, depending on site
1292 conditions. Case studies reviewed suggest that the potential for a complete PVI pathway may
1293 exist at non-UST (i.e., petroleum refinery) sites with large-volume LNAPL releases, particularly
1294 where there are large buildings or a capping effect based on geologic conditions.

whole analysis

your analysis (8.2.2) did not support

1295 The mathematical modeling studies reviewed, in general, support the empirical analysis
1296 in that model simulations for dissolved PHC sources predict very low vapor attenuation factors,

this statement very well

or maybe just want very clearly worded.

1297 except for small source-separation distances (i.e., less than about 5 ft [1.5 m]). For LNAPL
 1298 sources, the modeling simulations suggest hydrocarbon vapor attenuation behavior consistent
 1299 with the case studies and empirical data. Although the modeling studies are instructive, there has
 1300 been limited evaluation of the range of possible mechanisms for oxygen migration to below
 1301 buildings, including diffusive oxygen transport through concrete foundations and processes for
 1302 advective soil gas transport, which could be important at LNAPL source sites.

this has implications for PVI assessment scope

1303 **9.2 Methods and Characteristics of the Database**

1304 The results of the analysis may be used to derive exclusion distances based on the
 1305 probability of benzene vapor concentrations being less than defined thresholds for varying
 1306 contamination source-building separation distances and qualitative comparisons of soil vapor
 1307 concentrations to risk-based soil vapor concentrations for other compounds. The clean soil
 1308 method is an alternative method for defining exclusion distances, but requires interpolation to
 1309 avoid overly conservative results. This site-by-site interpolation process introduces uncertainty
 1310 particularly for sites where there is poor resolution with respect to vertical concentration
 1311 gradients (i.e., from soil gas probes that are too far apart).

how far is too far? This has implications for the site characterization too

1312 The database is representative of a broad range of environmental site conditions, climatic
 1313 conditions (including dry areas), soil types, and land-surface covers that may be found at UST
 1314 sites. Although the data analysis indicates that the type of surface cover (e.g., building
 1315 foundation, pavement, open ground) can have an effect on the attenuation of benzene vapor and
 1316 oxygen concentrations, the database includes subslab or vapor data from deeper distances below
 1317 buildings for 38 sites with small- to medium-sized buildings. This is considered a sufficiently
 1318 large data set, such that exclusion distances derived from the analysis will include the potential
 1319 influence of surface cover.

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 slow the O2 profile data and do O2 flux calculations

1320 The sites in the database were investigated between 1995 and 2011. Gasoline containing
 1321 ethanol (10 percent vol/vol) was generally introduced to the United States in 2000 with a large
 1322 increase in use in 2006 (U.S. EPA, 2009). Information on whether gasoline containing ethanol is
 1323 present at specific sites is not available in the current database, but some sites in the database
 1324 with recent releases likely have gasoline containing ethanol.

pretty vague and unconvincing

1325 The sources of uncertainty associated with the analysis, and for which additional
 1326 validation studies should be considered, include the influence of ethanol content in gasoline on
 1327 methane generation rates and aerobic biodegradation of PHC vapors (particularly high ethanol
 1328 content fuels), sites with extensive high organic matter content soils (e.g., peat) with potentially
 1329 high natural oxygen demand, and large buildings where there may be increased potential for
 1330 oxygen limitations for certain foundation conditions. Although this analysis included an
 1331 evaluation of data for non-UST (e.g., petroleum refinery, fuel terminal) sites, uncertainty about
 1332 aerobic biodegradation of PHC vapors remains for larger volume NAPL releases than typically
 1333 encountered at UST sites.

specifically, what is uncertain?

1334 Subsurface utilities are commonplace in urban areas, but their presence does not
 1335 necessarily equate to a preferential pathway of significance for PVI. However, a utility corridor
 1336 that directly connects an LNAPL source and the interior of a building may represent a significant
 1337 preferential pathway and is considered an inclusionary factor for PVI assessment. This analysis

You shouldn't just assume the reader is familiar with these topics and gloss over them

Is it methanogenesis and associated oxygen demand?

1338 also does not include results for fractured rock unsaturated zone systems between the PHC
1339 source and building receptor. *need to make sure these conditions are*

1340 **9.3 Data Analysis Results** *carried through*

1341 For dissolved sources, the vertical distance method indicates that the probability of
1342 benzene vapor concentrations being less than the defined concentration thresholds (50 and
1343 100 µg/m³) is 94 to 97 percent (Kaplan-Meier statistics) for small source-separation distances (as
1344 little as 0 ft), meaning that PVI is unlikely to occur unless a dissolved source is very close to a
1345 building foundation. For development of exclusion distances for dissolved sites, allowance
1346 should be made for uncertainty in water table elevations due to seasonal variability. For LNAPL
1347 sources, the vertical distance method indicates that there is a very low probability of benzene
1348 vapor concentrations being less than the defined thresholds at distances less than about 15 ft
1349 (4.6 m) when just UST facilities are considered and about 30 ft (9.1 m) when all facility types
1350 evaluated are considered.

1351 The data indicate a weak correlation between benzene concentrations in groundwater and
1352 deep soil vapor, but for the clean soil method, a trend was observed when the clean soil
1353 thicknesses needed for benzene vapor attenuation increased when dissolved benzene
1354 concentrations were above approximately 5 mg/L (i.e., indicative of LNAPL source zones).

1355 **9.4 Exclusion Distance Assessment Framework**

1356 The assessment framework for vertical exclusion distances requires identification of the
1357 PHC source type (dissolved phase or LNAPL) based on a multiple lines of evidence approach
1358 similar to that described earlier in this report (see **Table 6**). This framework could include
1359 groundwater concentration thresholds for benzene (and potentially other chemical parameters),
1360 but given the uncertainty in the relation between groundwater and soil vapor concentrations, this
1361 should not be the primary factor for screening sites. Thresholds for soil vapor concentrations
1362 (e.g., minimum oxygen thresholds) could also be considered; however, this is not considered
1363 mandatory as long as there is sufficient rigor in the site characterization approach to delineate
1364 PHC sources and define clean soil zones along with robust methods for identifying LNAPL
1365 versus dissolved sites. For sites with dissolved-phase contamination, it will also be important to
1366 characterize water table fluctuations in relation to building structures.

1367 An exclusion distance approach for LNAPL sources should also include inclusionary
1368 criteria designed to capture sites that fall outside of the findings of the above analysis, including
1369 non-UST facilities (related to size of petroleum release), high organic-rich soils (e.g., peat), large
1370 building foundations (e.g., associated with apartment complexes or commercial/industrial
1371 buildings), and significant subsurface preferential pathways. Future research may indicate certain
1372 ethanol contents in gasoline may also warrant inclusion and PVI assessments because of their
1373 tendency to generate methane that can interfere with the biodegradation of PHCs.

1374 **9.5 Lateral Exclusion Distances**

1375 Greater attenuation of PHC vapors is expected when hydrocarbon sources are offset
1376 laterally from buildings compared with sources that are directly below buildings. Although the

what specifically makes these conditions and no vapor intrusion? fresh water lens.
seems I've read this several times, but each time, it is just a passing comment.
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
except for preferential pathways, fractured rock, naturally high foc, large footprint buildings?
poorly worded and hard to follow
2 ideas, 2 sentences
only for LNAPL? Wouldn't you need correlation, to show dissolved sites with all source
a preferential pathway significant?

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.

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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.

describe exactly what makes this uncertain. Is it data? density? data quality? poor knowledge of the processes?

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9.6 Comparison with Other Studies

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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.

1389

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.

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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.

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2. For dissolved sources:

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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:

Specify whether this includes preferential pathways, fractured rock large buildings, etc, etc, etc.

except

Virtually all of section 9 is either vague or redundant. I would suggest a complete rewrite. It needs to answer several basic questions, see "Global Comments". "screening evaluation method" includes sample collection and analysis procedures, sample spacing and frequency specifications and criteria for decision making. All of this is completely missing and the document is incomplete without it.

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.

Therefore, you must also provide guidance on what methods and scope and QA/QC and criteria are necessary and sufficient to accomplish this

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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.

excluding preferential pathways, fractured rock etc, etc, etc

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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).

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

would it matter if this category was dropped from this group?

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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.

It's confusing to have 3 categories and the UST LNAPL shows up in 2 of them

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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).

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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.

by 10X? by 100X? by 1000X? can the others be ignored? 3 categories

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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.

intervals? depths?

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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.

double-negative

and therefore, what?

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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.

not a separate point

why not include recommendations? right here?

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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

seems like a stretch. Can you really say this?

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.

1452 gasoline may also warrant inclusion and PVI assessments because of their tendency to generate
 1453 methane that can interfere with the biodegradation of PHCs.

It makes it sound as if other hydrocarbons are not methanogenic and that's not true

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

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

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Oklahoma Refinery (McAty et al 2010)

OHIO Refinery (Michaelshki et al 2010)

these two have very detailed data sets and should be considered because they show important aspects of temporal variability that has not been adequately addressed.

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Table 2. Select Three-Dimensional Abreu and Johnson (2005) Model Simulation Results from U.S. EPA (2012b)

Source Hydrocarbon Vapor Concentration (mg/L)	Vapor Intrusion Attenuation Factor	
	Single Soil Layer	Two Soil Layers (Capping Scenario)
200	6.7×10^{-5}	6.8×10^{-4}
2	N/A	7.1×10^{-15}

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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} .

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

Location	Sites	Location	Sites
United States			
California	7	Ohio	4
Maine	13	South Carolina	1
Maryland	1	Utah	15
Minnesota	22	United States unknown	1
New Jersey	3		
Other Countries			
Canada	2	Australia	1
Total Sites = 70			

1691

Ohio
Oklahoma
OK
1
how many are "research" sites?
(i.e. 100s of times more samples)

Table 5. Soil Vapor Analyses in PVI Database

Site Name	City	Benzene	Toluene	Ethylbenzene	Xylenes	Naphthalene	2,2,4-Trimethylpentane	Hexane	Heptane	MTBE	1,3-Butadiene	TPH	TPH Method	MADEP TPH Fractions	Oxygen	Carbon	Methane
Alameda Naval Air Station	Alameda	2	0	0	0	0	0	0	0	0	0	12	Iso-pentane	0	12	12	8
Coachella	Coachella	27	0	0	0	0	0	0	0	0	0	0	N/A	0	26	25	26
Huntington Beach	Huntington Beach	26	0	0	0	0	0	0	0	0	0	0	N/A	0	26	26	26
Mission Valley Terminal	San Diego	84	0	0	0	0	0	0	0	0	0	84	TPHg 8260	0	24	22	0
Newport Beach	Newport Beach	20	0	0	0	0	0	0	0	0	0	0	N/A	0	20	20	20
Port Hueneme	Port Hueneme	0	0	0	0	0	0	0	0	0	0	62	GC/FID	0	55	47	0
Former Chevron Station #9-5669	South San Francisco	27	18	18	18	0	0	0	0	0	0	9	Modified TO-3 GC/FID	0	18	18	9
Dave's Amoco	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
NYM	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Jacobsen Residence	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Larsons 66	N/A	4	4	4	4	0	0	3	4	0	0	4	TPH as Gas	0	0	0	0
D&E Sales	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Moen Oil	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Johnsons Auto	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Midtown Service	N/A	10	0	0	0	0	0	10	10	0	0	10	TPH as Gas	0	0	0	0
John's Garage	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Buchannon Nursing Home	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Red & White Service	N/A	4	4	4	4	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0
Side Lake Store	N/A	5	2	2	2	0	0	5	5	0	0	5	TPH as Gas	0	0	0	0
Ossippe Store	N/A	4	0	0	0	0	0	4	4	0	0	4	TPH as Gas	0	0	0	0

probe type? (temporary or implant)
 Lab type? (mobile or fixed)
 name of sample collector firm? name of lab?

How much do you really know if they didn't measure these?

1700

Table 6. Potential LNAPL Hydrocarbon Indicators

Type	Indicator	Measures and Screening Values
Adopted for this study		
Direct	Current or historic presence of LNAPL in groundwater or soil	Laboratory and/or field observations, sheens, results of paint filter, dye and shake tests
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 ₂ and CO ₂ profiles	PHC vapor and CO ₂ concentrations in soil gas that show no decrease (or O ₂ 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 ³ suggest LNAPL because dissolved plumes are primarily composed of soluble aromatic hydrocarbons (Lahvis et al., In prep.)

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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).

this has implications for the site characterization. the document should specify whether and to what extent these data are necessary before a PVI assessment is adequate

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Table 7. Risk-Based Indoor Air Concentration for Primary Chemicals of Potential Concern

Chemical	Toxicity Endpoint	Risk-Based Indoor Air Concentration (µg/m ³) ¹	Source
Benzene	Carcinogenic	2.9 (1 × 10 ⁻⁵ ILCR); 0.29 (1 × 10 ⁻⁶ ILCR)	U.S. EPA IRIS ²
Toluene	Non-carcinogenic	5,000 (RfC)	U.S. EPA IRIS
Ethylbenzene	Non-carcinogenic	1,000 (RfC)	U.S. EPA IRIS
Xylenes	Non-carcinogenic	100 (RfC)	U.S. EPA IRIS
Naphthalene	Non-carcinogenic	3 (RfC)	U.S. EPA IRIS
n-Hexane	Non-carcinogenic	700 (RfC)	U.S. EPA IRIS
MADEP Aliphatic C5-8	Non-carcinogenic	200	MADEP (2003)
MADEP Aliphatic C9-18	Non-carcinogenic	200	MADEP (2003)
MADEP Aromatic C9-18	Non-carcinogenic	50	MADEP (2003)

1708 ¹ Assumes residential receptor, and continuous exposure over a lifetime.
 1709 ² Midpoint of the range provided in U.S. EPA IRIS database.
 1710 ³ ILCR = Incremental lifetime cancer risk; RfC = reference concentration.
 1711 ⁴ IRIS database accessed February 2012.

Table 8. Summary of Results for Vertical Distance Method

	Dissolved Source	LNAPL Source—UST Sites	LNAPL—All Sites
Oxygen	Most O ₂ conc. > 4%, and no O ₂ < 1%	Many data points with O ₂ < 4%, and O ₂ < 1% to 6 ft (1.8 m) separation	Many data points with O ₂ < 4%, and O ₂ < 1% to 11-ft (3.4-m) separation, greater O ₂ depletion than UST only
Benzene (100 µg/m ³ threshold)	P _{KM} > 97% for 0 ft separation increasing to 99% at 5 ft (1.5 m)	P _{KM} > 61% for 0 ft separation increasing to ~ 95% for 15-ft (4.6-m) separation	P _{KM} > 48% for 0-ft separation increasing to > 90% at 15 ft (4.6 m) and ~95% at 30 ft (9.1 m)
Benzene (50 µg/m ³ threshold)	P _{KM} > 94% to 95% for 0 ft to 5 ft (1.5 m)	P _{KM} > 57% for 0 ft separation increasing to ~ 93% for 15-ft (4.6-m) separation	P _{KM} > 46% for 0 ft separation increasing to > 90% at 15 ft (4.6 m) and ~95% at 30 ft (9.1 m)
Xylenes	One vapor concentration > RBC _v for separation distance of 3 ft (0.9 m)	>10 vapor concentrations > RBC _v for separation distance up to 11 ft (3.4 m)	>10 vapor concentrations > RBC _v for separation distance up to 12 ft (3.7 m)
Hexane	All vapor concentrations < RBC _v 0 ft	Five vapor concentrations > RBC _v for separation distance up to 4 ft (1.2 m)	N/A
C5-8 Aliphatic	Two vapor concentrations > RBC _v for separation distance up to 3 ft (0.9 m)	Five vapor concentrations > RBC _v for separation distance up to 3 ft (0.9 m)	N/A
C9-12 Aliphatic	All vapor concentrations < RBC _v 0 ft	Eight vapor concentrations > RBC _v for separation distance up to 2 ft (0.6 m)	N/A
C9-10 Aromatic	All vapor concentrations < RBC _v 0 ft	Four vapor concentrations > RBC _v for separation distance up to 2 ft (0.6 m)	N/A

confirms most existing guidance on exclusion distances

Naphthalene? MTBE? TMBs?

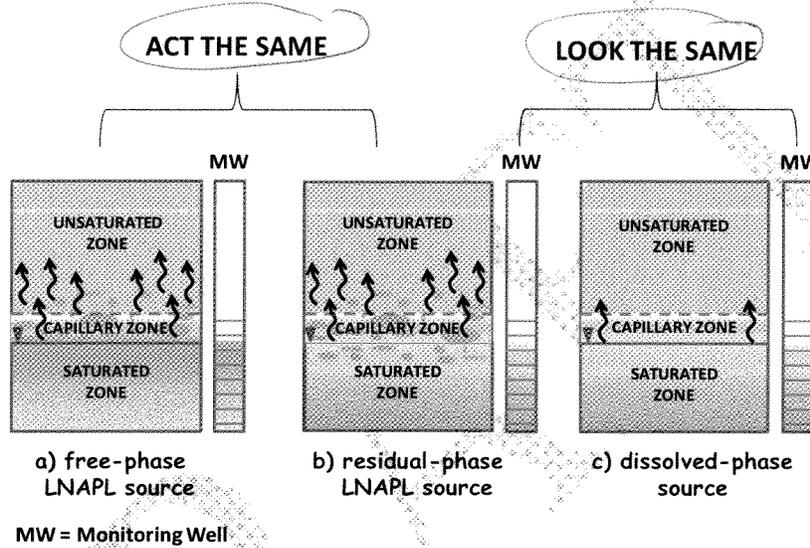
The findings and conclusions in this report have not been formally disseminated by EPA and should not be construed to represent any Agency determination or policy.

1713 ¹ P_{KM} = Probability estimated using Kaplan-Meier method for exceeding threshold.

1714 **Table 9. Summary of Results for Clean Soil (Davis) Method**

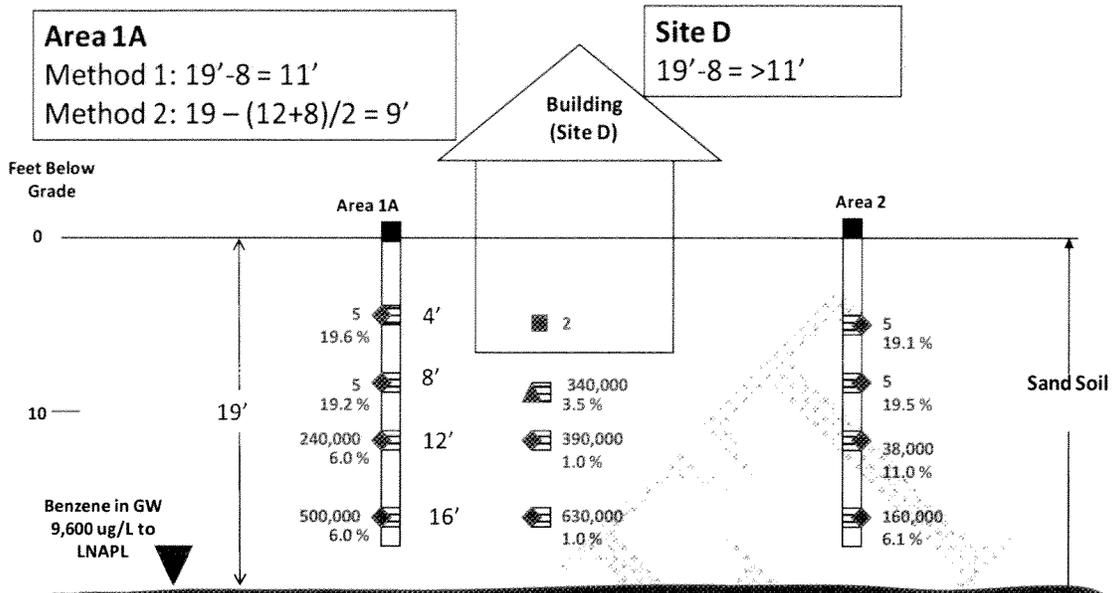
Source Scenario and Facility Type	Number Sites	Number Data Points	95th Percentile Clean Soil Thickness	
			Method A	Method B
Dissolved	47	170	10.0 ft (3.0 m)	5.4 ft (1.6 m)
LNAPL (UST only)	53	172	13.9 ft (4.2 m)	13.5 ft (4.1 m)
LNAPL (all facilities)	60	216	20.0 ft (6.1 m)	16.2 ft (4.9 m)

1715 Note: The above statistics include site data when no benzene groundwater concentration was available.



1716
1717 **Figure 1. Conceptual Model Illustrating the Potential for Vapor Intrusion for a) Free-Phase**
1718 **LNAPL Source, b) Residual-Phase LNAPL Source, and c) Dissolved-Phase**
1719 **(source Lahvis et al., In prep.; used with permission).**

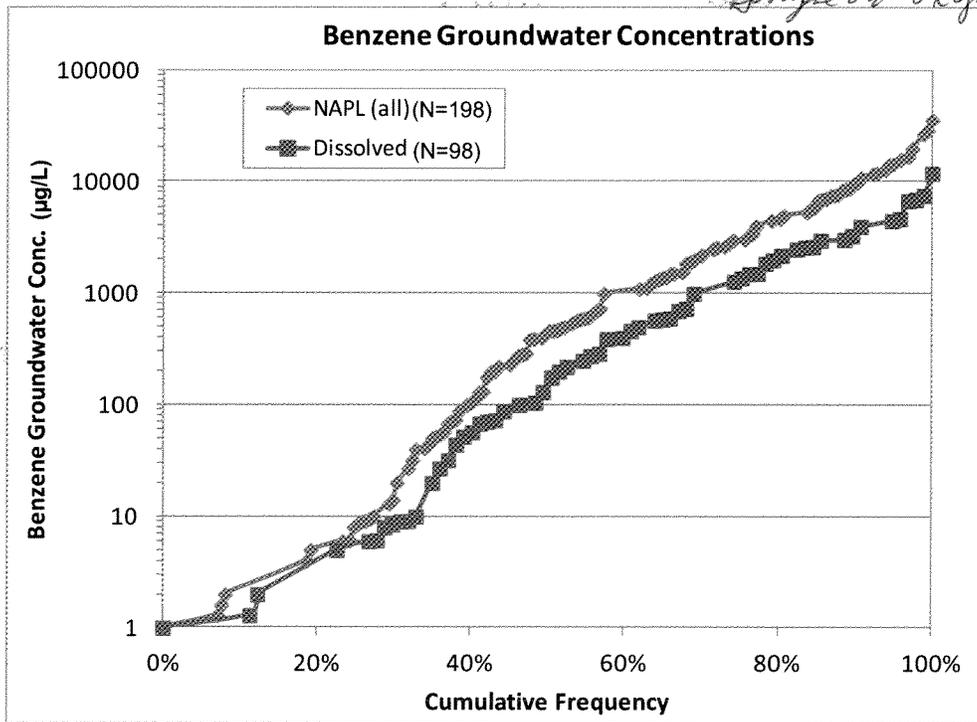
need more verbage to describe what "acting" and "looking" means.



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 1747

Figure 6. Example Calculation of Clean Soil Distances.

add legend to specify what red and blue numbers are (TPH and oxygen?) (benzene and oxygen?)



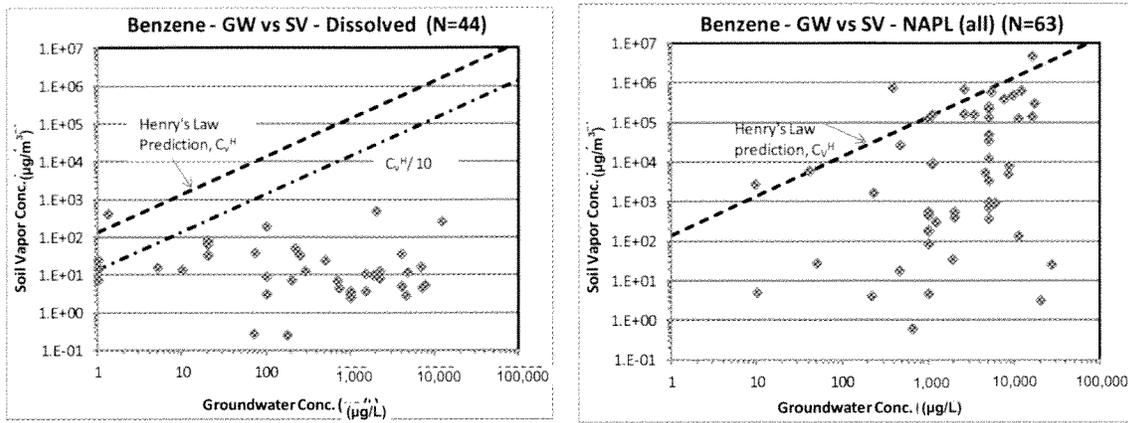
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Figure 7. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites).

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Why not also plot soil vapor concentrations? By itself, this plot is intuitively obvious (detection limit to saturation limit; what else would you expect?)

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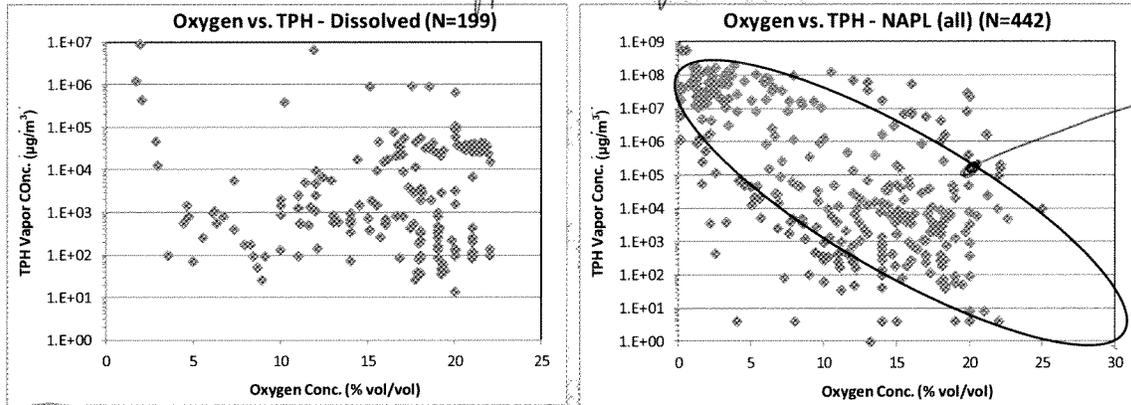


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Figure 8. Groundwater Concentrations Measured Near Soil Vapor Sampling Locations for Dissolved and LNAPL Source Zones (all refers to UST, terminal, and refinery sites). Only detectable benzene vapor concentrations shown.

why not plot non detect values as a different symbol?



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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.

do you really expect 100,000 µg/m³ TPH with 20% O₂?

not sure. 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? what does that say about your ability to use these data to build an argument?

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.

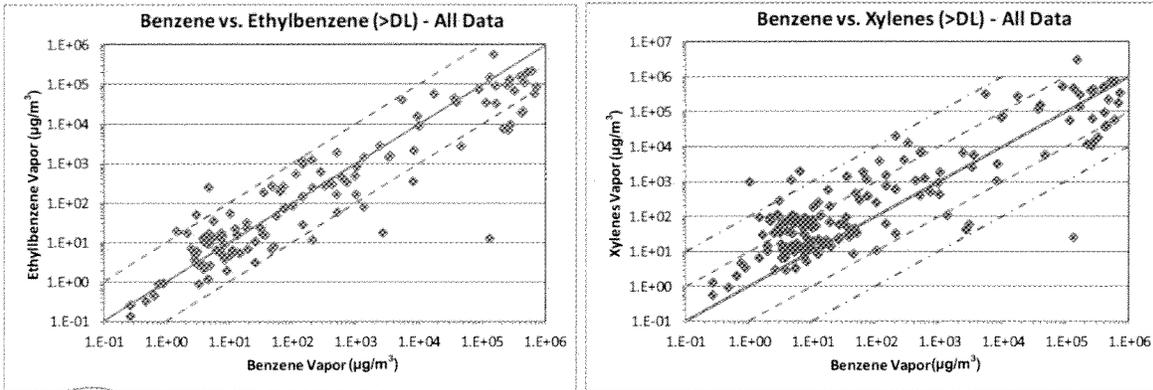
What is the explanation for all the other data? is it a data quality issue? shouldn't the ellipse be on both Fig 9 plots? what does that say about your ability to use these data to build an argument?

How closely do the data agree with theoretical expectations?

Is there even a negative slope?

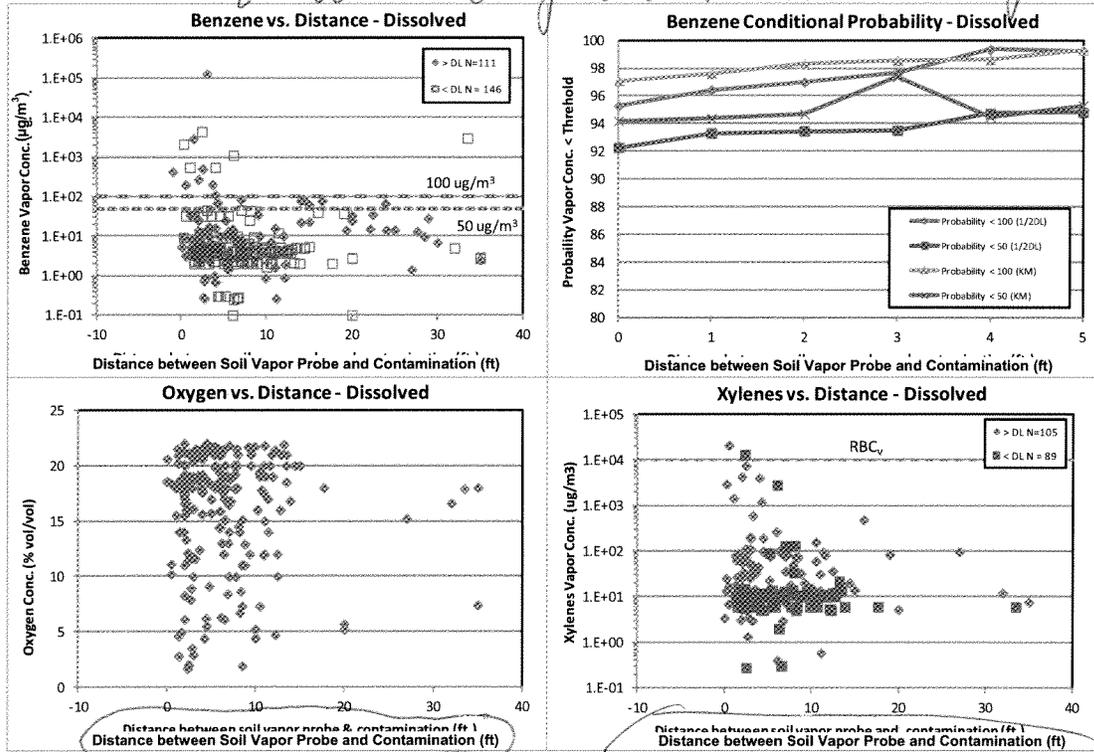
What is the explanation for all the other data? is it a data quality issue? shouldn't the ellipse be on both Fig 9 plots? what does that say about your ability to use these data to build an argument?

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Figure 10. Relation between Benzene and Ethylbenzene and Benzene and Xylenes Vapor Concentrations. Data points shown are where both compounds were above detection limits. *not really clear why these are included or what they add to the analysis*



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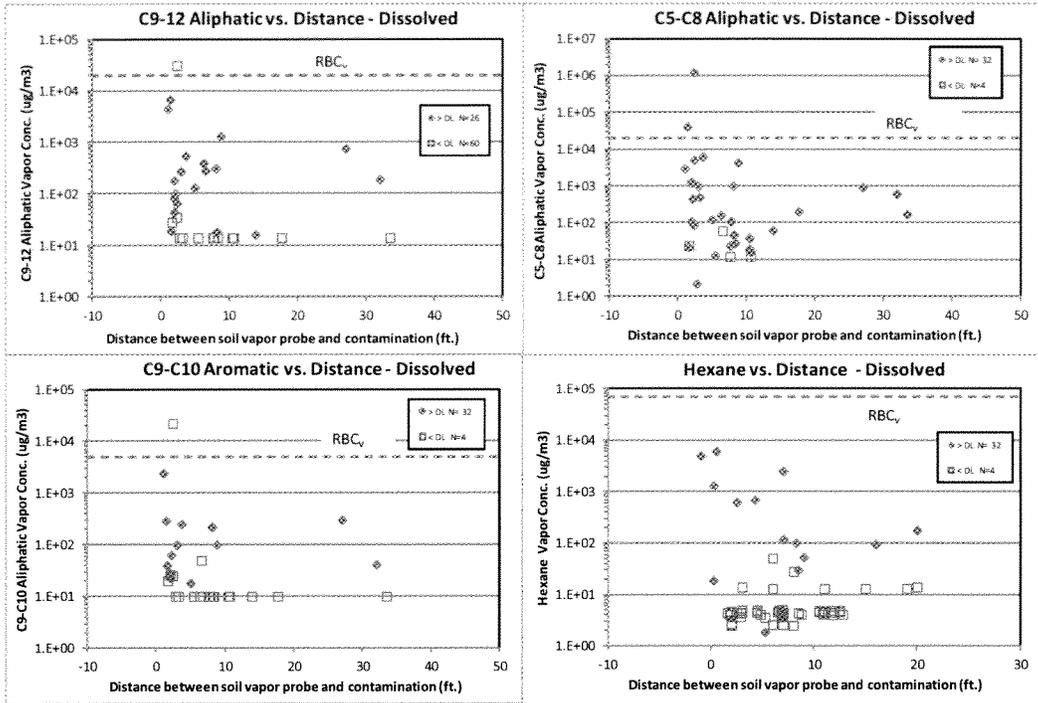
Figure 11. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for Dissolved Sites (KM = Kaplan-Meier).

*Two axes labels
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*

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60 *outcome is 5ft ± 50ft?*

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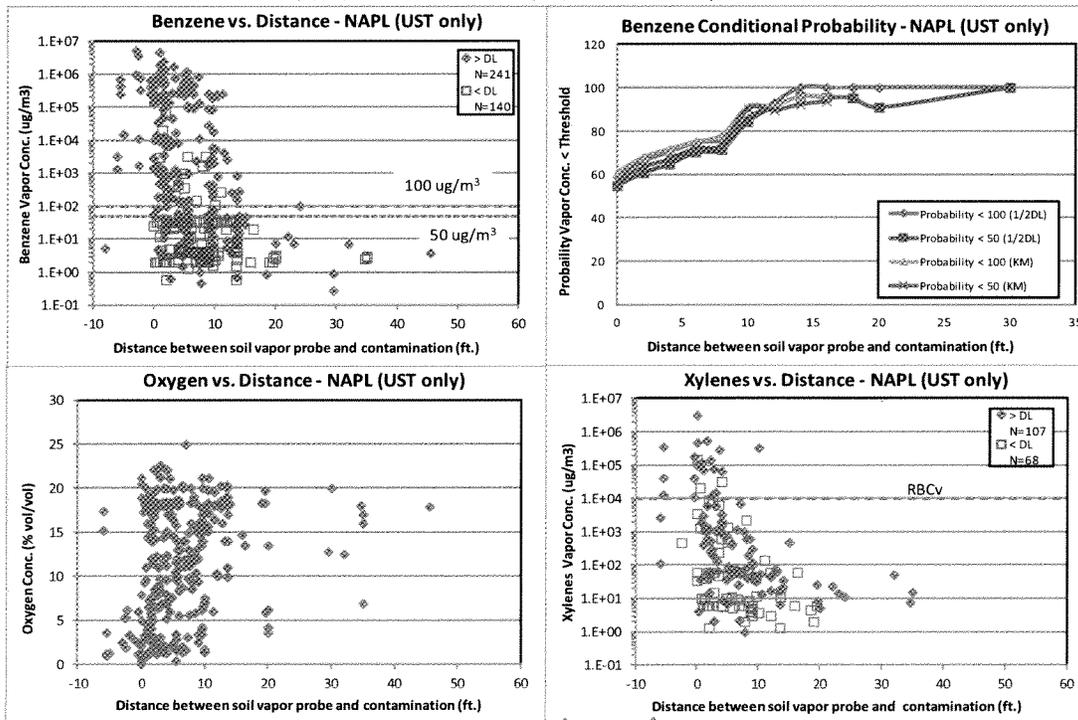
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Figure 12. Vertical Distance Method–PHC Fraction and Hexane Data for Dissolved Sites.

*MTBE?
Naphthalene?
TMBs?
TBA?*

1771



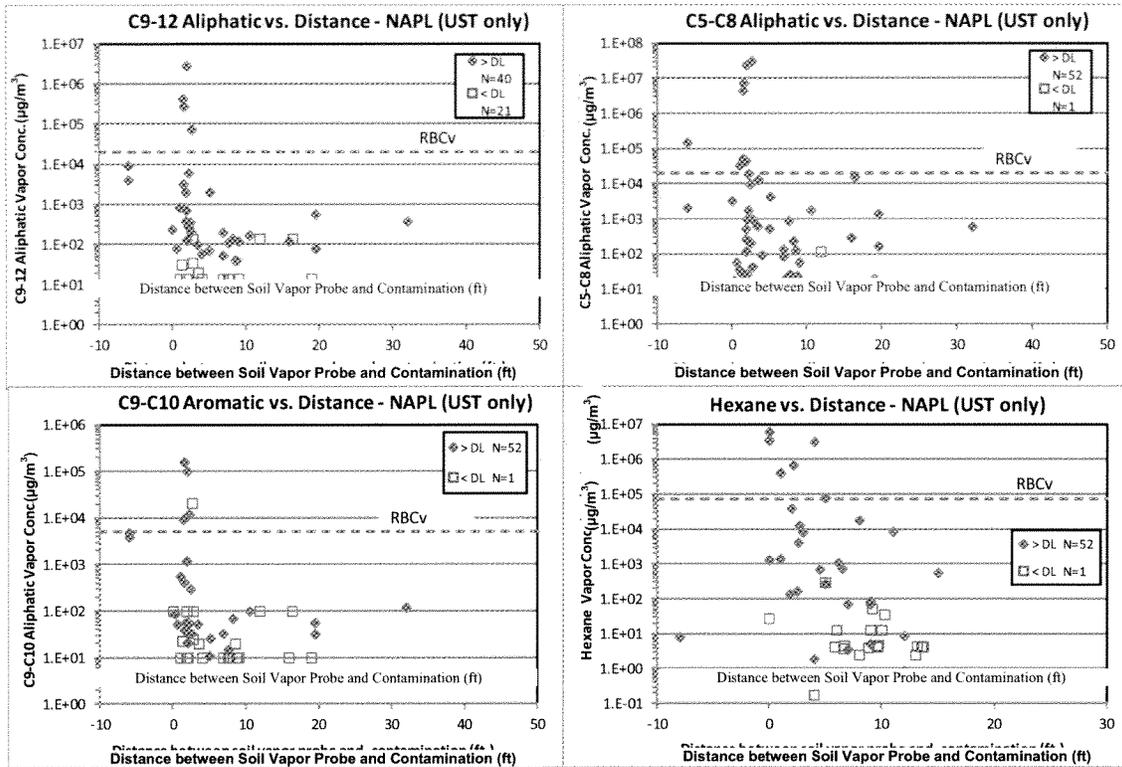
same comment as for dissolved source: what are the error bars

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on the calculated probabilities?

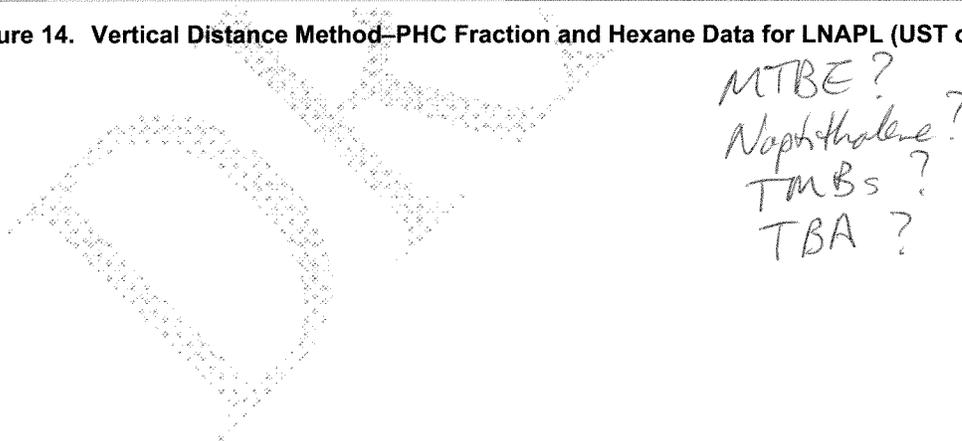
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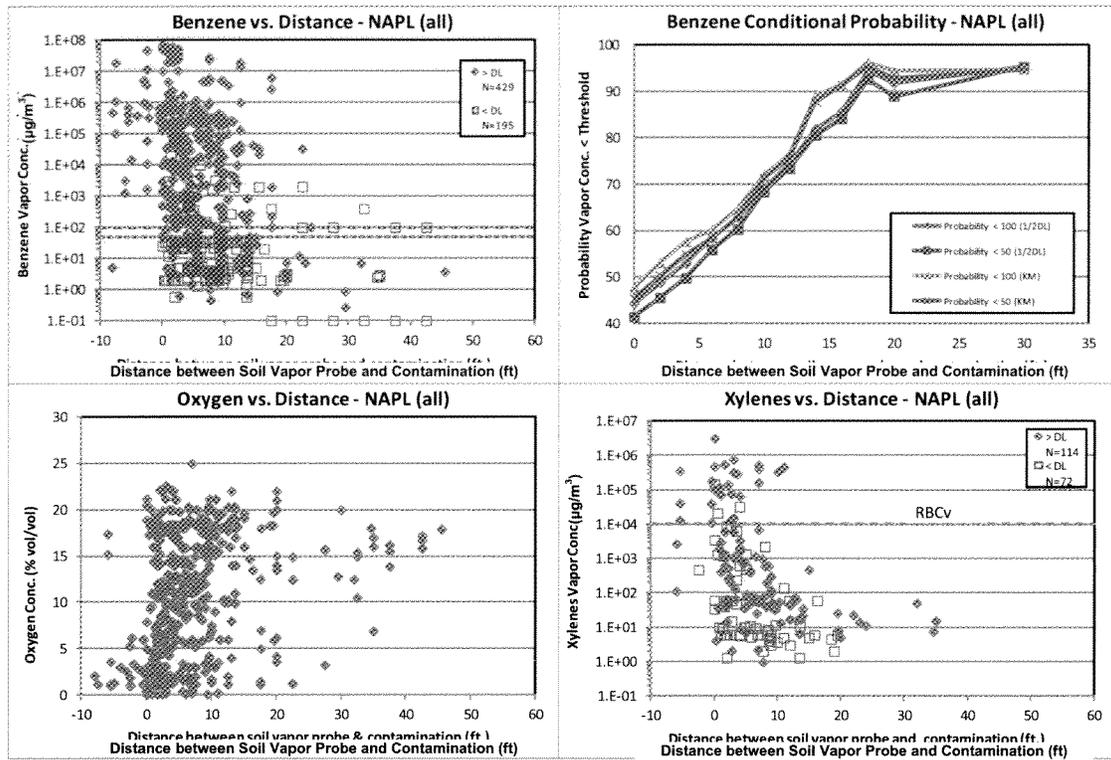
Figure 13. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (UST only) Sites (KM = Kaplan-Meier).



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1775

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

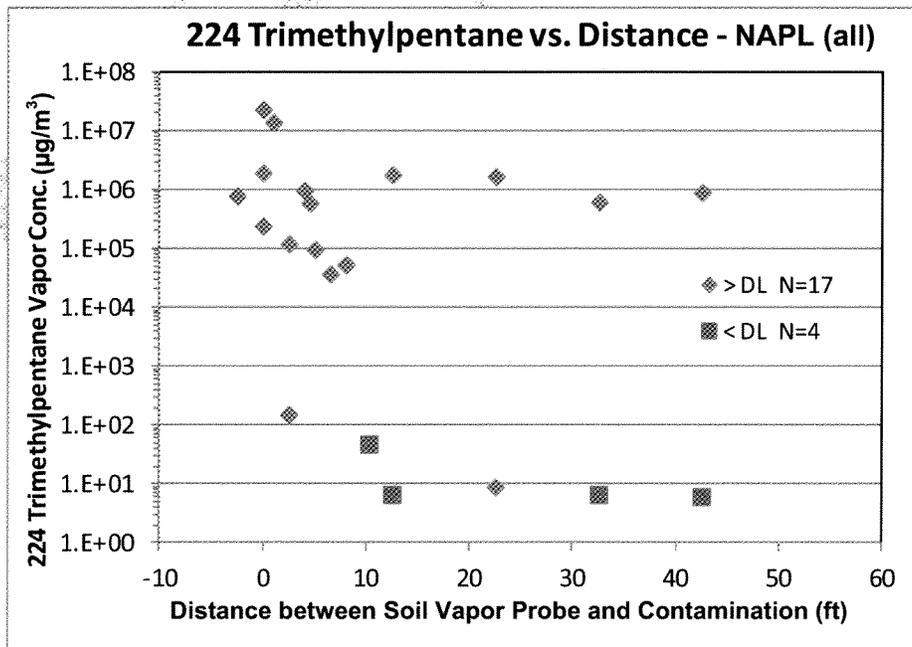




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Figure 15. Vertical Distance Method–Benzene, Xylenes and Oxygen Data for LNAPL (all sites) Sites (KM = Kaplan-Meier).

error bars?

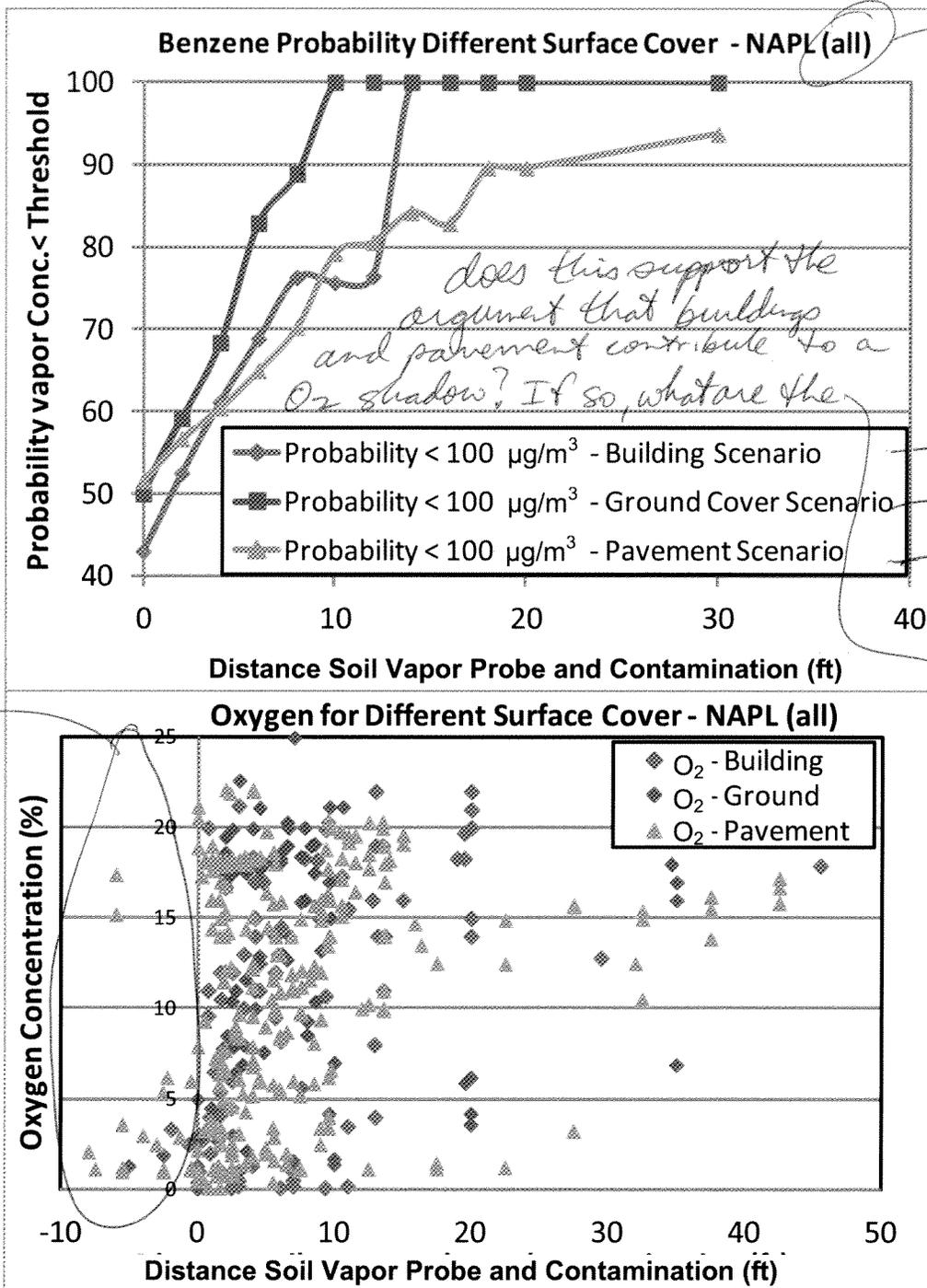


RBCv

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1780

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

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does this support the argument that buildings and pavement contribute to a O_2 shadow? If so, what are the

[Scribbled out text]

*n = _____
n = _____
n = _____*

implications for PVI site assessment scope and methods?

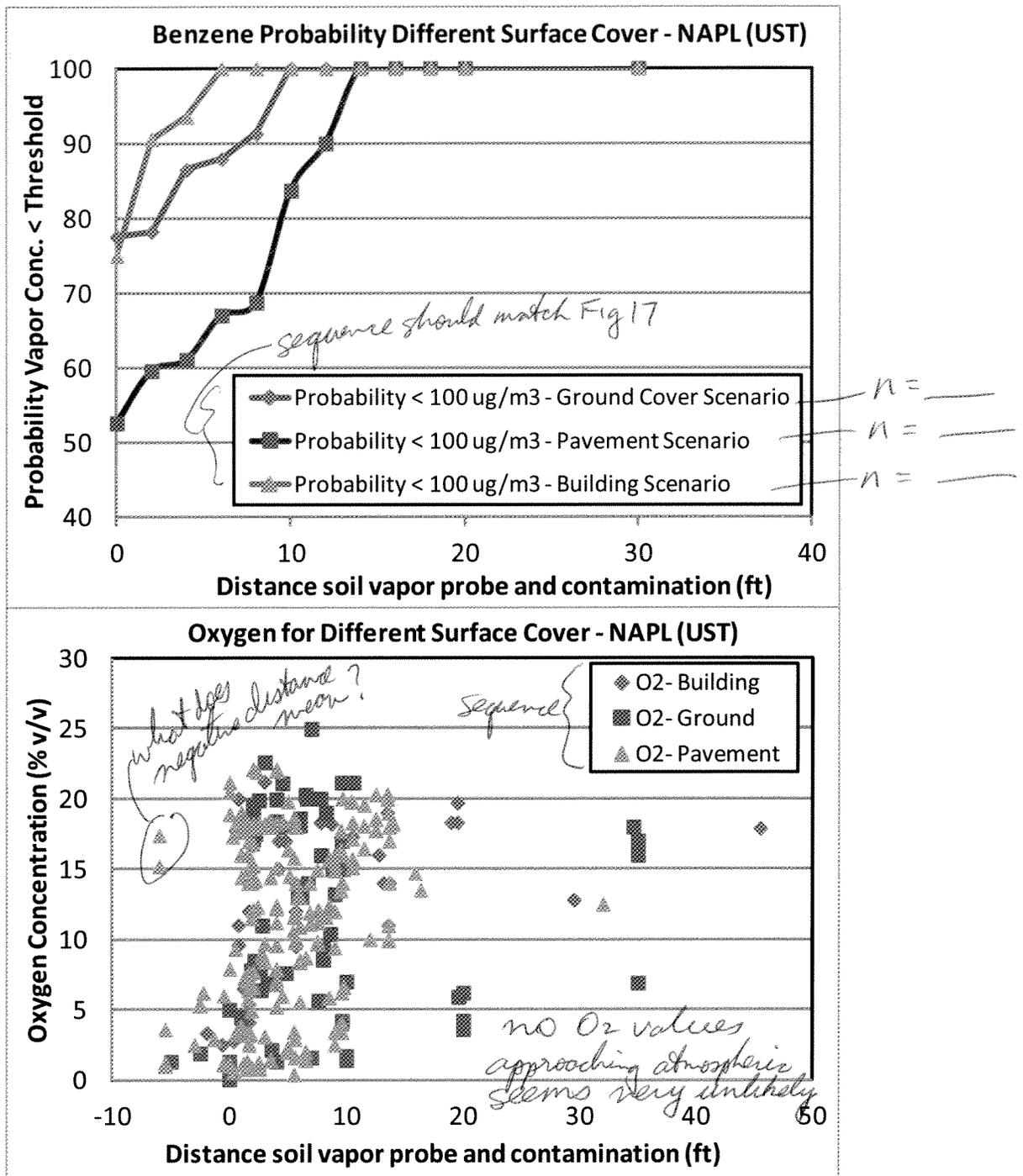
what does negative distance mean?

considering the scatter, what are the error bars on the probabilities?

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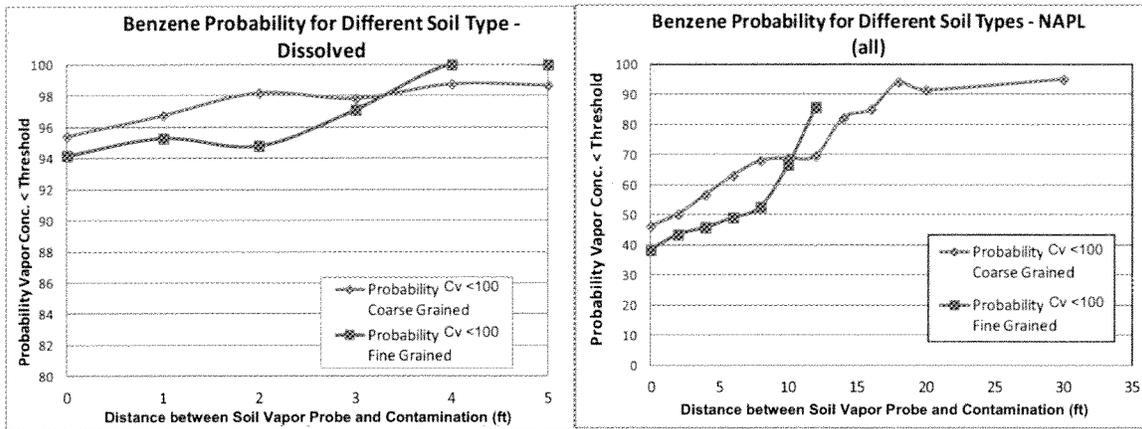
Figure 17. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (all sites). Below detection limit concentrations replaced with half the detection limit for analysis.

could plot them as open symbols



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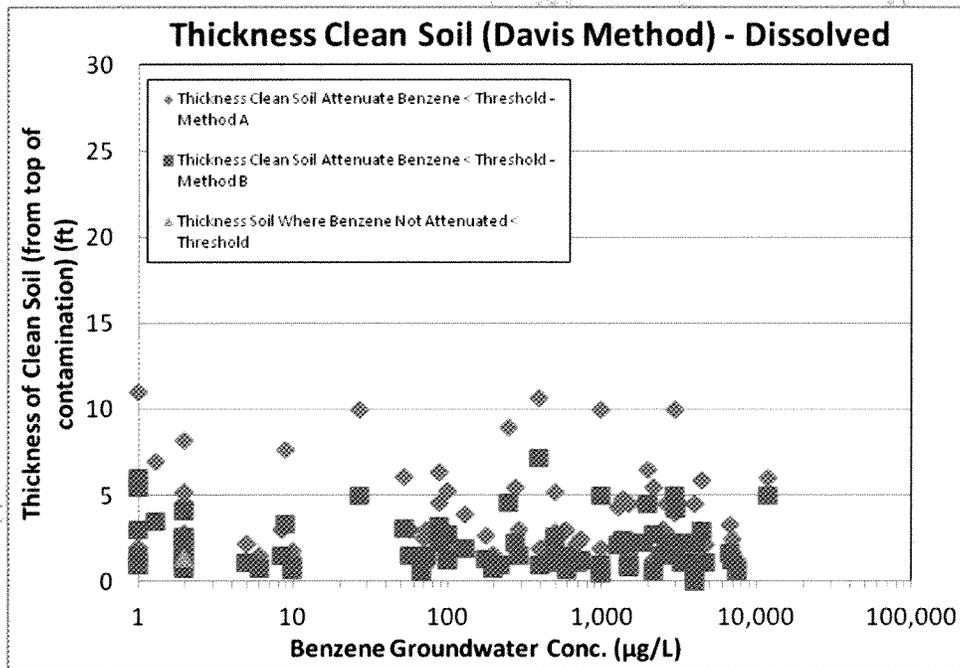
Figure 18. Comparison of Probability for Benzene Soil Vapor Concentrations to Exceed Threshold and Oxygen Concentrations for Different Surface Covers for LNAPL (UST sites). Below detection limit concentrations replaced with half the detection limit for analysis.



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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.

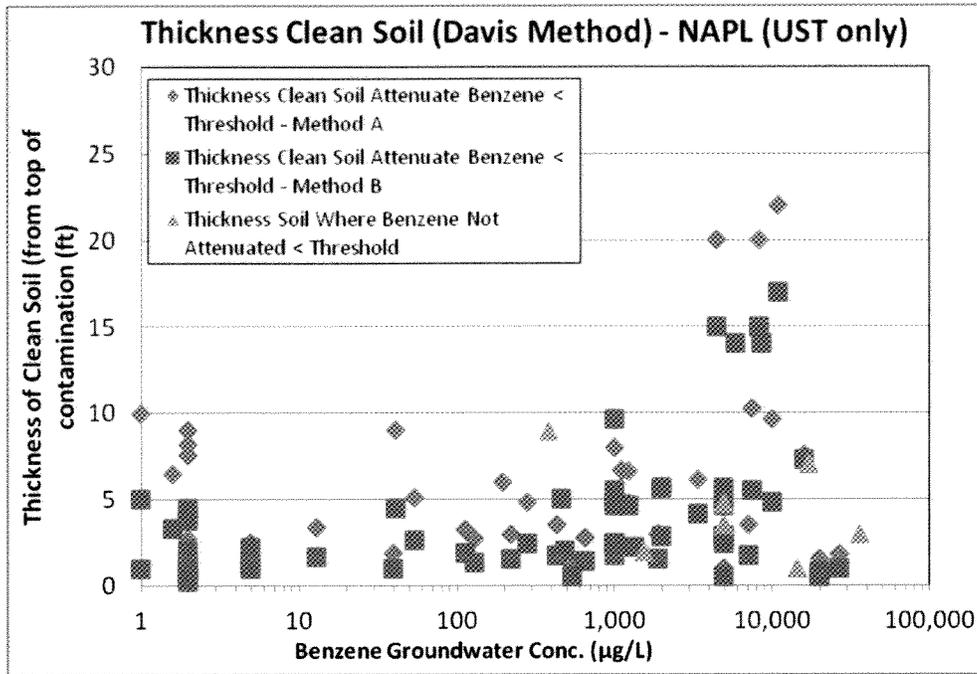
error bars



1795
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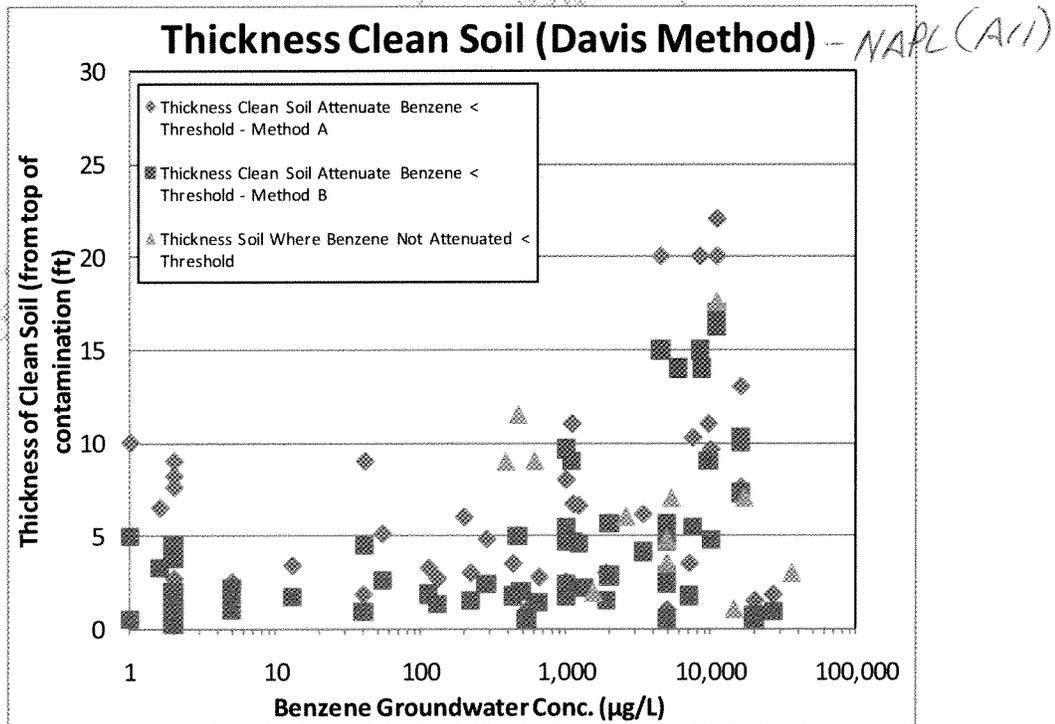
Figure 20. Results of Clean Soil (Davis) Method for Dissolved-Source Sites. 47 sites, N = 170.

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?



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



1800
1801

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

Chapter 13

**A CASE STUDY ON THE INFLUENCE OF AEROBIC
BIODEGRADATION ON VAPOR INTRUSION AT A
FORMER REFINERY PROPERTY**

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Santa Barbara, CA - 93101

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:
 - Spatial distribution of petroleum hydrocarbon vapors and biodegradation indicators (oxygen [O₂], carbon dioxide [CO₂] and methane [CH₄]);
 - Short-term (i.e., daily) temporal variability of soil gas concentrations, and
 - 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.

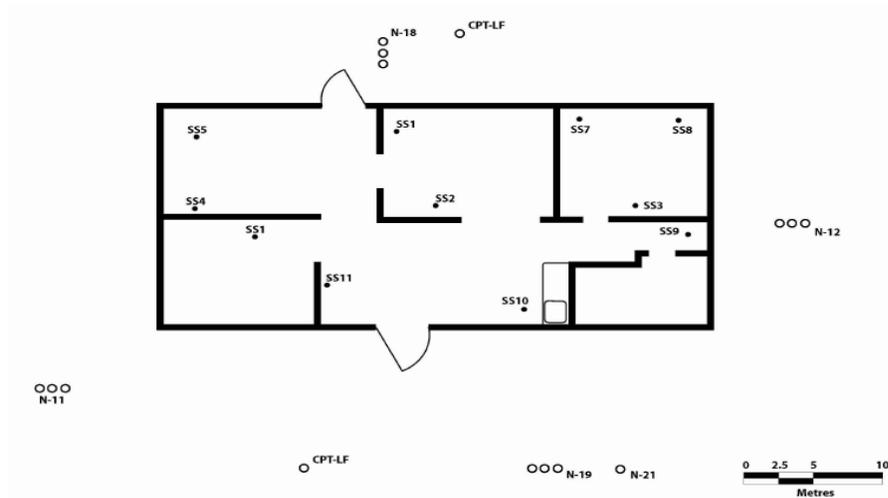


Figure 2. Layout of Office Building and Sampling Locations (scale in metres).

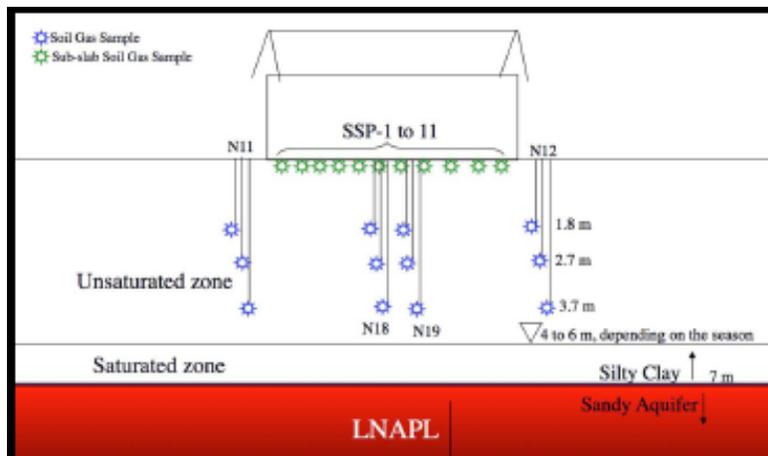


Figure 3. Cross-Section of Office Building and Sampling Locations (schematic) .

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 Nylaflo® 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-H₂O). After permeability testing and development, the probes were allowed to re-equilibrate at least overnight prior to purging and sampling.

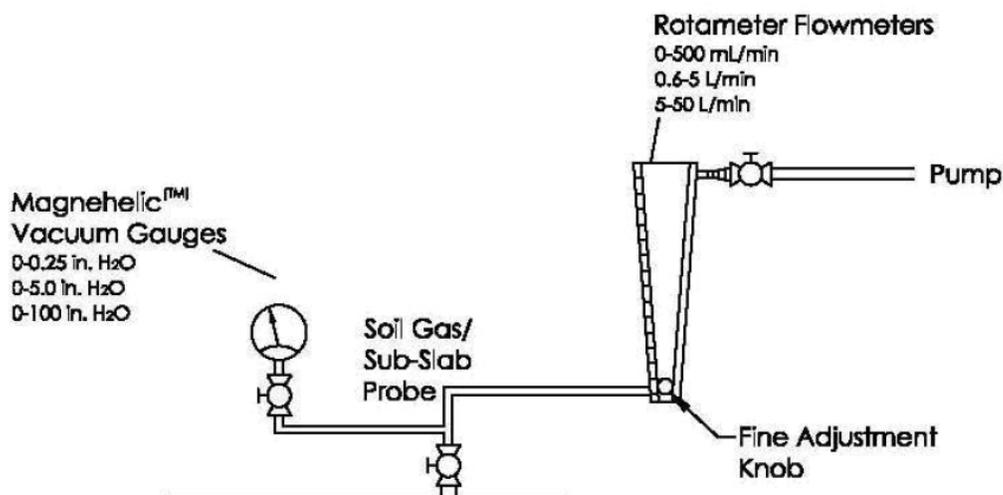


Figure 4. Schematic diagram of pneumatic testing apparatus.

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™ 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 O₂, CO₂ and CH₄. 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.

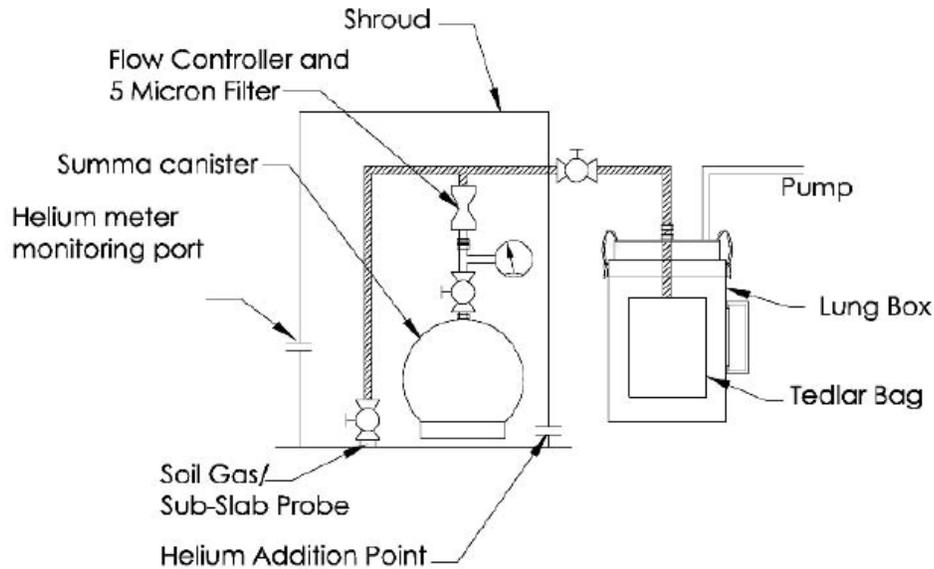


Figure 5. Soil Gas Sample Collection Apparatus.

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_v).

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 Nylaflo 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 Levelloggers 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
(after a very wet spring)**

Depth Range (m bgs)	In-Place Density (g/cm ³)	Moisture Content (weight %)	Porosity (%)	Calculated % Saturation	Fraction of Organic Carbon (g/kg)
0.3-0.6	1.60	18.2	39.2	74%	7.20
1.2-1.5	1.62	18.9	38.8	79%	7.25
2.1-2.4	1.70	20.4	36.1	96%	3.50
3.0-3.3	1.58	21.1	39.7	84%	7.25
4.0-4.3	1.72	19.8	35.4	96%	1.95
5.2-5.5	1.75	15.8	34.1	81%	2.25
5.5-5.8	1.65	19.3	37.9	84%	2.05
5.8-6.1	1.65	19.3	38.1	83%	2.35

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).

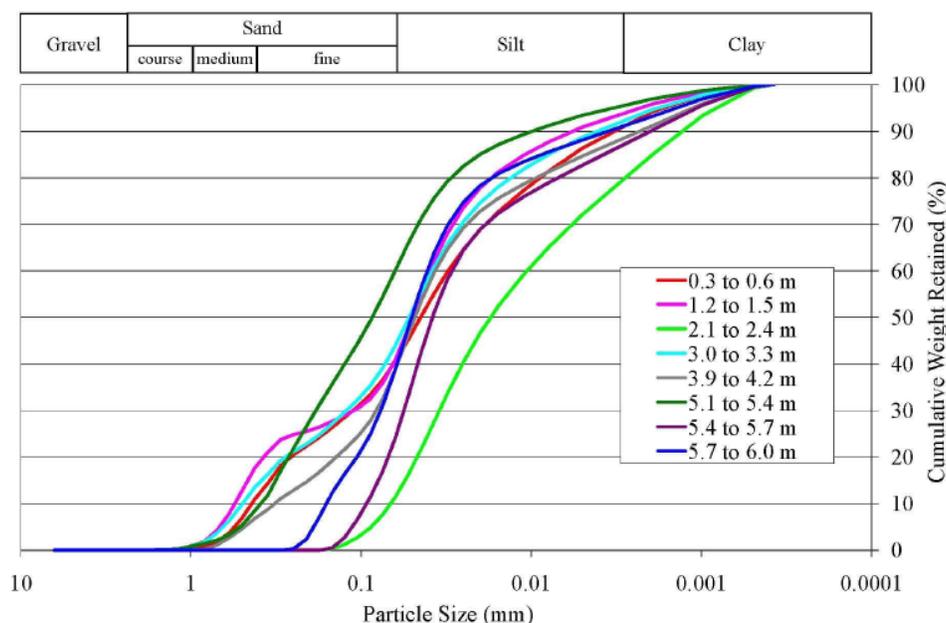


Figure 6. Grain Size Distributions for Soil Samples from Boring N-21.

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).

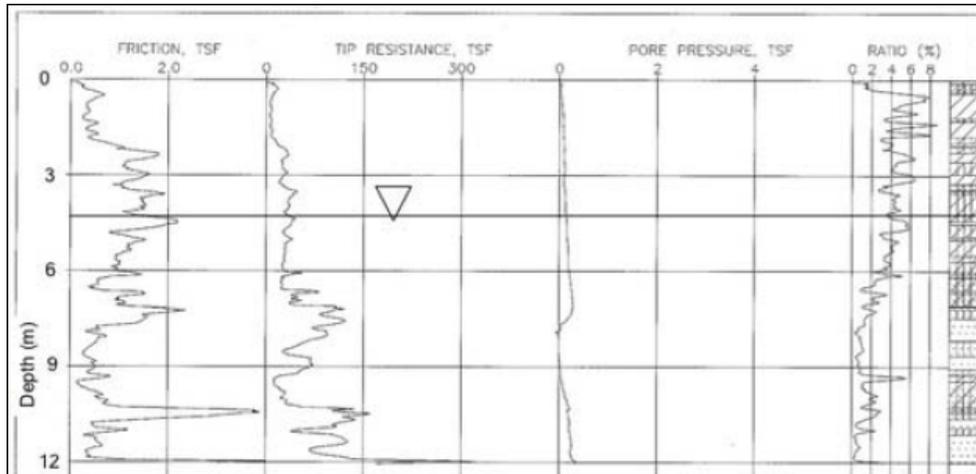


Figure 7. Cone-Penetrometer Log for CPT-LIF-2 Showing Inferred Geology.

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.

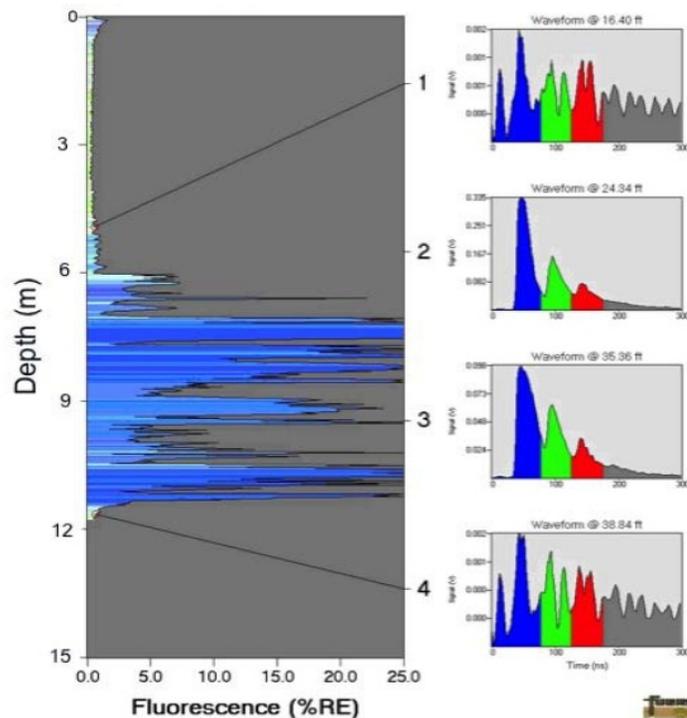


Figure 8. Laser-Induced Fluorescence Log for CPT-LIF-2 showing residual LNAPL in 6.1 to 11.3 m bgs interval.

Table 2. Helium Tracer Data

Well ID	Date	Helium Tracer Gas (%)				Percentage of Sample Volume Attributable to Influx from the Shroud
		Shroud		Field Screening Sample	Laboratory Sample	
		Minimum	Maximum			
N-11A	17-Oct-06	30.9	44.2	0.0	0.0085	0.0%
N-11B	17-Oct-06	30	47	0.0	4.0	13.3%
N-11C	22-Oct-06	30	30	NA	0.01	0.0%
N-12A	18-Oct-06	39	58	0.0	0.0056	0.0%
N-12B	22-Oct-06	30	65	NA	0.012	0.0%
N-12C	19-Oct-06	25.0	85.0	NA	0.0077	0.0%
SSP-01	18-Oct-06	41	47	0.0125	0.0061	0.0%
SSP-02	18-Oct-06	35	61	0.0	0.0062	0.0%
SSP-03	18-Oct-06	40	54	0.0	0.0064	0.0%
N-11A	6-Jun-07	14	31	NA	0.005	0.0%
N-11B	6-Jun-07	10	13	NA	0.0049	0.0%
N-12A	8-Jun-07	10	30	NA	0.0052	0.1%
N-12B	11-Jun-07	11.0	25.0	NA	0.011	0.1%
N-12C	10-Jun-07	16.0	31.2	NA	0.008	0.1%
N-18A	7-Jun-07	17.0	28.0	NA	0.013	0.1%
N-18B	7-Jun-07	29.0	56.0	NA	0.23	0.8%
N-18C	7-Jun-07	29.0	56.0	NA	0.0084	0.0%
N-19A	7-Jun-07	23.0	38.0	NA	0.24	1.0%
N-19B	7-Jun-07	17.0	53.0	NA	0.0063	0.0%
N-19C	7-Jun-07	30.0	49.7	NA	0.012	0.0%
N-20A	7-Jun-07	18.2	21.5	NA	0.92	5.1%
N-20B	7-Jun-07	18.2	21.5	NA	0.0052	0.0%
N-20C	7-Jun-07	18.2	21.5	NA	0.011	0.1%
SSP-01	6-Jun-07	10	16	0.0	0.0054	0.1%
SSP-02	6-Jun-07	10	12	0.0	0.0052	0.1%
SSP-03	6-Jun-07	10	15	0.0	0.032	0.3%
SSP-04	7-Jun-07	23.2	31.4	0.0	0.015	0.1%
SSP-05	7-Jun-07	18.4	26.9	0.0	0.054	0.3%
SSP-06	7-Jun-07	10.9	29.3	0.0	0.0045	0.0%
SSP-07	7-Jun-07	13.9	27	0.0	0.0054	0.0%
SSP-08	7-Jun-07	10	24	0.0	0.087	0.9%
SSP-09	7-Jun-07	10.4	25.6	0.0	0.0083	0.1%
SSP-10	7-Jun-07	28	32	0.0	0.028	0.1%
SSP-11	7-Jun-07	11	63	0.0	0.017	0.2%

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

Depth		N-11		N-12		N-18**	N-19
		Oct-06	Jun-07	Oct-06	Jun-07	Jun-07	Jun-07
1.8 m	Benzene $\mu\text{g}/\text{m}^3$	<3.2	2,200	7.9	500/ 418 ^F	20	55
	TPHs $\mu\text{g}/\text{m}^3$	2,000	8,000,000	1,000	1,000,000	40,000	30,000
	Oxygen %	18	0.0	20.3	0.2	18.5	7.6*
	Carbon Dioxide %	3	7.7	2.7	4.0	1.0	2.3*
	Methane %	6.4	19.4	0.2	3.0	0.0	<0.7*
2.7 m	Benzene $\mu\text{g}/\text{m}^3$	40,000	41,000	12,000	16,000	30	920
	TPHs $\mu\text{g}/\text{m}^3$	46,000,000	40,000,000	700,000	2,000,000	40,000	3,000,000
	Oxygen %	1.0	0.6	4.6	2.0	17.7	15
	Carbon Dioxide %	14.3	14.6	8.6	8.9	1.2	2.3
	Methane %	70	70	11.7	27	0.1	0.5
3.6 m	Benzene $\mu\text{g}/\text{m}^3$	42,000	NA	33,000	44,000	7,100	2,900
	TPHs $\mu\text{g}/\text{m}^3$	40,000,000	NA	10,000,000	10,000,000	400,000	9,000,000
	Oxygen %	4.1	NA	5.0	6.5	18	4.7*
	Carbon Dioxide %	13.3	NA	6.9	11.4	1.1	5.9*
	Methane %	NM	NA	36.7	39.3	0.1	1.9*

* - 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

		Day				
		1	2	3	4	5
SS-1	TPHs $\mu\text{g}/\text{m}^3$	10,000	400,000	300,000	200,000	200,000
	Benzene $\mu\text{g}/\text{m}^3$	11	<190	<87	<68	<41
	O ₂ %	1.21	1.1	0.5	1.27	0.1
SS-2	TPHs $\mu\text{g}/\text{m}^3$	600,000	700,000	200,000	300,000	400,000
	Benzene $\mu\text{g}/\text{m}^3$	<42	<130	<44	<61	<43
	O ₂ %	1.39	0.8	0.5	1.1	0.1
SS-3	TPHs $\mu\text{g}/\text{m}^3$	1,000	900	600	1,000	400
	Benzene $\mu\text{g}/\text{m}^3$	<2.2	<2.8	<2.5	11	<2.3
	O ₂ %	2.11	1.3	5.2	5.85	3.5

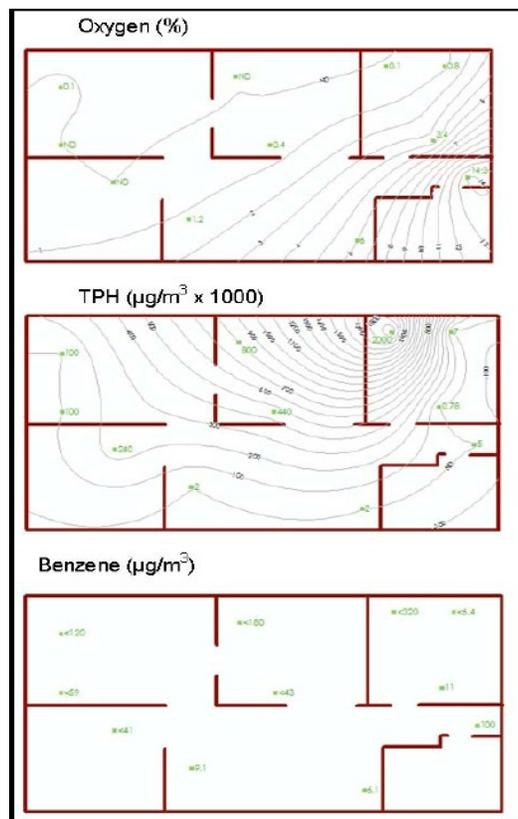
The results of seasonal sampling at sub-slab probes SS-1, SS-2 and SS-3 are shown in Table 5. There was an increase of over one order of magnitude in the TPH concentrations in SS-1 and SS-2, corresponding with a decrease in oxygen, with similar results at SS-3, except that the TPH concentration decreased.

Table 5. Long-Term Temporal Data from Sub-Slab Probes inside the Office Building

	SS-1		SS-2		SS-3	
	Oct-06	Jun-07	Oct-06	Jun-07	Oct-06	Jun-07
Benzene ($\mu\text{g}/\text{m}^3$)	<48	<41	<12	<43	<8.8	11
TPHs ($\mu\text{g}/\text{m}^3$)	10,000	200,000	10,000	300,000	10,000	1,000
Oxygen (%)	6.6	0.0	6.6	0.4	12.8	3.4

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.

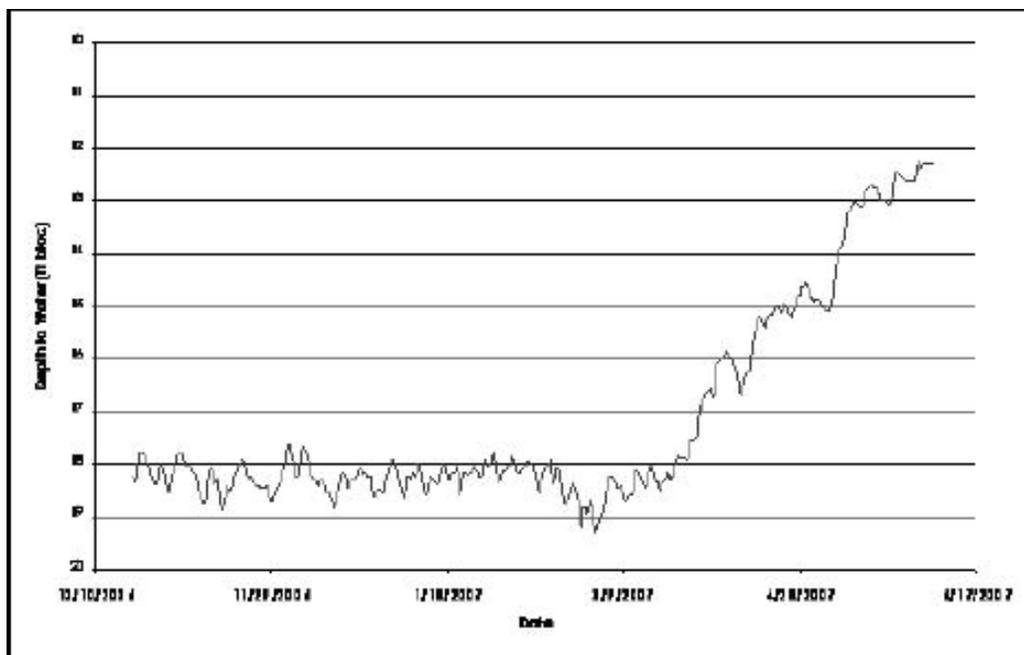


Figure 10. Water level data between first and second sampling rounds

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.

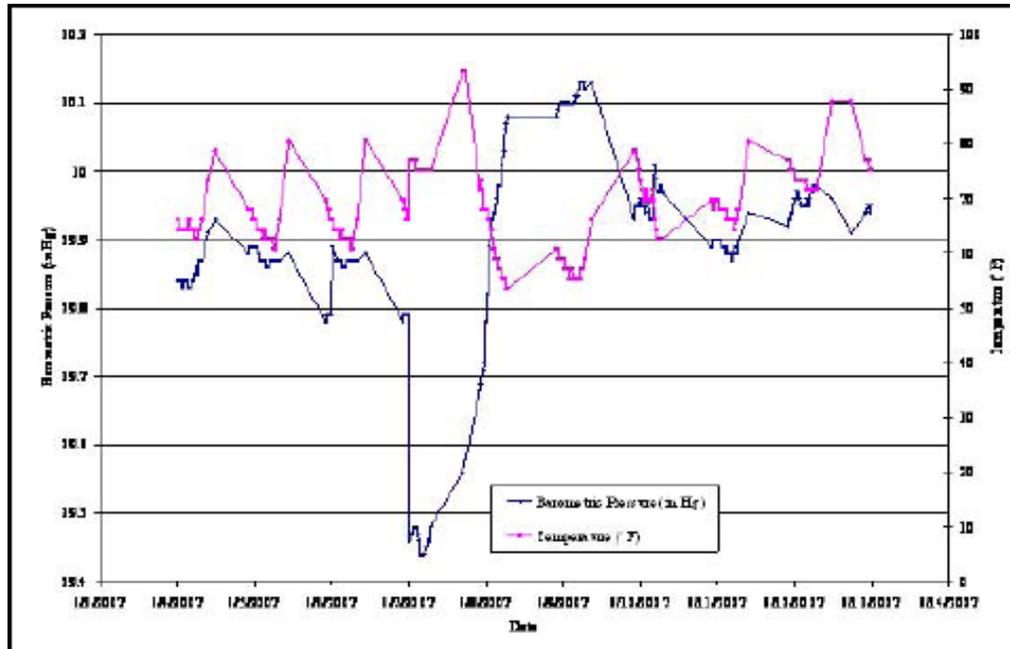


Figure 11. Barometric Pressure and Temperature during July 2007 Sampling Event.

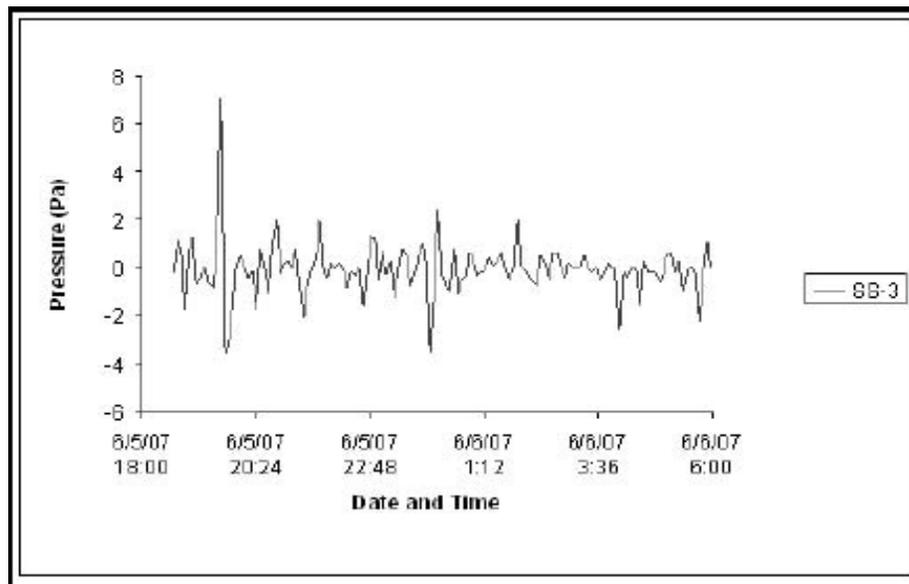


Figure 12. Differential Pressure from Sub-Slab to Indoor Air.

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

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 (DeVaul 2007).

Input values for the modeling are presented in Table 6.

Table 6. Fate and Transport Modeling Input Parameters

Model Input Parameter	Value Used	Rationale
Soil Properties		
Average Soil / Groundwater Temperature (Ts), oC	18	Area-specific average
Depth below grade to bottom of enclosed space floor (LF), cm	15	Slab construction
Thickness of soil stratum A (hA), cm	183	Based on Soil Borings, 6 ft
Stratum A soil total porosity, unitless	0.390	Based on soil physical property measurements
Stratum A soil water-filled porosity, cm ³ /cm ³	0.293	Based on soil physical property measurements
Thickness of soil stratum B (hB), cm	183	Based on Soil Borings, 6 ft
Stratum B soil total porosity, unitless	0.380	Based on soil physical property measurements
Stratum B soil water-filled porosity, cm ³ /cm ³	0.348	Based on soil physical property measurements
Crack-to-total-area ratio (λ), unitless	0.005	Default assumption
Building Parameters		
Enclosed space floor thickness (Lcrack), cm	10	Default assumption
Enclosed space floor length (LB), cm	1000	Default assumption (10 meters)
Enclosed space floor width (WB), cm	1000	Default assumption (10 meters)
Floor-wall seam crack width (w), cm	0.1	Default assumption
Average vapor flow rate into building (Qsoil), L/m	5	Based on 5 L/min per 100 m ² of building floor space
Residential Building Parameters		
Enclosed space height (HB), cm	300	Proposed ceiling height (8 feet or 2.44 meters)
Indoor air exchange rate (ER), hour ⁻¹	0.5	Residential building assumption

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.

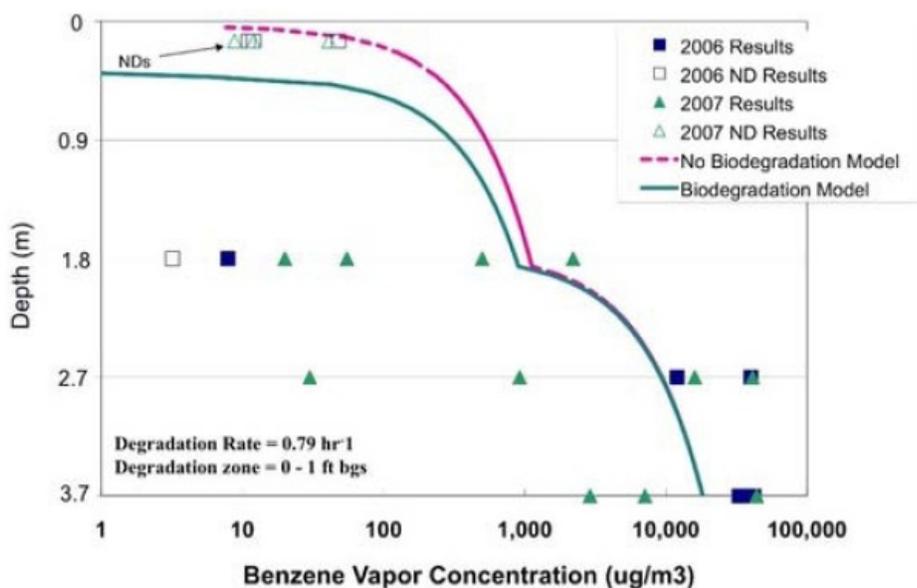


Figure 13. Comparison between measured vertical profiles of benzene and profiles calculated using the Johnson and Ettinger (1991) model and the Dominant Layer Model (1998).

One dimensional modeling was also used to calculate the vapor intrusion attenuation factor, α , 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 ($\mu\text{g}/\text{m}^3$) to less than $100 \mu\text{g}/\text{m}^3$ 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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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 (O₂) is present at sufficient concentrations, soil microbes will

metabolize the petroleum hydrocarbons in the pore moisture, while consuming O_2 and producing carbon dioxide (CO_2). Microbiologic degradation also occurs in the absence of O_2 , producing methane (CH_4). The CH_4 will subsequently diffuse upward and be degraded aerobically along with other hydrocarbons at shallower depths where O_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_2 and volatile constituents in the soil vapor are optimal for the growth of petrophilic bacteria, as described by DeVaul et al. 1997¹. Aerobic biodegradation has the potential to reduce soil gas concentrations by several orders of magnitude, as long as the supply of O_2 is not rate limiting (DeVaul et al. 1997¹, DeVaul et al. 2002², Roggemans et al. 2001³, Abreu et al. 2009⁴).

Oxygen in the atmosphere diffuses down into the unsaturated zone when a concentration gradient is present. Atmospheric O_2 also migrates downward advectively via barometric pumping and by infiltration of dissolved O_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 1992⁵). This process ensures that the upper 1 to 3% of the thickness of the vadose zone is well aerated (O_2 concentrations similar to atmospheric levels). In the absence of aerobic degradation, O_2 levels will approach atmospheric levels throughout the vadose zone. Where O_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 2005⁶, NYSDOH 2005⁷, Batterman 2007⁸, USEPA 2008⁹, MADEP 2008¹⁰, Dawson and McAlary 2009¹¹, 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_2 , and CO_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. 1997¹², Hers and Zapf-Gilje 1998¹³,

McAlary et al. 2007¹⁴, Luo et al. 2009¹⁵) and numerical modeling (Abreu and Johnson 2005¹⁶ and 2006¹⁷) of a single building scenario. Roggemans et al. 2001³ 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., O₂ and CO₂) 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.³ 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 (CO₂ 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 O₂ and production of CO₂, 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 O₂ concentrations usually approach atmospheric conditions at ground surface.
- Behavior B (“Aerobic Biodegradation Rate-Limited Settings”) – hydrocarbon vapor concentrations decrease and O₂ concentrations increase above the source at depth to the ground surface, similar to the Behavior A wells. However, O₂ 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 (“O₂ Deficient Subsurface Settings”) – hydrocarbon vapor concentrations are persistent and O₂ is depleted throughout the vertical profile. Volatile petroleum constituents migrate by diffusion from the source to the shallow subsurface. Roggemans et al. 2001³ 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 O₂ 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 O₂ 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. 2001³ 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.

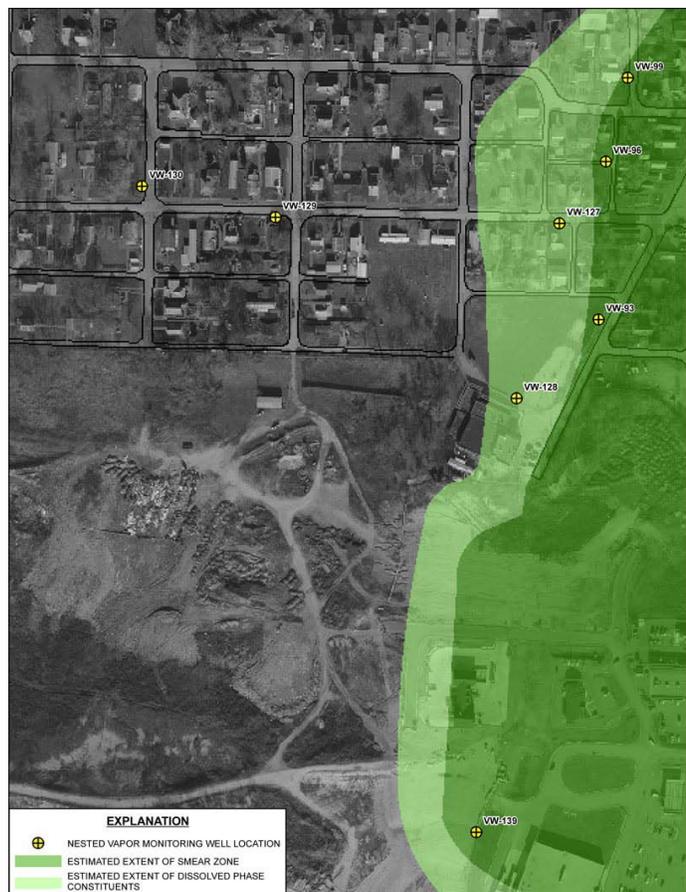
It is important to understand the processes contributing to or limiting aerobic biodegradation and the affect on vapor flux at petroleum release sites. This becomes particularly important when multiple sources are present because shallow alternate sources are rarely well characterized yet have the potential to significantly affect the VI pathway, primarily by depleting O₂ as it diffuses through the vadose zone. The data collected during this study provide information regarding the spatial and temporal variability of O₂ 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

Figure 1: Nested Vapor Monitoring Well Locations and Limits of Smear Zone/Dissolved Phase Hydrocarbons



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* (2005¹⁸) 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. 2009¹⁹.

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)^a and O₂

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 O₂ 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. 2001³. 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. 2001³. 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

Figure 2: TVPH and Oxygen Profiles, Well VW-93 (1997-1999)

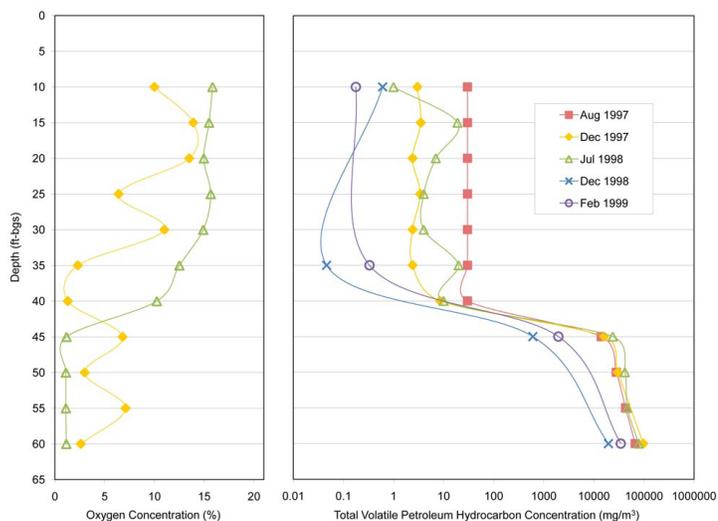
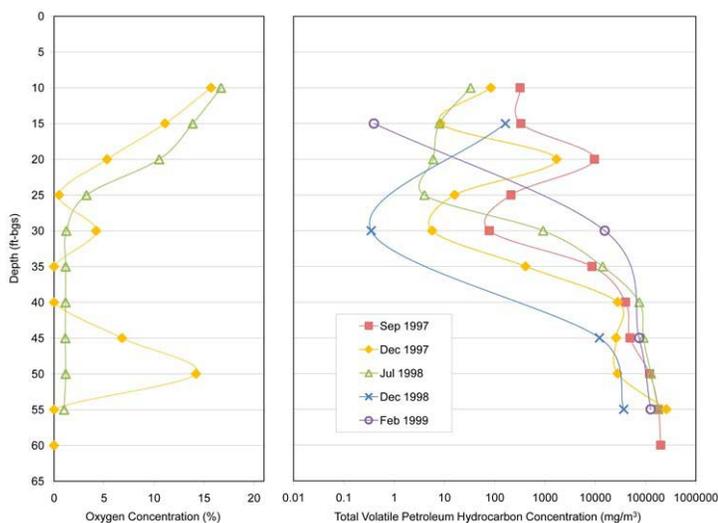


Figure 3: TVPH and Oxygen Profiles, Well VW-96 (1997-1999)



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.

Figure 4: TVPH and Oxygen Profiles, Well VW-99 (1997-1999)

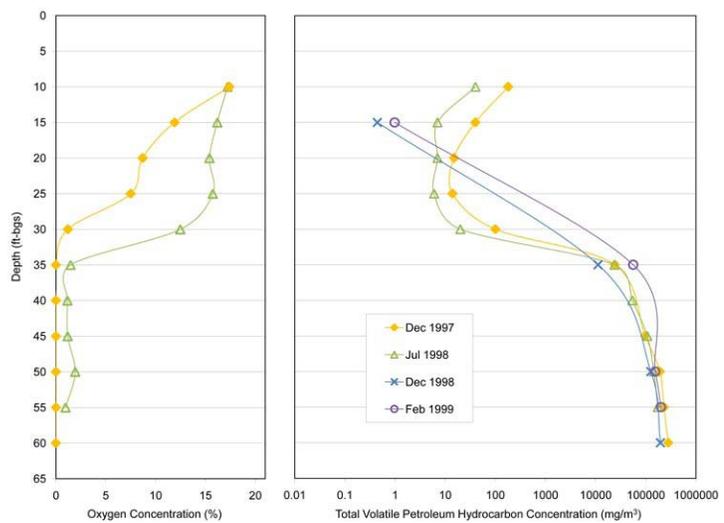
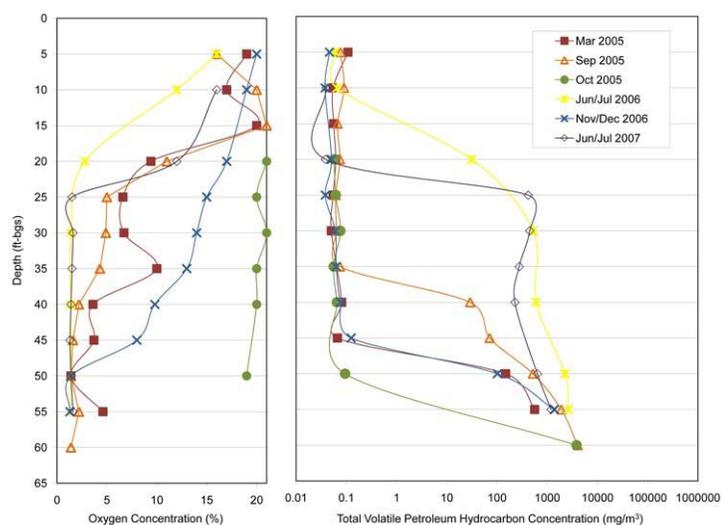


Figure 5: TVPH and Oxygen Profiles, Well VW-96 (2005-2007)



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. 1985²⁰ and Conn and Seigrist 2009²¹, document releases of volatile petroleum-related constituents from septic systems. Robertson et al. 1991²² 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,

Figure 6: TVPH and Oxygen Profiles, Well VW-99 (2005-2007)

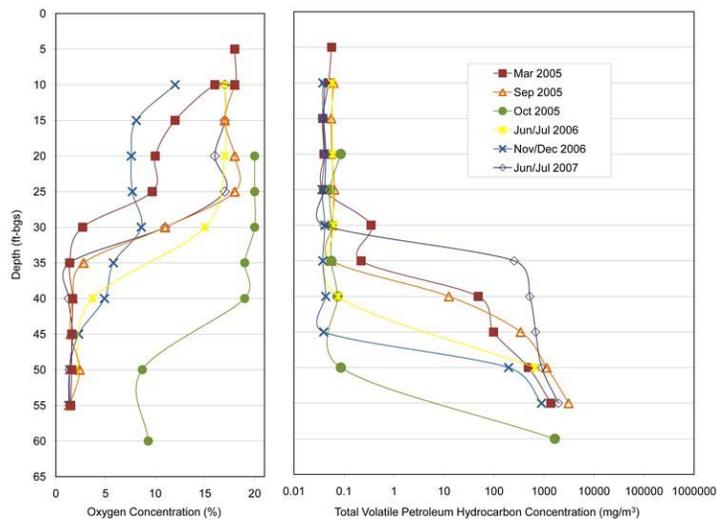
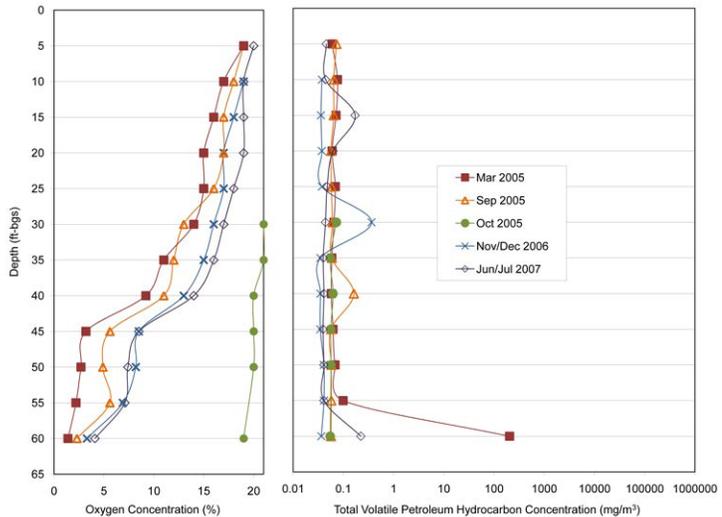


Figure 7: TVPH and Oxygen Profiles, Well VW-93 (2005-2007)



show that O₂ 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 O₂ 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 O₂ 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 O₂ 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. 2001³, 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/m³) in all three of these wells located above the smear zone (VW-96, VW-99, and

Figure 8: TVPH and Oxygen Profiles, Well VW-127 (2005-2007)

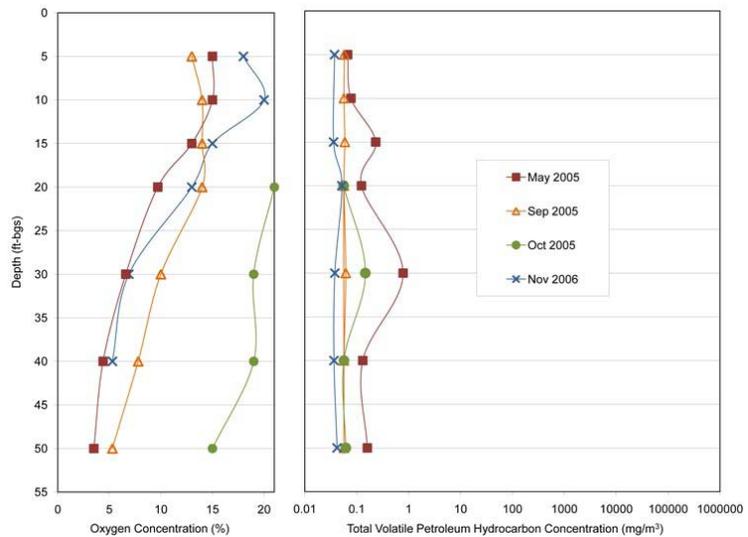
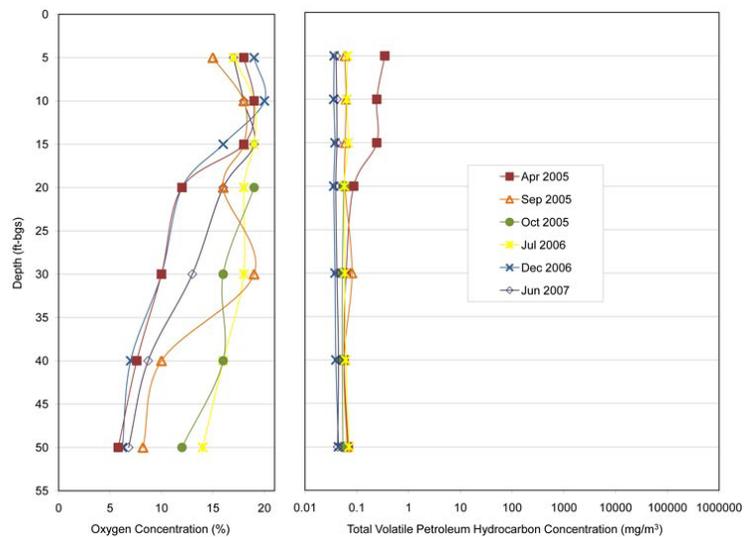
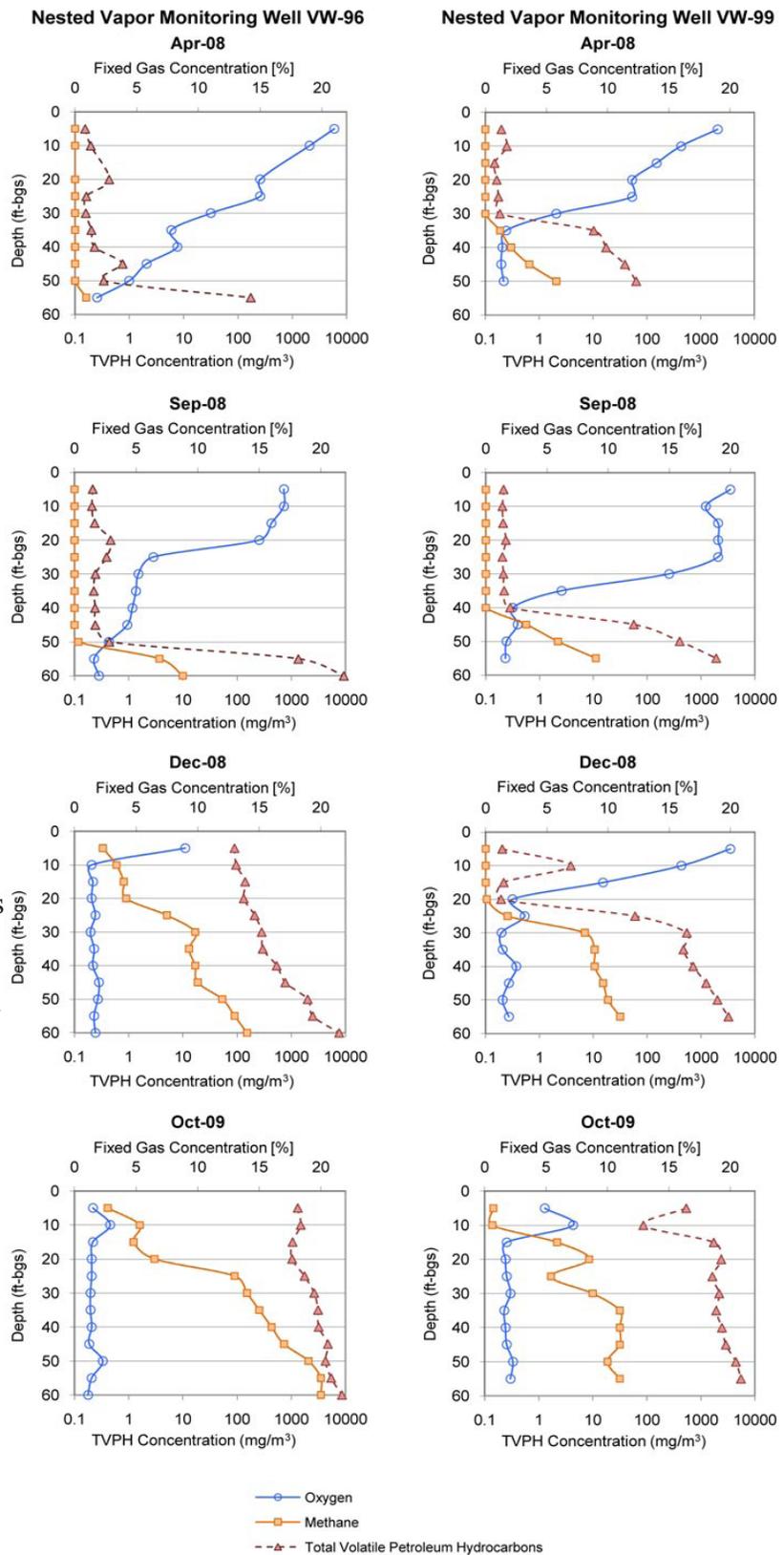


Figure 9: TVPH and Oxygen Profiles, Well VW-128 (2005-2007)



VW-139). There are no potential alternate sources of petroleum-related constituents observed at VW-139. Therefore, O₂ 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.

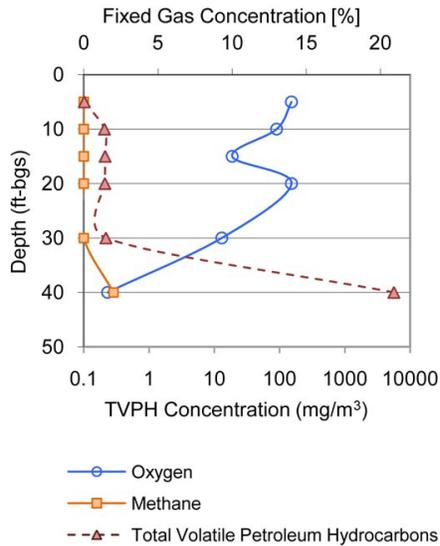
Figure 10: TVPH and Fixed Gas Profiles, Wells VW-96 and VW-99 (2008-2009)



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

Figure 11: TVPH and Fixed Gas Profiles, VW-139 (Oct 2009)



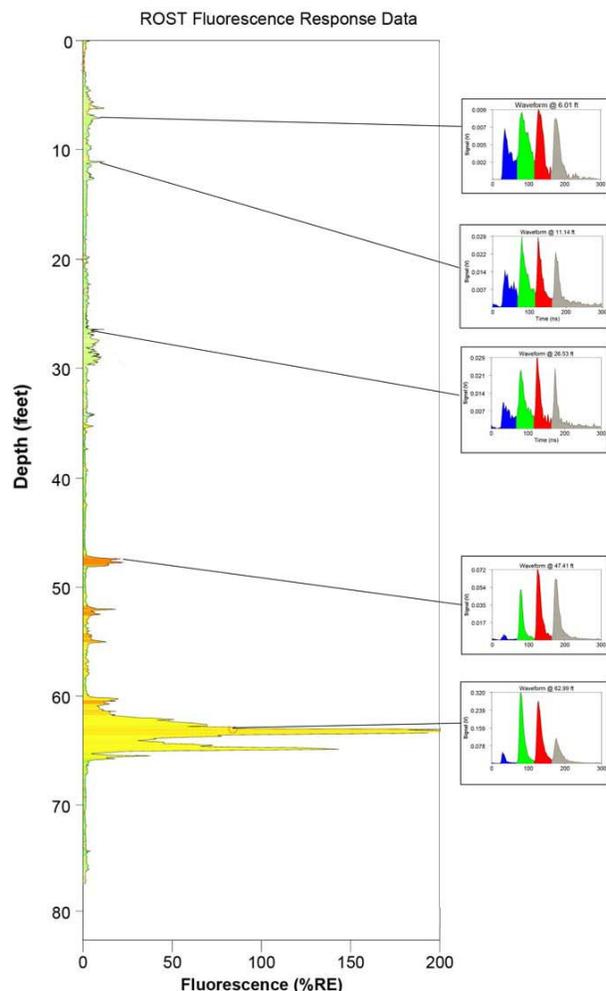
and 50 feet (with the exception of a spike near 47 ft-bgs associated with the upper limits of the smear zone). The elevated intensities observed within the upper 30-feet of the profile during these two events are indicative of alternate petroleum-related sources in the vadose zone, because these responses 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.

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

Figure 12: ROST Profile, Well VW-96 (Dec 2009)

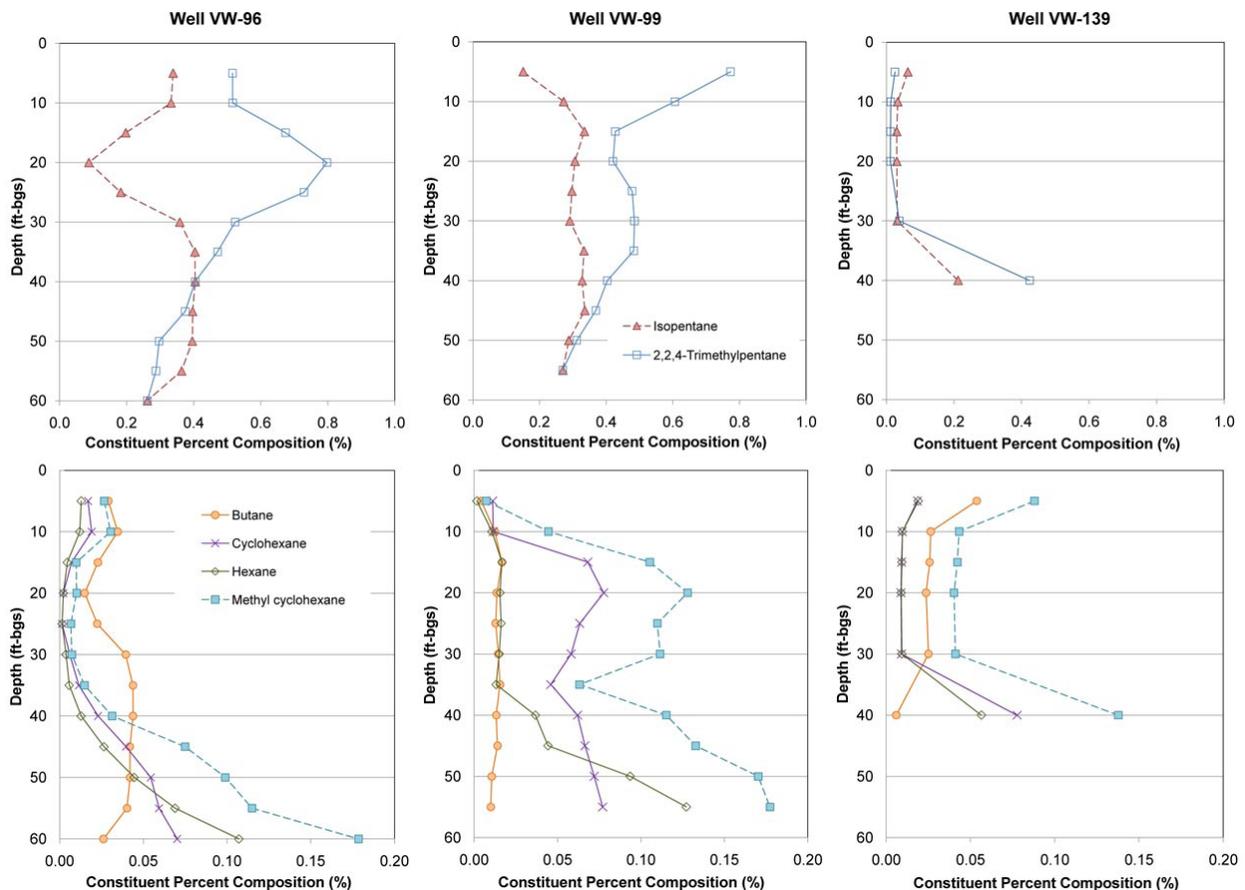


Percent Compositional Profiles

Individual petroleum-related constituents are expected to degrade at different rates based on the availability of O_2 , 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

Figure 13: Constituent Compositional Profiles (Oct 2009)



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_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_2 consumption and decreased hydrocarbon degradation.

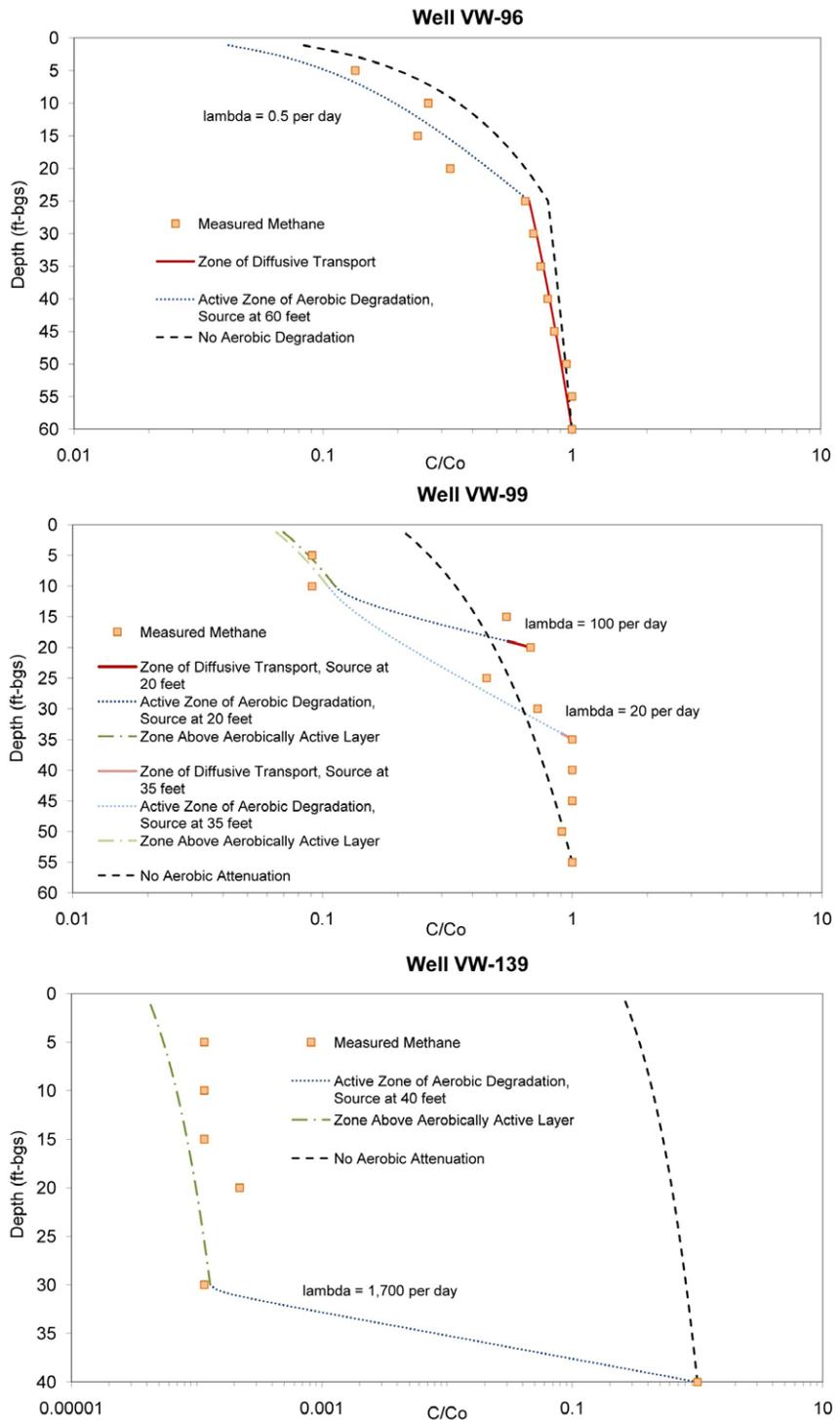
Mathematical Modeling

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. 1999²³. The time series profiles (Figure 10) for wells VW-96 and VW-99 show an evolution in the O_2 and CH_4 profiles from an initial condition that is predominantly aerobic throughout the vadose zone to predominantly anaerobic conditions with a nearly linear CH_4 profile during October 2009. This would be consistent with diffusion dominated transport with minimal aerobic biodegradation. In October 2009, the concentrations of CH_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_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_4 was far greater than the remainder of petroleum hydrocarbons, it would impose the highest O_2 demand. As such, DLM simulations were performed using CH_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 (λ) that generated the best match

between the data and the model was consistent with literature cited values. According to a compilation by DeVaul 2007²², aerobic biodegradation rates are typically in the range of about 96 to 28,000 day⁻¹ for straight-chain aliphatic hydrocarbons. However, longer-chained hydrocarbons generally degrade at slower rates, so CH₄ 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 CH₄ 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⁻¹, which is the median rate for aliphatic compounds reported by DeVaul 2007²⁴. This profile is consistent with expectations where O₂ transport is not rate limited and CH₄ is completely degraded within a very short distance of the source, typical of Behavior A profiles described by Roggemans et al. 2001³.

Figure 14 : DLM Simulations (Oct 2009)



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 DeVaul 2007²⁴. 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.

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Todd A. McAlary
Principal

**subsurface vapor transport and inhalation exposure
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 co-authors (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, \$1Million 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 Intursion, 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 (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 Lumpur Philippines, Thayer 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

RCRA Supplemental Guidance for Subsurface Vapor Intrusion to Indoor Air: One of 3 primary co-authors for the first US EPA Guidance on screening sites for the potential for health risks attributable to Vapor Intrusion (<http://www.epa.gov/epaoswer/hazwaste/ca/eis/vapor.htm>), December, 2001.

US EPA OSWER Guidance Expert Panel: Paid member of the Expert Panel for responses to comments on the 2002 Draft Federal US EPA (OSWER) Vapor Intrusion Guidance document (<http://www.epa.gov/correctiveaction/eis/vapor.htm>), the only non-regulator on the Panel for the seminar series to introduce the OSWER Guidance

(<http://www.epa.gov/ttnrml/presentations.htm>) 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/00000000001008492.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.

Atlantic Province PIRI Appendix 9: Co- author of the Atlantic Provinces Partnership for RBCA Implementation (PIRI) Guidance for Soil Vapour and Indoor Air Monitoring Assessments (http://www.atlanticrca.com/eng/soil_vapour_guidance.html), July, 2006.

Soil Vapour Intrusion Guidance for Health Canada Screening Level Risk Assessment: Invited peer technical reviewer (http://www.hc-sc.gc.ca/ewh-semt/contamsite/res/proj_pubs_journal_e.html), 2007.

ITRC Vapor Intrusion Guidance: Awarded the 2006 Industry Recognition Award for contribution to the Interstate Technical and Regulatory Council (ITRC) document Vapor Intrusion Pathway: A Practical Guideline (<http://www.itrcweb.org/Documents/VI-1.pdf>), January, 2007.

Ontario Ministry of Environment Rationale for the Development of Generic Soil and Groundwater Standards for Use at Contaminated Sites in Ontario: Paid Peer technical reviewer of 2007 draft (<http://www.ebr.gov.on.ca/ERS-WEB-External/displaynoticecontent.do?noticeId=MTAwMTU1&statusId=MTQ5NTc1>)

Canadian Council of Ministers of the Environment: primary author of “Scoping Assessment of Soil Vapour Monitoring Protocols for Evaluating Subsurface Vapour Intrusion to Indoor Air”, July, 2008
http://www.ccme.ca/assets/pdf/pn_1427_vapour_scoping1.pdf

Ontario Ministry of Environment Paid Peer Reviewer of draft Vapour Intrusion Guidance, 2009.

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

affected by contamination”, (available online at: <http://www.tsoshop.co.uk/bookstore.asp?FO=1160526&Action=Book&ProductID=9780860176855&From=Subject>) June, 2009.

US Navy SPAWAR Systems: Primary author of “Review of Best Practices, Knowledge and Data Gaps, and Research Opportunities for the US Department of Navy Vapor Intrusion Focus Areas, Performance Work Statement RO13”, 2009. <http://www.spawar.navy.mil/sti/publications/pubs/tr/1982/tr1982cond.pdf>

UK Energy Institute: Primary Author of “Introductory Guidance on Petroleum Hydrocarbon Soil Vapour Assessment: available on-line at: www.energyinstpubs.org.uk/cgi-bin/download/download.cgi?articleid=1711&sessionid=1313682614&code=KJVGGOBG

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 ESTCP/SERDP Partners’ Conference, Washington, D.C., giving a talk entitled Think Outside the Summa: Time Weighted Average and Volume Averaged Sampling to Manage Temporal and Spatial Variability in Vapor Intrusion Assessment Data, in the Vapor Intrusion Technical Session, December 1, 2010.

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 Federal Remediation Technologies Roundtable, November 10, 2009, presenting a paper entitled Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques, ESTCP Project #08EB-ER3-036.

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 at the AEHS Vapor Intrusion Workshop, San Diego, CA, March 2008, presenting a talk entitled: "Lessons from Petroleum Hydrocarbon and Chlorinated Solvent Sites Extensively Monitored for Vapor Intrusion".

Invited Speaker for the University Consortium for Field Focused Groundwater Research meeting, Hockley Valley, ON, May, 2008, presenting a talk entitled "Current Trends 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 Ground Water 2007: A Technical and Regulatory Update Focusing on Site Remediation Issues by the Site Remediation Committee of the New Jersey Water Environment Association and the New Jersey Department of Environmental Protection, June 5, 2007. Presentation entitled "Vapor Intrusion: Technical Issues and Updates".

Invited Speaker at the Conference on Contaminated Property Transactions – Mitigating the Risks of Redevelopment, Washington, D.C., April 11-13, 2007 by RTM Communications, Inc. Presentation entitled "Screening and Evaluating Sites for Vapor Intrusion During Contaminated Property Transactions".

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, Monterrey, CA, May 2006.

Invited Speaker at the Annual Project Manager’s meeting of a confidential Industrial Manufacturing client, presenting a talk and white-paper entitled “Developing a Vapor Intrusion Policy Document”, 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 and Panel Member at the AEHS Vapor Intrusion Attenuation Workshop at the 15th Annual West Coast Conference on Soils, Sediments and Water, San Diego, CA, March 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

- 11-1 McAlary, T., Bertrand, D., Nicholson, P., Wadley, S., Rowlands, D. Thrupp, G. and R. Ettinger, 2011. Pneumatic Testing, Mathematical Modeling and Flux Testing to Assess and Optimize the Performance and Establish Termination Criteria for Sub-Slab Depressurization Systems, invited platform presentation at the EPA Workshop on Vapor Intrusion at the AEHS Soils and Sediment Conference, San Diego, CA, March 2011.
- 11-2 McAlary, T., Groenevelt, H., Seethapathy, S., and T. Gorecki, 2011. Recent Advances in Techniques for Measuring Soil Vapor Concentrations, invited platform presentation at the University Consortium for Field Focused Groundwater Research meeting, Guelph, ON, June, 2011.
- 11-3 McAlary, T.A., P.Nicholson, H. Groenevelt, D. Bertrand and R.Ettinger, 2011. A Case Study on the influence of aerobic biodegradation on vapor intrusion at a former refinery property, in “Vapor Emission to Outdoor Air and Enclosed Spaces for Human Health Risk Assessment: Site Characterization, Monitoring and Modeling” Ed: Sabrina Saponaro, Elena Sezenna and Luca Bonomo (Politecnico di Milano, Italy), Nova Publishers, ISBN: 978-1-61728-692-6.
- 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.
- 11-5 McAlary, T., 2011. Keys to Vapor Intrusion Assessment and Mitigation – Specifically for the Florida Brownfields Market. Invited Platform Presentation, November 16, 2011.
- 10-1 McAlary, T., H. Groenevelt, T. Gorecki, S. Seethapathy, P. Sacco, D. Crump, M. Tuday, B. Schumacher, J. Nocerico, H. Hayes and P. Johnson, 2010. Quantitative Passive Diffusive-Adsorptive Sampling Techniques for Vapor Intrusion Assessment, Poster presented at the ESTCP/SERDP Partners Conference, December 2, 2010, Washington, D.C.
- 10-2 McAlary, T., 2010. Think Outside the Summa: Time Weighted Average and Volume Averaged Sampling to Manage Temporal and Spatial Variability in Vapor Intrusion Assessment Data, platform presentation at the Vapor Intrusion Technical Session, ESTCP/SERDP Partners’ Conference, Washington, D.C., December 1, 2010.
- 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)
- 10-4 McAlary, T.A., J. Provost and H. Dawson, 2010. Vapor Intrusion. Chapter in: Swartjes, F.A. (ed). Dealing with Contaminated Sites. From Theory Towards Practical Application. Springer, Dordrecht.
- 10-5 Bertrand, D., H. Groenevelt, J. Lanzon, W. Bingham and T. McAlary, 2010. Passive (Wind-Driven) Systems for Sub-slab Venting to Mitigate Potential Vapor Intrusion. Platform presentation and proceedings paper in Proceedings of the 7th Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 25, 2010.
- 10-6 Nicholson, P., D. Bertrand and T. McAlary, 2010. High Purge Volume Tests for Managing Variability in Sub-Slab Soil Gas. Poster and proceedings paper in Proceedings of the 7th Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 25, 2010.
- 10-7 Groenevelt, H., T. McAlary, S. Seethapathy, T. Gorecki, and H. Hayes, 2010. A New Quantitative Passive Sampler for Vapor Intrusion Assessment: the Waterloo Membrane Sampler™, Platform presentation and proceedings paper in Proceedings of the 7th Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 25, 2010.
- 10-8 Groenevelt, H., T. McAlary, B. Chadwick, and I. Rivera, 2010. Quantitative Passive Samplers for Indoor and Outdoor Air Monitoring of VOCs During Vapor Intrusion Investigations, Poster presented at the 7th Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 25, 2010.
- 10-9 McAlary, T., H. Groenevelt, T. Gorecki, S. Seethapathy, P. Sacco, D. Crump, M. Tuday, B. Schumacher, J. Nocerico, H. Hayes and P. Johnson, 2010. Quantitative Passive Diffusive-Adsorptive Sampling Techniques for Vapor Intrusion Assessment, Poster presented at the 7th Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 25, 2010.
- 10-10 McAlary, T., H. Groenevelt, H. Hayes, S. Seethapathy and T. Gorecki, 2010. Recent Developments, Applications and Commercialization of the Waterloo Membrane Sampler™. Invited Presentation at the University Consortium for Field-Focused Groundwater Contamination Research Program for Annual Progress Meeting: May 19-21, 2010, Guelph, Ontario
- 10-11 Groenevelt, H. and T. McAlary, 2010. Quantitative Passive Diffusive-Adsorptive Sampling Techniques for Vapor Intrusion Assessment, ESTCP

- Project 08 EB-EBR-036, a platform presentation at the DOD Environmental Monitoring and Data Quality Workshop, Louisville, KY, April 15, 2010.
- 10-12 McAlary, T., 2010. New Methods for Vapor Intrusion Assessment to Minimize Variability, Maximize Value and Optimize Mitigation in One Step, an invited platform presentation at the 2010 Air Force Restoration and Technology Transfer Workshop, San Antonio, April 9, 2010.
- 10-13 Johnson, P. and T. McAlary, 2010. Vapor Intrusion Pathway Assessment – Challenges, Developments and On-Going Research, an invited platform presentation at the 2010 Air Force Restoration and Technology Transfer Workshop, San Antonio, April 9, 2010.
- 10-14 McAlary, T.A., R. Ettinger and P. Johnson, 2010. Cutting Edge Vapor Intrusion Research, an invited platform presentation at the EPA Workshop on Vapor Intrusion at the AEHS Conference on Contaminated Soils and Sediments, San Diego, March 16, 2010.
- 10-15 McAlary, T.A., W.Wertz and L. Siegel, 2010. Multiple Lines of Evidence for Assessing Vapor Intrusion, an invited platform presentation at the EPA Workshop on Vapor Intrusion at the AEHS Conference on Contaminated Soils and Sediments, San Diego, March 16, 2010.
- 10-16 McAlary, T., H. Groenevelt, T. Górecki, S. Seethapathy, and H. Hayes, 2010. PDMS Membrane Samplers for Quantitative Passive Monitoring of Soil Vapor Intrusion to Indoor Air, Platform presentation at North American Environmental Field Conference & Exposition, January 2010, Tampa, FL.
- 10-17 McAlary, T.A., Nicholson, P., Yik, L.K., Bertrand, D. and G. Thrupp, 2010. High Purge Volume Sampling - A New Paradigm for Sub-Slab Soil Gas Monitoring, Groundwater Monitoring and Remediation, V. 30, No. 2, pp 73–85, Spring 2010.
- 10-18 Michaelski, P., Thompson, S., DeWolf, C., Nicholson, P. and T. McAlary, 2010. Effects of Alternate Petroleum Hydrocarbon Sources in the Vadose Zone on the Vapor Intrusion Pathway beneath a Residential Community, in Proceedings of the Air and Waste Management Association Specialty Conference on Vapor Intrusion, Chicago, September 29, 2010.
- 09-1 McAlary, T.A., 2009. Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques, ESTCP Project #08EB-ER3-036, Environmental Data Quality Workgroup Meeting At the ESTCP/SERDP Partners Conference, December 2, 2009, Washington, D.C.

- 09-2 Majcher, E.H., P. Nicholson, D. Himmelheber, A. Krasnopoler, T. McAlary, and R. Ettinger, J. Harris and J. Wrobel, 2009. Implementation of a Strategic Approach for Complex VI Assessment at a Large Military Facility: CSM Development Through Field Investigation and Assessment, Poster presentation at the ESTCP/SERDP Partners Conference, December 2, 2009, Washington, D.C.
- 09-3 McAlary, T.A., 2009. Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques, ESTCP Project #08EB-ER3-036, Invited Presentation at the Federal Remediation Technologies Roundtable, November 10, 2009.
- 09-4 McAlary, T.A., 2009. Current Challenges and New Directions for Vapor Intrusion Assessment and Management, Invited Presentation at the RTM Conference on Sustainable Property Transactions: Reconfiguring the Business of Contaminated Site Redevelopments, San Francisco, October 30, 2009.
- 09-5 Groenevelt, H., P. Nicholson, D Bertrand, and T. McAlary, 2009. High Purge Volume Sampling: A New Paradigm for Sub-slab Soil Gas Monitoring, Platform presentation, 25th Annual International Conference on Soils, Sediments, Water & Energy, University of Massachusetts, October 2009, Amherst, MA.
- 09-6 McAlary, T.A., R. Ettinger, P. Johnson, B. Eklund, H. Hayes, T. Shields, B. Chadwick and I. Rivera, 2009. A Review for the U.S. Navy of Best Practices, Knowledge and Data Gaps and Research Directions for Vapor Intrusion, Platform presentation at the DOD Environment, Energy and Sustainability Symposium, Denver, May 2009.
- 09-7 Abreu, L. D. V.; Ettinger, R. A. and T. A. McAlary, 2009. "Simulating the Effect of Aerobic Biodegradation on Soil Vapor Intrusion into Buildings: Evaluation of Low Strength Sources associated with Dissolved Gasoline Plumes," API Technical Bulletin #4775. API, Washington, DC.
- 09-8 McAlary, T.A., R. Ettinger, P. Johnson, B. Eklund, H. Hayes, T. Shields, B. Chadwick and I. Rivera, 2009. A Review for the U.S. Navy of Best Practices, Knowledge and Data Gaps and Research Directions for Vapor Intrusion, Platform presentation at the DoD Environmental Monitoring and Data Quality Workshop, San Antonio, TX, April 2009.
- 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.
- 09-10 Abreu, L., R. Ettinger and T. McAlary, 2009. Simulated Soil Vapor Intrusion Attenuation Factors Including Biodegradation for Petroleum Hydrocarbons, *Groundwater Monitoring and Remediation* 29, no. 1/ Winter 2009/pages 105–117.
- 09-11 Dawson, H. and T. McAlary, 2009. A Compilation of Order Statistics for VOCs from Post-1990 Indoor Air Concentration Studies in North American Residences Unaffected by Subsurface Vapor Intrusion, *Groundwater Monitoring and Remediation* 29, no. 1/ Winter 2009/pages 60–69.
- 09-12 McAlary, T.A. and P.C. Johnson, 2009. Editorial Column – Focus Issue on Vapor Intrusion, *Groundwater Monitoring and Remediation*, 29, no. 1/ Winter 2009/pages 40-41.
- 09-13 McAlary, T.A., P. Nicholson, H. Groenevelt, and D. Bertrand, 2009. A Case-Study of Soil Gas Sampling in Silt and Clay-rich (Low-Permeability) Materials, *Groundwater Monitoring and Remediation*, 29, no. 1/ Winter 2009/pages 144–152.
- 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)
- 09-15 McAlary, T. A., H. Groenevelt, T. Gorecki, S. Seethapathy and H. Hayes, 2009. PDMS Membrane Samplers for Quantitative Passive Monitoring of Soil Vapor to Indoor Air, in *Proceedings of the Air and Waste Management Specialty Conference – Vapor Intrusion 2009*, January 27 to 30, 2009, San Diego.
- 09-16 Abreu, L., R. Ettinger and T. McAlary, 2009. Simulating the Effect of Aerobic Biodegradation on Soil Vapor Intrusion into Buildings Evaluation of Low Strength Sources Associated with Dissolved Gasoline Plumes, *API Publication* 4775, April 2009.
- 08-1 McAlary, T.A., 2008. Guidance, Guidance Everywhere, but What Does it all Mean? Invited Platform Presentation at the Air and Waste Management’s Specialty Conference on Vapour Intrusion, Toronto, September, 2008.
- 08-2 Groenevelt, H.G. and T. McAlary, 2008. Quantitative Passive Sampling for Vapor Intrusion Studies, Platform Presentation at the Air and Waste

- Management's Specialty Conference on Vapour Intrusion, Toronto, September, 2008.
- 08-3 McAlary, T.A., 2008. Lessons From Petroleum Hydrocarbon and Chlorinated Solvent Sites Extensively Monitored for Vapor Intrusion, Invited Platform Presentation at the USEPA Workshop on Vapor Intrusion at the AEHS Conference on Contaminated Soils and Sediments, San Diego, March, 2008.
- 08-4 McAlary, T.A., 2008. Planning Soil Vapor Intrusion Investigations Based on Various Conceptual Models – Understanding the Processes and Mechanisms to Design an Efficient and Effective Characterization Program, Platform Presentation at the AFCEE Technology Transfer Workshop, March 25-28, 2008, San Antonio, TX.
- 08-5 McAlary, T.A., 2008. Current Directions and Research Trends for Vapor Intrusion, Invited Platform Presentation at the University Consortium for Field-Focused Groundwater Research semi annual meeting, May 6, 2008, Hockley Valley.
- 08-6 McAlary, T.A., 2008. Screening and Evaluating Sites for Vapor Intrusion During Property Transactions, Invited Platform Presentation at the RTM Symposium on Contaminated Property Transactions, April 4, 2008, Philadelphia.
- 08-7 McAlary, T.A., 2008. Soil Gas Sampling Methods. An Invited half-day Workshop Sponsored by the Federation of Environmental Technologists, Southeast Wisconsin Chapter, and the WDNR Bureau of Remedation and Redevelopment, September 23, 2008.
- 07-1 Abreu, L., R. Ettinger and T. McAlary, 2007. Application of 3D Numerical Modeling to Assess Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Sites. Platform Presentation at the Air and Waste Management Association's Specialty Conference on Vapor Intrusion, Providence, RI, September 26, 2007.
- 07-2 Nicholson, P., D. Bertrand, and T. McAlary, 2007. Soil Gas Sampling in Low-Permeability Materials. Platform Presentation at the Air and Waste Management Association's Specialty Conference on Vapor Intrusion, Providence, RI, September 28, 2007.
- 07-3 McAlary, T., P. Nicholson, D. Bertrand, L. Abreu, and R. Ettinger, 2007. A Case Study on the Influence of Aerobic Biodegradation on Vapor Intrusion at a Former Refinery Property. Platform Presentation at the Air and Waste

- Management Association's Specialty Conference on Vapor Intrusion, Providence, RI, September 27, 2007.
- 07-4 McAlary, T. and E. McNally, 2007. Vapor Intrusion: Technical Issues and Updates. Platform Presentation at the New Jersey Water Environment Association and New Jersey Department of Environmental Protection Seminar "Ground Water 2007", East Windsor, New Jersey, June 5, 2007.
- 07-5 McAlary, T. and K. Berry-Spark, 2007. Screening and Evaluating Sites for Vapor Intrusion During Contaminated Property Transactions. Platform presentation at RTM Symposium on Contaminated Property Transactions – Mitigating the Risks of Redevelopment, April 13, 2007, Washington, D.C.
- 07-6 Abreu, L., R. Ettinger and T. McAlary, 2007. Application of 3D Numerical Modeling to Assess Vapor Intrusion Screening Criteria for Petroleum Hydrocarbon Sites. Platform presentation at the AEHS Conference on Contaminated Soils and Sediments, San Diego, March, 2007
- 06-1 McAlary, T., 2006. Screening and Evaluating Sites for Vapor Intrusion During Contaminated Property Transactions. Platform presentation at the RTM Webinar on Vapor Intrusion – Deals and Due Diligence, November 29, 2006.
- 06-2 McAlary, T., 2006. Screening and Evaluating Sites for Vapor Intrusion During Contaminated Property Transactions. Platform presentation at the RTM Symposium on Contaminated Property Transaction – Navigating the Complex Deals, San Francisco, October 20, 2006.
- 06-3 McAlary, T., 2006, "Recommended Soil Gas Sampling Techniques for Vapor Intrusion Investigations," platform presentation at the Air and Waste Management Association Specialty Conference on Vapor Intrusion, Los Angeles, September 2006.
- 06-4 McAlary, T., 2006, "Soil Gas Sampling Methods," platform presentation at the Midwestern States Risk Assessment Symposium, Indianapolis, IN, August, 2006.
- 06-5 McAlary, T. and R. Ettinger, 2006, "Modeling the Vapor Intrusion Pathway," presentation at the Electric Power Research Institute Annual Meeting, Bar Harbor, Maine, June 22, 2006.
- 06-6 McAlary, T., 2006, "Sub-Slab Soil Gas Monitoring for Assessing Subsurface Vapor Intrusion to Indoor Air," presentation at the Rutgers University Seminar on Vapor Intrusion, June 14, 2006.
- 06-7 Luo, H., P. Dahlen, P. Johnson, T. Creamer, T. Peargin, P. Lundegard, B. Hartman, L. Abreu and T. McAlary, 2006, "Spatial and Temporal Variability in

- Hydrocarbon and Oxygen Concentrations Beneath a Building Above a Shallow NAPL Source,” Platform Presentation at the Battelle Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterrey CA, May 2006.
- 06-8 Creamer, T., and T. McAlary, 2006, “The Effects of Purge Rate and Volume on Sub-slab Soil Gas Samples,” A Platform Presentation at the Battelle Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterrey CA, May 2006.
- 06-9 McAlary, T., 2006, “Beyond Screening – The Site Characterization Process,” 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.
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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
ESTCP/SERDP Partners Conference, December, 2008, 2009, 2010, 2011, Washington, D.C.
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.
Federal Remediation Technologies Roundtable, November 10, 2009.
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.
NDIA Environment Energy & Sustainability Symposium and Exhibition, Denver, CO, May 4 – 7, 2009.
AWMA Specialty Conference: Vapor Intrusion, 2009. San Diego, CA, January, 2009.
AWMA Specialty Conference on Vapour Intrusion, Toronto, September, 2008.

WIDNR/FET Course Vapor Intrusion Sampling for Environmental Professionals, Milwaukee, WI, September, 2008.

University Consortium for Field-Focused Groundwater Contamination, May, 2008, Hockley Valley, On.

AFCEE Conference – Focus on the Goal RIP by 2012, San Antonio, March 2008.

AWMA Specialty Conference on Vapor Intrusion: Learning from the Challenges, Providence, RI, September 2007

Ground Water 2007: A Technical and Regulatory Update Focusing on Site Remediation Issues by the Site Remediation Committee of the New Jersey Water Environment Association and the New Jersey Department of Environmental Protection, June 5, 2007.

RTM Conferences on Contaminated Property Transactions: Philadelphia, April, 2008, Washington, D.C., April, 2007 and San Francisco, CA, October 2006.

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

First, Second, Third, Fourth, Fifth and Sixth *International Conferences on Remediation of Chlorinated and Recalcitrant Compounds*, 1998, 2000, 2002, 2004, 2006 and 2008, Monterey, CA.

University Consortium for Field-Focused Groundwater Contamination, Nov., 2006, Denver, CO.

AWMA Specialty Conference on Vapor Intrusion: The Next Great Environmental Challenge, Philadelphia, PA, January 2006.

ITRC Vapor Intrusion Workgroup, 2004, 2005, 2006, 2007.

California Groundwater Resources Association Seminar: “Subsurface Vapor Intrusion to Indoor Air: An Update”, May 25, 2005, San Jose, CA

AEHS 15th Annual West Coast Conference on Soils, Sediments and Water, San Diego, March 2004, 2005.

AEHS Conference on Soils, Sediments and Water, Amherst, MA, October 2004.

Air and Waste Management Annual Conference, Indianapolis, IN, June 2004.

California Groundwater Resources Association Seminar: “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.

Indoor Air 2002, 9th International Conference on Indoor Air Quality and Climate, Monterey, July 2002.

RCRA National Meetings, Washington, D.C., 2000, 2002.

Addressing Indoor Air Contamination: Measurement & Models, MADEP Training Seminar, Marlboro, October 2001.

Fractured Rock 2001, International Conference in Toronto, March 2001.

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

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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

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.

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 benzeneto 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.

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EDUCATION

Ph.D., Civil Engineering, Auburn University, 1987.
MS, Water Resources Engineering, University of Kansas, 1984.
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.
Engineering Technician, Shaw, Weiss & DeNaples, Consulting Engineers, Dayton, Ohio, 1980-81.
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".
SEAM3D: A Code for Simulating 3-D Transport and Biodegradation in Groundwater (with Dan W. Waddill), Virginia Polytechnic Institute and State University, 1997.
NAS: Natural Attenuation Software (with F.H. Chapelle, E. Mendez, J.S. Brauner, C. Casey), Virginia Polytechnic Institute and State University, 2002.

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:

- Parker, J.C., Kim, E., Widdowson, M., Kitanidis P., and Gentry, P. "Effects of model formulation and calibration data on uncertainty in predictions of DNAPL source dissolution rate", *Water Resources Research* 46, W12517, doi:10.1029/2010WR009361, 2010
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- Rectanus, H.V., M. Widdowson, F. Chapelle, C. Kelly, and J. Novak. "Investigation of reductive dechlorination supported by natural organic carbon", *Ground Water Monitoring and Remediation*, 27(4), 53-62, 2007.
- Widdowson, M., E. Mendez and Chapelle, F.H. "Estimating cleanup times for groundwater contamination remediation strategies", *Journal of the American Water Works Association*, 99(3), 40-46, 2007.
- Marr, L.C., E.C. Booth, R.G. Andersen, M.A. Widdowson and J.T. Novak. "Direct volatilization of naphthalene to the atmosphere at a phytoremediation site". *Environmental Science & Technology*, 40(17), 5560-5566, 2006.
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- Widdowson, M.A., S. Shearer, R. Andersen, J.T. Novak. "Remediation of polycyclic aromatic hydrocarbon compounds in groundwater using poplar trees", *Environmental Science and Technology*, 39(6), 1598-1605, 2004.
- Widdowson, M.A. "Modeling natural attenuation of chlorinated ethenes under spatially-varying redox conditions". *Biodegradation*, 15, 435-451, 2004.
- Zoeckler, J.R., M.A. Widdowson and J.T. Novak. "Aerobic biodegradation of MTBE in gasoline-contaminated aquifer sediments". *ASCE Journal of Environmental Engineering*, 129(7), 642-650, 2003.
- Robinson, S.L., J.T. Novak, M.A. Widdowson, S.B. Crosswell, and G.J. Fetterolf. "Field and laboratory evaluation of the impact of tall fescue on PAH degradation in an aged creosote-contaminated surface soil". *ASCE Journal of Environmental Engineering*, 129(3), 232-240, 2003.
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- Molz, F.J. and M.A. Widdowson. "Internal inconsistencies in dispersion-dominated models that incorporate chemical and microbial kinetics", *Water Resources Research*, 24(4), 615-619, 1988.
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- Widdowson, M., Chapelle, F., Casey, C. and Kram, M.A. "Estimating cleanup times associated with combining source-area remediation with monitored natural attenuation", NAVFAC Technical Report TR-2288-ENV, February 2008.
- Chapelle, F.H., J.T. Novak, J.C. Parker, B.B. Campbell and M.A. Widdowson. "A framework for assessing the sustainability of monitored natural attenuation", U.S. Geological Survey Circular 1303, Feb. 2007.
- Chapelle, F.H., M.A. Widdowson, J.S. Brauner, E. Mendez*, and C.C. Casey. "Methodology for estimating times of remediation associated with monitored natural attenuation", USGS Water Resource Investigation Report 03-4057, 51 pp., 2004.
- Dortch, M.S., C.J. McGrath, J.J. Nitao, M.A. Widdowson, and S. Yabusaki. "Development of simulators for in situ remediation evaluation, design, and operation: final report", ERDC/EL TR-01-33, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 75 pp., 2001
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- Harvey, R.W. and M.A. Widdowson. "Microbial distributions, activities and movement in the terrestrial subsurface: Experimental and theoretical studies", in *Advances in Soil Science*, R.J. Wagenet, P. Baveye and B.A. Stewart (eds.), Lewis Publishers, Boca Raton, FL, 185-225, 1992.

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- Widdowson, M.A., F.H. Chapelle, and J.S. Brauner. "Analytical method for optimizing monitored natural attenuation in contaminated aquifers", ASCE World Water and Environmental Resources Congress, Philadelphia, PA, June 23-26, 2003.
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- Robinson, S.L., Novak, J.T., Widdowson, M.A., and M. Elliot. "Microbial degradation of PAHs under various redox conditions at a creosote contaminated site", In: A. Leeson, E.A. Foote, M.K. Banks, and V.S. Magar (Eds.), *Natural Attenuation of Environmental Contaminants*, Sixth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, June 4-7, 6(5), 1-8, 2001.
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- Brauner, J.S. and M.A. Widdowson. "Sequential electron acceptor model for evaluation of in situ bioremediation of petroleum hydrocarbon contaminants in groundwater." In *Annals of the New York Academy of Sciences*, vol. 829, 399-419, 1997. Engineering Foundation Conference on Bioremediation, Palm Coast, FL, January 21-26, 1996.
- Waddill, D.W., M.A. Widdowson and J.S. Brauner. "SEAM2D: A numerical model for two-dimensional solute transport and sequential electron acceptor-based bioremediation of LNAPL-contaminated aquifers." In L.N. Reddi (ed.), *Proceedings of the ASCE Conference*, ASCE, New York, NY, 466-477, 1996. ASCE Environmental Engineering Division Conference on Non-Aqueous Phase Liquids (NAPLs) in the Subsurface Environment: Assessment and Remediation, Washington, DC, November 21-25, 1996.
- Widdowson, M.A., C. M. Aelion, R. P. Ray, and H. W. Reeves. "Soil vapor extraction pilot study at a piedmont UST site." In R. E. Hinchee, R. N. Miller, and P. C. Johnson (eds.), *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*, Battelle Press, Columbus, OH, 3(2), 455-461, 1995. The Third International In Situ and On-Site Bioreclamation Symposium, San Diego, CA, April 24 - 27, 1995.
- Aelion, C. M., M. A. Widdowson, R. P. Ray, H. W. Reeves, and J. N. Shaw. "Soil vapor and off-gas monitoring during soil venting and air sparging." In R. E. Hinchee, R. N. Miller, and P. C. Johnson (eds.), *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*, Battelle Press, Columbus, OH, 3(2), 127-134, 1995. The Third International In Situ and On-Site Bioreclamation Symposium, San Diego, CA, April 24 - 27, 1995.

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- Widdowson, M.A., R.P. Ray, H.W. Reeves, C.M. Aelion, and K.W. Holbrooks. "Investigation of soil venting-based remediation at a UST site in the Appalachian Piedmont", in *Bioremediation of Pollutants in Soil and Water*, Brian S. Schepart (ed.), ASTM STP 1235, 135-148, 1994. Symposium on Bioremediation of Pollutants in Soil and Water, Ft. Worth, TX, Oct. 20-22, 1993.
- Widdowson, M.A. and C.M. Aelion. "Application of a numerical model to the performance and analysis of an in situ bioremediation project", in R.E. Hinchee and R.F. Olfenbuttel (eds.), *In Situ Bioremediation: Application and Investigations for Hydrocarbon and Contaminated Site Remediation*, Butterworth-Heinemann, Boston, 227-244, 1991. The First International In Situ and On-Site Bioreclamation Symposium, San Diego, CA, March 24 - 26, 1993.
- Widdowson, M.A. and F.J. Molz. "Solution technique for a coupled system of equations describing advection-dominated Transport and biotransformations in the subsurface", in *Computational Mechanics*, S.N. Alturi and G. Yagawa (eds.), vol. 2, 58iv(1-4), 1988.

Recent Papers Presented at Professional Meetings

- King, L. M. Widdowson, E. Mendez, R. Barton, J. Novak, F. Chapelle, J. Parker, M. Singletary and C. Lebron. "Bioavailable Organic Carbon and the Natural Attenuation of Chlorinated Solvents", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 24-27, 2010.
- Stewart, L., M. Widdowson, J. Nyman, R. Deeb, M. Kavanaugh, and J. Mercer. "Field Characterization of Mass Transfer at a NAPL Source Zone", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 24-27, 2010.
- Widdowson, M., M. Mobile, L. Stewart, J. Nyman, R. Deeb, M. Kavanaugh, and J. Mercer. "Modeling Plume Longevity Following Partial NAPL Source Remediation", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 24-27, 2010.
- Pruden, A. and M. Widdowson. 1053221 RAPID Response Research for the Gulf of Mexico Oil Spill: "Effect of Petroleum Deposit Geometry on Biodegradation Potential and Long-Term Persistence", JSOST Deepwater Horizon Oil Spill Principal Investigator (PI) Conference, St. Petersburg, FL, October 5-6, 2010.
- Widdowson, M. and A. Pruden. "Effect of Petroleum Deposit Geometry on Biodegradation Potential and Long-Term Persistence", Gulf Oil Spill Conference, New Orleans, LA, November 1-2, 2010.
- Lebron, C., F. Chapelle, J. Parker, M. Widdowson, and J. Novak. "Verification of Methods for Assessing the Sustainability of Monitored Natural Attenuation (MNA)", Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, November 30-December 2, 2010.
- Nyman, J., M. Kavanaugh, R. Deeb, L. Stewart, M. Widdowson, and J. Mercer. "Improved Field Evaluation of NAPL Dissolution and Source Longevity", Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, November 30-December 2, 2010.
- Parker, J., P. Kitanidis, X. Liu, M. Cardiff, U. Kim, and M. Widdowson. DNAPL Source Strength vs. Time – Model Formulation, Calibration and Uncertainty", Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, December 1-3, 2009.
- Widdowson, M.A. "Predicting Remedial Time Frames – Models and Approaches" for publication in *Proceedings*, Monitored Natural Attenuation of Polycyclic Aromatic Hydrocarbons at Manufactured Gas Plant Sites, USEPA workshop, Irving, Texas, May 27-29, 2009 (invited).

- Widdowson, M., H. Rectanus, and P. Taucher. "Natural attenuation of benzene in a coal seam aquifer", Ninth International *In Situ and On-Site Bioremediation* Symposium, Baltimore, MD, May 7-10, 2007.
- Rectanus, H.V., M. Widdowson, J. Novak, and F. Chapelle. "Application of potentially bioavailable organic carbon at chlorinated solvent sites", Ninth International *In Situ and On-Site Bioremediation* Symposium, Baltimore, MD, May 7-10, 2007.
- Widdowson, M. "Natural Attenuation Software (NAS): A system for assessing combining source zone remediation with monitored natural attenuation", Federal Remediation Technologies Roundtable meeting, Arlington, VA, May 2, 2007 (invited).
- Widdowson, M., C. Quezada, and E. Mendez. "Time estimates for reaching compliance using source remediation combined with monitored natural attenuation", Annual Meeting and Exposition of the Geological Society of America, Philadelphia, PA, October 22-25, 2006.
- Widdowson, M. and E. Mendez. "Time of remediation estimates at a NAPL-contaminated fractured-rock site", Annual Meeting and Exposition of the Geological Society of America, Philadelphia, PA, October 22-25, 2006 (invited).
- Chapelle, F.H., B.G. Campbell, and M.A. Widdowson. "Assessing the long-term sustainability of monitored natural attenuation", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-26, 2006.
- Rectanus, H.V., M. Widdowson, J. Novak, and F. Chapelle. "Evaluation of potentially bioavailable organic carbon at chlorinated solvent sites", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-26, 2006.
- Widdowson, M., F. Chapelle, C. Casey, and M. Kram. "Estimating cleanup times associated with combining source area remediation with monitored natural attenuation", Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-26, 2006.
- Chapelle, F.H., B.G. Campbell, M.A. Widdowson, B.B. Looney, T.H. Weidemeier, and C.H. Sink. "A deterministic approach to assessing monitored and enhanced natural attenuation", In B. Sass (ed.), *Remediation of Chlorinated and Recalcitrant Compounds – 2006*, Paper G-53. Proceedings of the Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May, 2006.
- Widdowson, M., F. Chapelle, M. Kram, and C. Casey. "Estimating cleanup times associated with combining source area remediation with MNA", Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, November 29 - December 1, 2005.
- 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.
- Mendez, E, M. Widdowson, F. Chapelle and C. Casey. "Natural Attenuation Software (NAS): Assessing remedial strategies and estimating timeframes", Eighth International *In Situ and On-Site Bioremediation* Symposium, Baltimore, MD, June 6-9, 2005.
- Rectanus, H, M. Widdowson, J. Novak, and F. Chapelle. "A method for quantifying bioavailable organic carbon in aquifer sediments", Eighth International *In Situ and On-Site Bioremediation* Symposium, Baltimore, MD, June 6-9, 2005.
- Widdowson, M.A. "Practical Use of Models to Assess Technical Impracticability and Monitored Natural Attenuation", National Ground Water Association Theis Conference – Environmental Decision Making: Restoration Versus Risk Reduction, Sedona, AZ, January 14-17, 2005 (invited).
- Widdowson, M., Q. Abdelal, and F. Chapelle. "Parameter estimation and calibration for modeling the fate and transport of chlorinated ethenes using SEAM3D and PEST", Partners in Environmental Technology Technical Symposium & Workshop, Washington, DC, November 30 - December 2, 2004.

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- Roller, J., Schreiber, M., Tadanier, C., Widdowson, M., and Johnson, J. "Arsenic Release Due to Dissimilatory Reduction of Iron Oxides in Petroleum-Contaminated Aquifers", Geological Society of America, Seattle, WA, November 2-5, 2003.
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- Chapelle, F.H., M.A. Widdowson, E. Mendez, and C.C. Casey. "Estimating times of remediation associated with natural attenuation", Remediation Innovative Technology Seminar (RITS), NAVFAC Pacific Division, Waipahu, HI, May 6, 2003.
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- Chapelle, F.H., M.A. Widdowson, E. Mendez, and C.C. Casey. "Estimating times of remediation associated with natural attenuation", Remediation Innovative Technology Seminar (RITS), NAVFAC Southern Division, Charleston, SC, April 29, 2003.
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- Chapelle, F.H., M.A. Widdowson, E. Mendez, and C.C. Casey. "Estimating times of remediation associated with natural attenuation", Remediation Innovative Technology Seminar (RITS), NAVFAC Southwest Division, San Diego, CA, April 22, 2003.

- Chapelle, F.H., M.A. Widdowson, E. Mendez, and C.C. Casey. "Estimating times of remediation associated with natural attenuation", Remediation Innovative Technology Seminar (RITS), NAVFAC Atlantic Division, Norfolk, VA, April 3, 2003.
- Chapelle, F.H., M.A. Widdowson, E. Mendez, and C.C. Casey. "Estimating times of remediation associated with natural attenuation", Remediation Innovative Technology Seminar (RITS), NAVFAC EFA Northeast, Philadelphia, PA, April 1, 2003.
- Novak, J.T. and M.A. Widdowson. "Characterization of degradation mechanisms for PAH compounds by poplar trees", Third International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 20-23, 2002.
- Filz, G.M., M.A. Widdowson, and J.C. Little. "Barrier-controlled monitored natural attenuation", Third International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 20-23, 2002.
- 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, May 14-15, 2001.
- Widdowson, M.A., J.T. Novak, M. Elliott, S. Robinson, M.S. Lawrence and E.M. Panhorst. "Phytoremediation of a creosote-contaminated cross tie treatment facility using poplar trees", Railroad Environmental Conference, Urbana-Champaign, IL, September 26-27, 2001.
- Novak, J.T., S. Robinson, S. Crosswell, G. Fetterolf and M.A. Widdowson. "Accelerated Degradation of creosote compounds in surface soils by grasses", Railroad Environmental Conference, Urbana-Champaign, IL, September 26-27, 2001.
- Widdowson, M.A., J.R. Zoeckler, and J.T. Novak, "Intrinsic aerobic biodegradation of MTBE in gasoline-contaminated aquifer sediments", First International Congress on Petroleum Contaminated Soil, Sediments and Water, London, England, August 14-17, 2001.
- Widdowson, M.A., F.H. Chapelle, H.V. Rectanus, and J.S. Brauner, "Relationship between NAPL mass and remediation time using monitored natural attenuation", First International Congress on Petroleum Contaminated Soil, Sediments and Water, London, England, August 14-17, 2001.
- Widdowson, M.A., J.S. Brauner, J.S. and F.H. Chapelle. "A decision-making tool for assessing monitored natural attenuation and estimating cleanup times", Sixth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, June 4-7, 2001.
- Chapelle, F.H., Widdowson M.A., and Casey, C.C. "Estimating cleanup times associated with monitored natural attenuation", Sixth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, June 4-7, 2001.
- Chapelle, F.H., Widdowson M.A., and Casey, C.C. "Estimating cleanup times associated with monitored natural attenuation", Spring Meeting - American Geophysical Union, Boston, MA, May 29-June 1, 2001.
- Widdowson M.A., "Validation of the SEAM3D Reductive Dechlorination Package at a TCE-contaminated facility", Partners in Environmental Technology Technical Symposium & Workshop, Arlington, VA, November 28-30, 2000.
- Widdowson, M.A., J.T. Novak, D.F. Berry, H.V. Rectanus, and F.Y. Wang. "Spatial variation of reductive dechlorination in a PCE-contaminated aquifer", Second International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-25, 2000.
- Novak, J.T. M.A. Widdowson, M. Elliott, and S. Robinson. "Phytoremediation of a creosote contaminated site - A field study", In: G.B. Wickramanayake, A.R. Gavaskar, B.C. Alleman, and V.S. Magar (Eds.), *Bioremediation and Phytoremediation of Chlorinated and Recalcitrant Compounds*, C2-4:493-500. Battelle Press: Columbus, OH. Second International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-25, 2000.

- Widdowson M.A., Novak, J.T., Berry, D.F., MacEwen, S.J., Dronfield, D.G., Errett, A.H., and Lade, N.A., "Investigation of intrinsic bioremediation at NAB Little Creek, Site 12: I. Hydrogeochemical Assessment", International Symposium on Subsurface Microbiology, Vail, CO, August 18-22, 1999.
- Berry, D.F., Higgins, M.J., Rectanus, H., Widdowson M.A., and Novak, J.T., "Investigation of intrinsic bioremediation at NAB Little Creek, Site 12: II. Microbiological Assessment", International Symposium on Subsurface Microbiology, Vail, CO, August 18-22, 1999.
- Brauner, J.S., M.A. Widdowson, J.T. Novak, and N.G. Love. "Intrinsic bioremediation of PAH compounds at a fuel-contaminated site", Fifth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, April 19-22, 1999, 5(6), 45-50, 1999.
- Brauner, J.S. and M.A. Widdowson. "Interpreting natural attenuation of petroleum hydrocarbons in a heterogeneous aquifer using SEAM3D", Fifth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, April 19-22, 1999.
- Fetterolf, G.J, J.T. Novak, S.B. Crosswell, and M.A. Widdowson. "Phytoremediation of creosote-contaminated surface soil", Fifth International Symposium on In Situ and On-Site Bioremediation, San Diego, CA, April 19-22, 1999, 5(8), 19-24, 1999.
- Widdowson, M.A., D.W. Waddill, and N.A. Lade. "Development and application of a sequential electron-accepting model (SEAM3D) for the transport and biodegradation of petroleum hydrocarbon compounds", U.S. Geological Survey Toxic Waste Program Technical Meeting, Charleston, SC, March 7-11. 1999. (Invited)
- Widdowson, M.A. and D.W. Waddill. "Modeling intrinsic bioremediation of chlorinated solvents in groundwater", First International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 18-21, 1998.
- Widdowson, M.A. "Modeling intrinsic bioremediation in groundwater", National Ground Water Association National Convention, AGWSE Technical Program "Biological Aspects of Ground Water", Las Vegas, NV, September 4-6, 1997 (Invited).
- Widdowson, M.A., D.W. Waddill, C.E. Ruiz. "SEAM3D: A numerical model for three-dimensional solute transport and sequential electron acceptor-based bioremediation in groundwater", *XXVIIth International Association of Hydraulic Research Congress*, San Francisco, CA, August 11-15, 1997.
- Killingstad, M.W., M.A. Widdowson, and R.L. Smith. "Two-dimensional numerical modeling of enhanced in situ denitrification", Spring Meeting, American Geophysical Union, Baltimore, MD, May 27-30, 1997.
- Widdowson, M.A., J.S. Brauner, and D.W. Waddill. "Sequential electron acceptor modeling for the assessment of intrinsic bioremediation", Fourth International Symposium on In Situ and On-Site Bioreclamation, New Orleans, LA, April 28-May 1, 1997.
- Waddill, D.W. and M.A. Widdowson. "3-D model for aerobic and sequential anaerobic biodegradation of groundwater contaminants", Fourth International Symposium on In Situ and On-Site Bioreclamation, New Orleans, LA, April 28-May 1, 1997.
- Waddill, D.W., M.A. Widdowson and J.S. Brauner. "SEAM2D: A numerical model for two-dimensional solute transport and sequential electron acceptor-based bioremediation of LNAPL-contaminated aquifers", ASCE Environmental Engineering Division Conference on Non-Aqueous Phase Liquids (NAPLs) in the Subsurface Environment: Assessment and Remediation, Washington, DC, November 21-25, 1996.
- Widdowson, M.A. "Intrinsic remediation", ASCE Virginia Section Annual Meeting, Roanoke, VA, September 20, 1996. (Invited)
- Widdowson, M.A., J.S. Brauner, and D.W. Waddill. "Numerical modeling of sequential electron acceptor-based biodegradation of solutes in groundwater", European Geophysical Society XXI General Assembly, The Hague, Netherlands, May 6-10, 1996.

- Brauner, J.S. and M.A. Widdowson. "Sequential electron acceptor model for evaluation of in situ bioremediation of petroleum hydrocarbon contaminants in groundwater." In *Annals of the New York Academy of Sciences*, vol. 829, 399-419, 1997. *Engineering Foundation Conference on Bioremediation*, Palm Coast, FL, January 21-26, 1996.
- Widdowson, M.A. and W.E. Orne. "A multi-level groundwater sampling device", Ninth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, Association of Ground Water Scientists and Engineers, Las Vegas, NV, May 2-4, 1995.
- Widdowson, M.A., C. M. Aelion, R. P. Ray, and H. W. Reeves. "Soil vapor extraction pilot study at a Piedmont UST site", Third International Symposium on In Situ and On-Site Bioreclamation, San Diego, CA, April 24 - 28, 1995.
- Aelion, C. M., M. A. Widdowson, R. P. Ray, H. W. Reeves, and J. N. Shaw. "Soil vapor and off-gas monitoring during soil venting and air sparging", Third International Symposium on In Situ and On-Site Bioreclamation, San Diego, CA, April 24 - 28, 1995.
- Widdowson, M. A., R. P. Ray, H. W. Reeves, and C. M. Aelion. "Integrated site characterization for soil vapor extraction design", Geoenvironment 2000 Specialty Conference, ASCE, New Orleans, LA, February 23 - 25, 1995.
- Aelion, C.M., M.A. Widdowson, R.P. Ray, and H.W. Reeves. "In situ air sparging and bioremediation in a saprolitic aquifer contaminated with gasoline", I&EC Special Symposium, American Chemical Society, September, 27-29, 1994.
- Widdowson, M.A. and S. Dufrense. "Numerical simulation of in situ bioremediation of BTEX with nitrate as an electron acceptor", Spring Meeting, American Geophysical Union, Baltimore, MD, May 23-27, 1994.
- Widdowson, M.A. and D.M. Scaturro. "Experimental evaluation of a multi-level drive point sampler for quantifying hydraulic conductivity", Spring Meeting, American Geophysical Union, Baltimore, MD, May 24-28, 1993.
- Ray, R.P., M.A. Widdowson, H.W. Reeves and C.M. Aelion. "Soil sampling and laboratory testing for SVE/sparging in Piedmont soils: Measurement of spatial variation and field confirmation", Spring Meeting, AGU, May 24-28, 1993.
- Widdowson, M.A. "Modeling and field experiments to determine mixing and hydraulic control at an *in situ* bioremediation project", Second International Symposium on In Situ and On-Site Bioreclamation, Battelle /EPA, San Diego, CA, April 5-8, 1993.
- Widdowson, M.A., D.M. Scaturro, L.M. Blakley and R.L. Nichols. "Evaluation of field data and procedures for hydraulic conductivity analysis using multi-level sampling rigs", Spring Meeting, American Geophysical Union, Montreal, Canada, May 11-16, 1992.
- Widdowson, M.A., W.H. Orne, D.M. Scaturro and R.L. Nichols. "Development of a computer-controlled data acquisition system for multi-level groundwater sampling at an aquifer tracer test", Spring Meeting, American Geophysical Union, Montreal, Canada, May 11-16, 1992.
- Widdowson, M.A., "Technical challenges to groundwater remediation", Conference on Environmental Law, Greenville, SC, Columbia, SC, and Charleston, SC. April 8-10, 1992, respectively. (Invited)
- Widdowson, M.A., R.L. Nichols and L.M. Blakley. "Application of tracer tests in groundwater remediation design", Hydraulics Division, American Society of Civil Engineers, Nashville, TN, July 29-August 2, 1991.
- Widdowson, M.A., M.E. Meadows, J.R. Dickerson, P. Talwani, M. Schaeffer and W.E. Orne*. "Hydrologic impact of reservoir filling on a fractured crystalline-rock aquifer", Irrigation and Drainage Division, ASCE, Honolulu, HI, August 11-15, 1991.

- Talwani, P., M. Salvador, G. Randall and M. Widdowson. "Induced seismicity studies at Bad Creek Project, South Carolina Phase 2 - the impoundment stage", Spring Meeting, American Geophysical Union, May 28-31, 1991.
- Dickerson, J.R., M.A. Widdowson and M.E. Meadows. "Low cost multi-purpose data acquisition", Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, Association of Ground Water Scientists and Engineers, Las Vegas, NV, May 11-15, 1991.
- Aelion, C.M. and M.A. Widdowson. "Numerical modeling and field application to the *in situ* bioremediation of subsurface contamination at a JP-4 jet fuel spill", Annual Meeting, American Society of Microbiology, May, 1991.
- Widdowson, M.A., "*In situ* groundwater remediation", Conference on Engineering and Management, Columbia, SC. January 24, 1991. (Invited)
- Talwani, P., A. Ownby, K. Rajendran, M. Widdowson and M. Schaeffer. "Bad Creek project: A progress report", Fall Meeting, AGU, December 3-7, 1990.
- Widdowson, M.A., and J.L. Sapp. "Denitrification in groundwater: Modeling the fate and transport of nitrate", Fall Meeting, American Geophysical Union, San Francisco, CA, December 3-7, 1990.
- Talwani, P., A. Ownby, K. Rajendran, M. Widdowson and M. Schaeffer. "A field study of reservoir induced seismicity at Bad Creek, S.C., the pre-impoundment phase", Meeting of the Eastern Section of the Seismological Society, October, 1990.
- Widdowson, M.A. "An analysis technique for multi-level and partially penetrating slug test data", Spring Meeting, American Geophysical Union, Baltimore, MD, May 29-June 1, 1990.
- Widdowson, M.A. "Modeling nitrate transport coupled to denitrification in the saturated zone", *National Water Conference*, Irrigation and Drainage Division, American Society of Civil Engineers, Newark, DE, July 11-15, 1989.
- Widdowson, M.A., F.J. Molz and J.G. Melville. "Analysis of multi-level slug test data to determine hydraulic conductivity distribution", *Solving Ground Water Problems with Models*, Conference and Exposition, Association of Ground Water Scientists and Engineers, Indianapolis, IN, February 14-16, 1989.
- Widdowson, M.A., F.J. Molz and L.D. Benefield. "Modeling multiple organic contaminant transport and biotransformations under aerobic and anaerobic (denitrifying) conditions in the subsurface", *Petroleum Hydrocarbons and Organic Chemicals in Ground Water*, Association of Ground Water Scientists and Engineers, Houston, TX, November 14-16, 1988.
- Widdowson, M.A. and F.J. Molz. "Solution technique for a coupled system of equations describing advection-dominated transport and biotransformations in the subsurface", *Computational Mechanics*, Atlanta, GA, April 6-8, 1988.
- Widdowson, M.A., F.J. Molz and L.D. Benefield. "A numerical transport model for oxygen- and nitrate-based respiration linked to substrate and nutrient availability in porous media", Fall Meeting, American Geophysical Union, San Francisco, CA, December 7-11, 1987.
- Molz, F.J. and M.A. Widdowson. "Internal inconsistencies in dispersion-dominated models that incorporate chemical and microbial kinetics", Spring Meeting, American Geophysical Union, May 18-21, 1987.
- Widdowson, M.A., F.J. Molz and L.D. Benefield. "Development and application of a model for simulation of microbial growth dynamics coupled to nutrient and oxygen transport in porous media", *Solving Ground Water Problems with Models*, Conference and Exposition, Association of Ground Water Scientists and Engineers, Denver, CO, February 14-16, 1987.
- 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.

Molz, F.J., Widdowson, M.A. and L.D. Benefield. "Simulation of microbial growth dynamics coupled to nutrient and oxygen transport in porous media", Spring Meeting, American Geophysical Union, May 19-22, 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).

U.S. Army Corps, "Bench Scale TNT Degradation Study, Groundwater Model and GIS Support", \$174,473, 24 months, Amy Pruden (co-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.

Environmental Security Technology Certification Program (ESTCP), "Verification of Methods for Assessing the Sustainability of Monitored Natural Attenuation", \$231,392, 36 months, J.T. Novak (co-PI).

U.S. Army Engineering Research and Development Center, "Development of a Model for Contaminant, Carbon, and Nutrient Mass Fluxes in Contaminated Sediment", \$45,000, 18 months.

U.S. Department of Education, "GAANN: An Interdisciplinary Program in Environmental Biogeochemistry", \$35,049, 12 months, John Little (PI).

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).

Environmental Security Technology Certification Program, "Estimating Cleanup Times Associated with Combining Source-Area Remediation with Monitored Natural Attenuation", \$121,090, 24 months.

U.S. Geological Survey, "Computational Model for the Uptake of Contaminants from Groundwater by Phreatophytes", \$40,000, 30 months.

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. Navy/U.S. Geological Survey, "Guidelines and Procedures for Determining Restoration Timeframes Associated with Monitored Natural Attenuation at Naval Facilities", \$140,000, 18 months.

U.S. Army Waterways Experiment Station, "SEAM3D Reductive Dechlorination Package for Simulation of Intrinsic Bioremediation in Aquifers", \$30,000, 12 months.

U.S. Army/Law Engineering and Environmental Services, "Bioventing Pilot Test at Building 900, Douge Creek Village, Ft. Belvoir", \$5,500, 8 months, J.T. Novak (co-PI).

U.S. Army/Law Engineering and Environmental Services, "Groundwater Flow Modeling of the Aquifer System at Ft. Belvoir: Phase II", \$15,000, 9 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).

U.S. Department of Defense/Army Research Office, "Modeling the Fate and Transport of BTEX and MTBE in Groundwater", \$132,608, 36 months.

U.S. Army/Law Engineering and Environmental Services, "Groundwater Flow Modeling of the Aquifer System at Ft. Belvoir: Phase I", \$14,480, 6 months.

Norfolk Southern Corporation, "Phytoremediation of Creosote - Contaminated Soil and Groundwater at the Oneida Tie Yard Site", \$400,364, 36 months, J.T. Novak (PI).

U.S. Army/Horne Engineering, "Evaluation of Intrinsic Bioremediation at the Douge Creek Subdivision Ft. Belvoir, VA", \$28,800, 12 months, J.T. Novak and N.G. Love (co-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.

Virginia Water Resources Research Center, "In Situ Bioremediation of Xenobiotic Compounds by Iron-Reducing Organisms in Groundwater: Development and Validation of a Numerical Model", \$9,367, 13 months.

U.S. Geological Survey, "Numerical Simulation of *In Situ* Bioremediation", \$17,892, 9 months.

South Carolina Hazardous Waste Management Research Fund, "Field Demonstration of *In Situ* Stripping and Bioremediation of Petroleum-Derived Contamination in the Piedmont Region", \$303,501, 24 months, R.P. Ray, H.W. Reeves and C.M. Aelion (co-PIs).

U.S. Department of Energy/Oak Ridge National Laboratory, "Partnership in Computational Science: Groundwater Transport", \$20,342, 8 months, R.P. Ray (co-PI).

U.S. Geological Survey, "Transport Modeling and Multi-level Monitoring at a Bioremediation Project", \$8,740, 12 months.

U.S. Department of Energy/Westinghouse Savannah River Co. (SCUREF), "Establishment of a Field Geohydrology Site", \$45,333, 20 months, M.E. Meadows (co-PI).

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).

U.S. Department of Energy/Westinghouse Savannah River Co. (SCUREF), "Field Tests for Groundwater Flow and Transport at the TNX Area", \$124,080, 19 months.

U.S. Geological Survey, "Solute Transport Modeling of a Bioremediation Project at Hanahan, SC", \$16,087, 12 months.

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

University of South Carolina	ENGR 360 Fluid Mechanics
	ECIV 350 Introduction to Environmental Engineering
	ECIV 563 Subsurface Hydrology
	ECIV 761 Numerical Methods in Subsurface Hydrology
	ECIV 763 Groundwater Hydraulics
	ECIV 764 Contaminant Transport
Auburn University	CE 310 Hydraulics I

OTHER PROFESSIONAL EXPERIENCE

Consultant – BEM Systems, Remedial Action Work Plan, Newark, NJ, 9/09-12/10.

Consultant – U.S. Air Force, Former Williams AFB, Phoenix, AZ, 3/07-4/11.

Expert testimony – Remediation Products, Inc., Patent pertaining to groundwater remediation, 9/08-5/10.

Consultant – U.S. Army Corps of Engineers, McCormick and Baxter Superfund Site, Sacramento, CA, 9/07-8/09.

Consultant – Groundwater resource development and feasibility study, South-Central Virginia, 7/07-11/07.

Expert testimony – Lincoln Preservation Foundation, 5/01-11/01.

Expert testimony - American Electric Power on Groundwater Contamination, 4/00-6/00.

Consultant - South Carolina Electric and Gas/Fluor Daniel GTI. Calhoun Park Area Superfund Site, Charleston, SC. Phytoremediation Feasibility Study, 9/98-1/99.

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.

Consultant and expert testimony - Hilton Head Island Public Service District #1, Hilton Head Island, SC. Recommendations for long-term Public Water Supply for Hilton Head Island. Technical Review of Engineering and Hydrogeologic Reports related to Groundwater Resource Development, 1/92-7/93.

Consultant and expert testimony - Forest Land Company, Columbia, SC. Investigation of Groundwater Contamination, Sabre Saw Chain Superfund Site, Pontiac, SC, 10/90-8/92.

Consultant - Post, Buckley, Schuh & Jernigan, Inc., Columbia, SC. Subsurface Contaminant Transport Modeling, Kalama Specialty Chemicals Superfund Site, Beaufort, SC, 11/90-1/92.

Consultant and expert testimony - J. Hollingsworth, Greenville, SC. Dewatering of a Limestone Aquifer, Williamsburg Co., SC, 1/89-5/90.

Consultant - Electric Power Research Institute, Palo Alto, CA. Analysis and Review of a Groundwater Flow Computer Program (EFLOW), 12/87-6/88.

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

SERDP/ESTCP Tools for Management of Chlorinated Solvent-Contaminated Sites. “Improved Field Evaluation of NAPL Dissolution and Source Longevity”, Partners in Environmental Technology, 1-day workshop, 80 attendees, Washington, DC, December 3, 2009.

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.

National Ground Water Association. "Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal", 2-day short course, 12 attendees, Providence, RI, March 23-24, 2009.

U.S. Navy/Battelle Memorial Institute. "Estimating MNA Remedial Timeframes with Natural Attenuation Software (NAS)", 1-day short course, 38 attendees, Norfolk, VA, May 6, 2008.

U.S. Navy/Battelle Memorial Institute. "Estimating MNA Remedial Timeframes with Natural Attenuation Software (NAS)", 1-day short course, 25 attendees, Honolulu, HI, April 29, 2008.

U.S. Navy/Battelle Memorial Institute. "Estimating MNA Remedial Timeframes with Natural Attenuation Software (NAS)", 1-day short course, 21 attendees, Silverdale, WA, April 17, 2008.

U.S. Navy/Battelle Memorial Institute. "Estimating MNA Remedial Timeframes with Natural Attenuation Software (NAS)", 1-day short course, 75 attendees, San Diego, CA, April 15, 2008.

National Ground Water Association. "Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal", 2-day short course, 14 attendees, Tucson, AZ, March 17-18, 2008.

Environmental Professionals' Organization of Connecticut. "Estimating cleanup times associated with combining source-area remediation with natural attenuation", 1-day short course, 52 attendees, Hartford, CT, March 28, 2007.

Licensed Site Professional Association of Massachusetts. "Estimating cleanup times associated with combining source-area remediation with natural attenuation", 1-day short course, 50 attendees, Boston, MA, March 26, 2007.

National Ground Water Association. "Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal", 2-day short course, 15 attendees, Tampa, FL, February 5-6, 2007.

Environmental Professionals' Organization of Connecticut. "Estimating cleanup times associated with combining source-area remediation with natural attenuation", 1-day short course, 55 attendees, Hartford, CT, November 6, 2006.

Battelle Memorial Institute, "Estimating remediation times using monitored natural attenuation", half-day short course, 26 attendees, Monterey, CA, May 21, 2006.

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.

Environmental Professionals' Organization of Connecticut. "Estimating cleanup times associated with combining source-area remediation with natural attenuation", 1-day short courses, 100 attendees (total), Hartford, CT, March 28-29, 2006.

National Ground Water Association. "Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal", 2-day short course, 15 attendees, Denver, CO, March 2-3, 2006.

National Ground Water Association. "Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal", 2-day short course, 16 attendees, Nashville, TN, October 3-4, 2005.

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.

State Coalition for Remediation of Drycleaners. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 32 attendees, Raleigh, NC, May 3-4, 2005.

American Institute of Professional Geologists. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 30 attendees, Saratoga Springs, NY, October 4-5, 2004.

Oklahoma Ground Water Association. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 18 attendees, Oklahoma, OK, March 10-11, 2004.

National Ground Water Association. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 36 attendees, Portland, OR, February 23-24, 2004.

Naval Facilities Engineering Command and Naval Facilities Engineering Service Center, “Estimating cleanup times associated with combining source-area remediation with natural attenuation”, 2-day short course, 30 attendees, Charleston, SC, August 5-6, 2003.

Naval Facilities Engineering Command and Naval Facilities Engineering Service Center, “Estimating cleanup times associated with combining source-area remediation with natural attenuation”, 2-day short course, 33 attendees, San Diego, CA, July 22-23, 2003.

Battelle Memorial Institute, “Estimating remediation times using monitored natural attenuation”, half-day short course, 32 attendees, Orlando, FL, June 4, 2003.

Battelle Memorial Institute, “Reactive transport modeling of natural attenuation”, 1-day short course, 28 attendees, Orlando, FL, June 1, 2003.

Washington Hydrology Society and Washington State Department of Ecology, “Estimating Remediation Times Using Monitored Natural Attenuation”, half-day workshop, 48 attendees, Tacoma WA, April 10, 2003.

Wyoming Department of Environmental Quality and National Ground Water Association, “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 46 attendees, Cheyenne WY, March 18-19, 2003.

National Ground Water Association. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 28 attendees, Orlando, FL, December 4-5, 2002.

National Ground Water Association. “Estimating Times of Remediation Associated with Monitored Natural Attenuation and Contaminant Source Removal”, 2-day short course, 31 attendees, Scottsdale, AZ, May 5-6, 2002.

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.

U.S. Navy Atlantic Division, Naval Facilities Engineering Command. “Intrinsic bioremediation in groundwater”, 1-day short course, 24 attendees, Norfolk, VA, November 6, 1996.

South Carolina Department of Health and Environmental Control. “Field techniques for measuring hydrologic properties”, 1-day short course, 84 attendees, Columbia, SC, March 1, 1992.

Professional and University Service

Session chair (“Sustainability of Monitored Natural Attenuation), Fifth International Conference on Chlorinated and Recalcitrant Compounds, Monterey, CA, May 22-26, 2006.

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 “Models for Natural Attenuation”, The Fourth International Symposium on In Situ and On-Site Bioreclamation, June, 2001.

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 Fourth International Symposium on In Situ and On-Site Bioreclamation, April-May, 1997.

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 Resources Committee, Myrtle Beach Aquifer Storage Recovery Project, SC Water Resources Commission, 1991-92.

Project Peer Review, U.S. Department of Energy/Office of Health and Environmental Research Subsurface Science Program: Deep Probe Microbiology Subprogram, Salt Lake City, UT, April 24-26, 1991.

Chair of technical session entitled "Surface Water/Ground Water Interaction: Model Development", ASCE Irrigation and Drainage Engineering Conference, 1991.

Technical Advisor to Earth Science Program on *In Situ* Bioremediation, Lawrence Livermore National Laboratory, May 1, 1990.

Technical Advisor to U.S. Department of Energy/Office of Health and Environmental Research Workshop on "Intermediate-Scale Experimentation to Investigate Microbiological, Chemical and Hydrologic Processes Affecting Subsurface Reactive Contaminant Migration", Lewes, Del., April 24-25, 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.

Advisory Committee, South Carolina Environmental Training Center, Sumter, SC, 1988 - 1990.

Manuscripts reviewed for presses and journals:

- *Environmental Science and Technology*, American Chemical Society.
- *Water Resources Research*, American Geophysical Union.
- *Ground Water*, National Ground Water Association.
- *Ground Water Monitoring and Remediation*, National Ground Water Association.
- *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.
- U.S. Agency for Toxic Substances and Disease Registry, US Department of Health and Human Services – Brookhaven National Lab, NY.

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)
 Geoenvironmental Engineering Graduate Option, Hydrosystems Representative (1996-2003)
 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)
CE Measurements, Working Group on CE Curriculum (1997)
CE Computer Applications, Working Group on CE Curriculum (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)
COE Cluster Hire Search Committee, Computational Science and Engineering (2003-2004)

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



VirginiaTech

College of Engineering

The Charles Edward Via, Jr. Department of
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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

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