3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration Below the Slab

External Peer Review Record
June 27-July 23, 2012

CONTENTS:

Peer Review Charge for:

U.S. Environmental Protection Agency (EPA). *3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab*. May 4, 2012. Draft report prepared by ARCADIS U.S., Inc.

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 may eliminate the need for unnecessary indoor air sampling or other sampling and monitoring.

Petroleum vapors have the potential to attenuate in the subsurface as a result of aerobic biodegradation, which is typically the most significant process affecting the attenuation of petroleum vapors in the subsurface at UST sites. Sufficient oxygen must be available beneath a building, however, to support biodegradation of petroleum hydrocarbon vapors (and vapors of other biodegradable volatile organic compound) and thus decrease or eliminate the potential for PVI into overlying buildings. Preliminary modeling results (Abreu et al. 2009; Abreu and Johnson, 2005, 2006) indicate that beneath buildings (and other impervious ground covers) soil vapor may become depleted of oxygen, forming an "oxygen shadow." The term "oxygen shadow" is defined qualitatively to mean an area of soil vapor beneath a building or impervious surface with an oxygen concentration low enough to substantially limit the rate of aerobic biodegradation.

The purpose of this project was to conduct additional 3-D finite difference vapor transport modeling simulations to systematically assess the oxygen shadow phenomenon in order to evaluate the relationships between building footprint, source strength and depth, and oxygen content in soil vapor beneath a building. These new simulation results are aimed at improving the understanding of the impact of building footprint size on the formation of an underlying oxygen shadow, and inform decision making by OUST as to whether there is a building footprint above which a permanent oxygen shadow may form beneath the center of a slab-on-grade building as one of a suite of site screening criteria. These scenarios extend the simulations presented in Abreu and Johnson (2005, 2006); Abreu et al. (2009a, b); and U.S. EPA (2012).

Starting from a "base case" model run, subsequent runs were conducted to determine the building size threshold. Subsequent simulations were chosen based on the results of these initial simulations and decreasing or increasing the building size. All other parameters were reasonably representative of typical conditions and were held constant during the modeling runs. Soil properties for the base cases were for a homogeneous sandy soil and the simulation was run for various durations to determine if quasi-steady state conditions had been achieved or to verify the length of time before oxygen is depleted. Additional scenarios were run for a sand soil overlain by a one meter silty clay layer.

Peer Review Charge Questions:

As a peer reviewer, you are being asked to review the report and provide opinion and perspective regarding:

- whether the model and model runs are suitable and sufficient for the stated simulation objectives;

- the scientific appropriateness of using results from a numerical model for developing screening criteria based on the dimensions of a building given the wide possibilities for the footprint of a building that might be impacted by PVI, and given the relatively limited empirical literature relating the dimensions of a building to the possibility for vapor intrusion;
- whether the model inputs are reasonably representative of worst-case conditions for oxygen depletion in the vadose zone immediately underlying a building; and
- whether the reported conclusions are adequately supported by the simulation results.

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 satisfy the goal 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. a) Are the simulations sufficiently representative of worst-case subsurface and building conditions for oxygen depletion in the vadose zone immediately underlying a building such that the results can appropriately support OUST’s development of screening criteria related to the oxygen shadow beneath buildings? b) Are the reported sensitivity analyses representative of worst-case subsurface conditions for oxygen depletion in the vadose zone immediately underlying a building?
5. Is the default biodegradation rate, including its dependence upon oxygen content in the vadose zone, scientifically appropriate? Is it representative of the range of toxic, vapor-forming substances found in petroleum fuels (currently or historically) and subsurface conditions that may be encountered in the United States? Do the reported sensitivity analyses for biodegradation rate capture reasonably expected worst-case subsurface conditions for vapor concentration and oxygen depletion in the vadose zone immediately underlying a building?
6. Are there other factors, or other choices of parameter values, that were not simulated that if included could potentially change the reported conclusions?
7. Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?
8. 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 Diane Dopkin of Environmental Management Support, Inc., either by phone (301-589-5318, ext. 22) or email (diane.dopkin@emsus.com).

References Cited:

Abreu, L.D.V. and P.C. Johnson. (2006). Simulating the Effect of Aerobic Biodegradation on Soil Vapor Intrusion into Buildings: Influence of Degradation Rate, Source Concentration, and Depth. *Environmental Science and Technology*. **40**(7); 2304-2315.

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Revised Draft Final Report: 3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab

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ARCADIS MALCOLM PIRNIE

3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab

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1. Introduction

1.1 Background

Vapor intrusion occurs when vapor-phase contaminants migrate from subsurface sources into buildings. One broad category of vapor intrusion is petroleum vapor intrusion (PVI), in which vapors from petroleum hydrocarbons such as gasoline, diesel, or jet fuel enter a building. The intrusion of contaminant vapors into indoor spaces is of concern due to potential threats to safety (e.g., explosive concentrations of petroleum vapors or methane) and possible adverse health effects from inhalation exposure to toxic chemicals.

Petroleum vapors have the potential to attenuate in the subsurface as a result of microbially-mediated biodegradation, with aerobic biodegradation typically the most significant process affecting the attenuation of petroleum vapors in the subsurface. Sufficient oxygen must be available beneath a building to support aerobic biodegradation of petroleum hydrocarbon (and other biodegradable volatile organic compound) vapors and thus decrease or eliminate the potential for PVI into overlying buildings. Preliminary modeling results (Abreu et al. 2009; Abreu and Johnson, 2005, 2006) indicate that beneath buildings (and other impervious ground covers) soil vapor may become depleted of oxygen, forming an “oxygen shadow.” This oxygen shadow is the result of an interrelationship between source concentration, depth of contaminant, building footprint, and potentially other factors. Where an oxygen shadow occurs, the potential for PVI into overlying buildings is increased. Additional discussion and simulations of the model used for this study is presented in U.S. EPA (2012).

1.2 Purpose

The purpose of this project was to conduct additional three-dimensional (3-D) finite difference vapor transport modeling simulations to systematically assess the oxygen shadow phenomenon in order to evaluate the relationships between building footprint, source strength and depth, and oxygen content in soil vapor beneath a building. These new simulation results are aimed at improving the understanding of the impact of building footprint on the formation of an underlying oxygen shadow, and inform decision making as to whether there is a building footprint above which a long lasting oxygen shadow may form beneath the center of a slab-on-grade building, as one of a suite of site screening criteria. These scenarios extend the simulations presented in Abreu and Johnson (2005, 2006); Abreu et al. (2009a,b); and U.S. EPA (2012).

We define the term “oxygen shadow” qualitatively to mean existence of a concentration of oxygen at which the availability of oxygen substantially limits the rate of aerobic biodegradation. In this report we define an oxygen shadow as being present if the concentration of oxygen falls to 1% or less in soil gas beneath the building (Abreu and Johnson, 2006).

2. Methods

2.1 Model Used

The Abreu/Johnson numerical model used for the simulations is a 3-D, finite difference model. The numerical accuracy of the code has been previously demonstrated through the comparison of model predictions with other analytical and numerical model results. The code has been shown to be capable of fitting field-measured vertical soil-gas profiles. These results are discussed in Abreu et al. (2009a,b and 2007) and Abreu and Johnson (2006 and 2005).

The Abreu & Johnson 3-D Numerical vapor intrusion model simultaneously solves transient equations for the soil-gas pressure field (from which the advective flow field is computed), transient advective and diffusive transport and reaction of multiple chemicals (including oxygen) in the subsurface, flow and chemical transport through foundation cracks, and chemical mixing in indoor air. Inputs to the model include geometry descriptors (e.g., building footprint, foundation depth, crack locations and widths, source depth), chemical properties, kinetic reaction rate parameters, the indoor-outdoor pressure differential, oxygen concentration at the ground surface, and the chemical vapor concentrations at the vapor source. The model uses a finite-difference numerical method to solve the model partial differential equations.

2.2 Model Inputs

Starting from a “base case” model run (10 m x 10 m building size), we performed subsequent runs with different building sizes to determine the building size threshold. The first subsequent runs used a building size of 90 m x 90 m; this size was chosen to reasonably include building sizes within the distribution found in the U.S. based on a literature review (see section 2.3). The subsequent simulations were chosen based on the results of these initial simulations and decreasing or increasing the building size. The simulations are summarized in Tables 1 through 5 (see Attachment 2). This process was repeated for three source depths (5, 15 and 30 ft), and source strengths in the range of 10,000 µg/m^3 to 10,000,000 µg/m^3). The depths chosen are arbitrary but are commonly referred to depth ranges in numerous existing guidance documents. This source strength range is reasonable because:

- As demonstrated below, concentrations below 10,000 µg/m^3 are very unlikely to exhibit an oxygen shadow regardless of what values were selected for the other model parameters (within the ranges for those parameters covered in this project).

- Results for concentrations above 10,000,000 µg/m^3 have been adequately described in a previous report (EPA, 2012, Section 5). The previous report examined cases at 20,000,000 through 200,000,000 µg/m^3 for a 10m by 10m building, and showed some cases where oxygen was depleted even for that relatively small building size.

- Published estimates of soil gas concentrations in equilibrium with gasoline LNAPL range from 1,300,000,000 µg/m^3 (1300 mg/L) for fresh gasoline to 220,000,000 µg/m^3 (220 mg/L) for weathered gasoline (Johnson et al. 1990). Thus, the modeled range is of interest because it can potentially occur in the environment even in the absence of LNAPL.

- It corresponds to a range from 0.01 mg/l to 10 mg/l in dissolved phase hydrocarbon concentration, which is typical for groundwater in equilibrium with LNAPL.

All other parameters were reasonably representative of typical conditions and were held constant during the modeling runs. Soil properties for the base cases were for a homogeneous sandy soil and the simulation was run for various durations to determine if quasi-steady state conditions had been achieved or to verify the time frame of transport before oxygen is depleted. Additional scenarios were run for a sand soil overlain by a one meter silty clay layer. Other specific parameter inputs are found in Table 1 of Abreu, et al. (2009) on page 107.

2.3 Building Parameters

In this section, we provide the results of the literature review for the building size parameters that were selected. According to Census Bureau data, the majority of the new single-family housing units sold in the U.S. between 1999 and 2007 have a footprint area that ranges between 1,000 square feet (sf) and 5,000 sf (92 to 464 m^2)(Census Bureau 2007). In 1986, the size distribution of commercial buildings indicates that more than 55% of commercial buildings are in the range of 1,001 to 5,000 sf; 22% of commercial buildings are in the range of 5,001 to 10,000 sf (464 to 924 m^2); 12% of commercial buildings are in the range of 10,001 to 25,000 sf (924 to 2322 m^2) and only 5.7% of commercial buildings are in the range of 25,001 to 50,000 sf (2322 to 4645 m^2) (Koomey 1990). In 1995, the vast majority of commercial buildings nationwide were in the smallest size categories. That is, more than half (52%) of the commercial buildings were in the smallest size category, ranging from 1,001 to 5,000 sf and 75% were in the two smallest size categories with a maximum size of 10,000 sf (Diamond 2001). Buildings in the U.S. with the largest usable space have footprint areas ranging from 348,000 sf to 4.3 million sf (35,674 to 399,483 m^2) (Wikipedia 2012, Boeing 2012). Exhibit 1 is an example of a building with a footprint at the upper end of the reported range.

Exhibit 1. Example of a very large US building (Boeing Facility, Everett WA) image downloaded from http://www.boeing.com/commercial/tours/images/K64532-14_lg.jpg

In addition to the reported floorplan size of the building, many U.S. buildings are surrounded by impervious surfaces, such as parking lots, sidewalks or roads that in some cases may extend the area subject to an oxygen shadow (Exhibit 2).

Exhibit 2. Example of U.S. building in which the parking lot area may have an effect on the total impervious surface

Thus, we initially prioritized simulations of the most common, smaller building sizes. However we found that most of those cases did not produce an oxygen shadow under the simulated conditions. Therefore in order to define the threshold at which an oxygen shadow might appear, we iteratively expanded the size of the modeled buildings, up to a maximum of 632m x 632m = 99,856 m^2 (1,074,841 ft^2).

Prior to this report the 3-D modeling simulations done to date (EPA 2012) were done with a 10 meter by 10 meter square building. In such a symmetrical square building, in a homogenous geology, oxygen transport to the center of the building footprint would occur uniformly from all four directions. However, a rectangular floor plan is the most common building footprint shape in the U.S.[1] It is reasonable to expect that in the larger rectangular building cases the oxygen that reaches the soil under the building center will come primarily from the closest edge of the building. Therefore,

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[1] http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.121.2572
http://www.isprs.org/proceedings/XXXVIII/4-W25/paper/153-158Huanghai.pdf
http://my.arch.ethz.ch/janha/downloads/01_eCAADe_proceedings_final_100810/CD/Low_Res/paper_069.pdf

our simulation matrix, Tables 1 through 5, included some rectangular cases. Approximately 160 simulations were performed.

2.4 Sensitivity Testing

From first principles verified by numerous simulations, the probability of an oxygen shadow forming:

- Increases with increasing building area
- Increases with increasing source vapor concentration
- Increases with increasing time (assuming the source hydrocarbon concentrations are relatively stable and quasi-steady transport conditions were not achieved)
- Increases with decreasing vadose zone thickness

Therefore, simulations were performed as shown in Table 1 for each vadose zone thickness and source vapor concentration, with increasing building sizes and durations in order to establish a threshold at which an oxygen shadow may form.

To evaluate the sensitivity of the model to an initial condition where hydrocarbons are released into a subsurface setting that contains less than atmospheric levels of oxygen, we performed some simulations with initial oxygen concentrations at 10.5% in soil gas instead of 21%. This value is in the range of background vadose zone soil oxygen content, which has been reported in various sources as 5-18%[2] and 15-21%[3].

To evaluate the time frame before oxygen was depleted and to evaluate the oxygen conditions when a quasi-steady transport condition was achieved, simulations were conducted with increasing transport times.

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[2] http://www.colorado.edu/engineering/civil/CVEN4474/resources/Biovent.pdf

[3] http://www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/bioventing/sitescreening/index.asp

3. Results and Discussion

3.1 Tabulated Results summaries

The results from numerous simulations are summarized in Tables 1 through 5. Tables 1 through 4 present the results for slab-on-grade buildings. Tables 1 through 3 present the results for a vadose zone consisting of a homogenous sand with source depths of:

- 1.6 m (5 ft) – Table 1
- 4.6 m (15 ft) – Table 2
- 9 m (30 ft) Table 3

In Tables 1 through 3, the results for square building footprints are presented first, followed by the results for rectangular buildings. Within each group of building shape, the results are presented in order of increasing source vapor concentration and foundation size.

Table 4 presents the results for simulations run with a 1-m silt clay layer overlying sand. Table 5 presents the results for buildings with a basement.

In the summary tables 1 through 5, an oxygen shadow is qualitatively defined to occur when the predicted oxygen content in soil gas beneath the slab is less than or equal to 1% by volume. The minimum oxygen concentration immediately below the slab and 1 m below the slab is also tabulated.

3.2 Graphical Conventions in Figures

The Abreu and Johnson 3-D model calculates the chemical vapor concentration in the subsurface, the mass flow rates into the building(s), and the indoor air concentration due to vapor intrusion. To facilitate the discussion and the presentation of results, the model output has been normalized using the source concentration (i.e., the predicted concentration is divided by the maximum vapor concentration in the subsurface). Figures showing soil vapor concentrations are also presented as source-normalized ratios, called “normalized soil vapor concentrations.” The normalized concentrations shown in the figures can be multiplied by the source concentration to convert into absolute concentrations. The hydrocarbon concentration contour lines in most of the figures show these normalized soil vapor concentrations, which are always dimensionless and range from 0 to 1, with 1 being equal to the concentration at the source.

Since these examples assume a homogenous soil system, there is symmetry in the soil gas concentration profile with relation to the centerline of the building. In Figure 1A, a soil gas hydrocarbon profile over the full width of a large example building is shown along with the corresponding half building 2-D contour plot that will generally be used in subsequent figures to present the results. Figure 1B shows the corresponding oxygen profile.

The modeled domain in all cases extends horizontally for 7 meters beyond the building footprint. As shown in Figure 1C, this provides a sufficient surface area for oxygen infiltration such that the results are not sensitive to further increases in the size of the modeled domain. However as illustrated in Figure 1C, the scale of the drawings for the larger buildings necessarily compresses the horizontal scale, so this area appears relatively small on the printed page.

3.3 Homogenous Sand Soil Results – Square Buildings

Based on the 133 model simulations conducted under this set of conditions, the following results were shown:

- Homogenous soil results are summarized in Tables 1 through 3. As shown in Figures 2 and 3, with relatively low source soil vapor concentrations of 10,000 µg/m^3 and 100,000 µg/m^3 and a relatively thin vadose zone of 1.6 m (5 ft), no oxygen shadow was predicted even with a very large building (632mx632m) and a very long transport time of 50 years. Therefore, one can infer that no oxygen shadow would be present at or below this soil vapor source concentration and with thicker vadose zones. It is also reasonable to infer that an oxygen shadow would be very unlikely to occur with source soil vapor concentrations below 10,000 µg/m^3.

- As shown in Figure 4 and Table 1, when the source soil vapor concentration is increased to 1,000,000 µg/m^3 and the source depth is only 1.6m (5ft), oxygen does become depleted after a period of 6 to 9 years under a very large building (632x632m). However, if the vadose zone is 4.6m (15 ft) thick, even under such a very large building, no oxygen shadow forms even after 20 years (Figure 5). An oxygen shadow does form with a 4.6 m vadose zone if the initial oxygen in the soil gas is reduced to 10.5%, or if the source persists for 50 years.

- Figure 6 (and Table 2) shows that at a source vapor concentration of 1,000,000 µg/m3 and intermediate depth 4.6 m (15 ft), there is a substantial difference after 8 years between the case in which the initial oxygen was set to 10.5% and the case with initial oxygen set to 21%. The case with 10.5% initial oxygen reaches our definition of an oxygen shadow at 9 years. The case with 21% initial oxygen still has 14.9% oxygen below the slab at 9 years.

- As shown in Figure 7, with the highest source soil vapor concentration modeled (10,000,000 µg/m^3), an oxygen shadow occurs in less than one year after release for the 4.6m (15 ft) vadose zone thickness combined with the largest modeled building size (632m x 632m). Therefore, one can infer that an oxygen shadow has a greater potential to occur with thinner vadose zones if soil source concentrations are in this range.

- For the highest source soil vapor concentration modeled (10,000,000 µg/m^3) and a shallow 1.6 m (5 ft) vadose zone, an oxygen shadow forms rapidly even with a small 10x10m building and 21% initial oxygen concentration (Table 1).

- For the highest source soil vapor concentration modeled (10,000,000 µg/m^3) and a medium vadose zone thickness (4.6m), a quasi steady state is achieved within a year of transport for building sizes of 10 m x 10 m, 20 m x 20 m and 30 m x 30 m. An oxygen shadow only occurs with a building dimension of 30 m x 30 m or larger (Figure 8 and Table 2).

- For the highest source soil vapor concentration modeled (10,000,000 µg/m^3) and a relatively large vadose zone thickness (9 m), only a limited number of simulations were run, since this depth was not included in the original scope of the project. The results show that oxygen is substantially depleted and rapidly comes to a steady state condition. However, the oxygen does not quite reach the operational definition of an oxygen shadow for buildings between 30 m x 30 m and 60 m x 60 m. (Figure 9 and Table 3).

Results for even higher source soil vapor concentrations and small (10mx10m) buildings are shown in EPA 2012, Section 5 and Abreu and Johnson (2005).

3.4 Homogenous Sand Soil Results –Rectangular Buildings

Based on the 23 model simulations under this set of conditions, the following results were shown:

- Several rectangular building simulations were performed for shallow sources at 1.6 m (5 ft). Three simulations were performed for a very thin limiting building footprint (10m x 632 m) with a relatively strong source vapor concentration (1,000,000 µg/m^3). These simulations came to quasi-equilibrium with a stable concentration of 15.6% oxygen, substantially higher than the analogous 632 m x 632 m case (1% oxygen) and close to the analogous 10 m x 10 m case (17.8%) (Table 1).

- A series of rectangular building simulations were performed at the intermediate depth of 4.6m (15 ft) with a long, thin (10m x 90 m) building. With the highest source vapor concentration of 10,000,000 µg/m^3, quasi-equilibrium was reached with a stable concentration of 4% oxygen. That result was intermediate between those for a 10 m x 10 m building (6.1%) and a 20 m x 20 m building (1.3%). Even when the extreme bounding case of a 10 m x 632 m building shape was simulated, quasi-equilibrium was reached with a stable concentration of 4.1% oxygen (Table 2 and Figure 10).

Thus, as a general rule of thumb, the minimum oxygen concentration beneath a rectangular building can be approximated from simulations of a square building with dimensions consistent with the smaller building side length (Figure 10). The minimum oxygen concentration in the rectangular buildings will be slightly lower than would be expected for a square building with the same length as the smaller side of the rectangular building.

3.5 Results with an Overlying Silt Clay Layer at Ground Surface

Based on the 30 model simulations under this set of conditions, the following results were shown:

- With the source depth of 1.6 m, the silty clay layer comprises the majority of the simulated vadose zone. Thus, it is not surprising that the resulting oxygen transport is substantially lower. For example, at a vapor concentration of 100,000 µg/m^3, a minimum oxygen concentration of 1% is reached beneath the largest building (632 m x 632 m) in 20 years (Table 4). This stands in contrast to the corresponding case with all sand, which had 17.9% oxygen after 20 years of simulated transport (Table 1). Nevertheless it should be noted that oxygen is not depleted until a transport time of over 9 years.

- Similarly, with a source depth of 1.6 m and a source vapor concentration of 1,000,000 µg/m^3, beneath the shallow silty clay layer, oxygen has been depleted to 1% in 9 years with a 30 m x 30 m building (Table 4). This stands in contrast to the corresponding all-sand condition, where oxygen was 12.3% after 9 years (Table 1).

- At the medium vadose zone thickness of 4.6 m (15 ft) with the 1 m silty clay layer at the surface and a source vapor concentration of 1,000,000 µg/m^3, oxygen is depleted to 1 % in 9 years (Table 4). Without the silty clay layer, the corresponding simulations do not reach 1% oxygen until sometime between 20 and 50 years.

- With the largest vadose zone thickness modeled (9 meters, 30 ft) and a source vapor strength of 10,000,000 µg/m^3, the overlying clay layer still has some effect. For example, with the 30 m x 30 m building footprint, the oxygen concentration beneath the building is reduced from 2.9 to 1.9%. With a 40 m x 40m building footprint, the oxygen concentration is reduced from 1.3 to 1% (Tables 3 and 4).

3.6 Results with a Basement

Based on the five simulation runs under this set of conditions, the following results were shown:

- With a 2 m deep basement (Table 5, figure 11) and the source located 1.6 m (5ft) below the basement, The oxygen concentration results were essentially the same as those for the corresponding slab on grade case (source located 1.6 m below the slab), although there are some slight differences. These slight differences are due to the atmospheric ground surface boundary being further away in the basement scenario. The corresponding slab on grade results are presented in Table 1 and discussed in section 3.3..

4. Primary Limitations

In conducting these model simulations, other subsurface processes that may affect the formation and persistence of an oxygen shadow were not accounted for. Some of these conditions would suggest that the model overestimates the depletion of oxygen in the subsurface, including:

1) Wind-induced advection. Wind impinging on buildings and topography can induce pressure differences in soil gas, thus inducing a sub-horizontal flow of soil gas under buildings, which may increase the rate of oxygen under a building, and reduce the potential for shadow formation. A limited number of simulations (Luo 2009, Abreu 2012) indicate that under some circumstances the effect of wind on oxygen replenishment is not sufficient to avoid an oxygen shadow.

2) Barometric-induced advection. Diurnal and longer-period barometric pressure fluctuations can induce the flow of soil gas into and out of shallow soils. This barometrically-induced advection may affect the rate of oxygen replenishment under a building.

3) Bi-directional soil gas exchange through foundation openings. Cracks and openings in building foundations have been shown to have bidirectional flow, depending on the differential pressure between the building and the adjacent soil gas (McHugh et al., 2006; Luo et al., 2012). During periods of positive differential pressure, oxygen may enter the subsurface through the foundation, thus increasing the rate of oxygen replenishment and decreasing the tendency for shadow formation.

4) Aerated foundation course. Many slab-on-grade buildings are constructed with a layer of gravel or other coarse-grained material beneath the slab. This coarse-grained layer may provide a conduit or “plenum” for enhanced advection of air under the building, which may provide a protective “blanket” of oxygen-rich soil gas under the building.

5) Source depletion. The model assumes that the source does not deplete and has a constant concentration beneath the full extent of the foundation.

6) Perfectly impermeable concrete. The model assumes the foundation concrete is impermeable and doesn’t account for the potential transport of oxygen

through the foundation. However, concrete is permeable to the flow of gases even in the absence of discrete openings (Haghighat et al., 2002; Patterson and Davis, 2009; Kobayashi and Shuttoh, 1991; Tittarelli, 2009; Yu et al., 1993).

On the other hand, other site specific conditions are possible that could result in the model underestimating the depletion of oxygen in the subsurface, including:

1) High natural oxygen consumption from unusually highly organic content soils
2) The presence of other gases providing a carbon substrate for microbial metabolism, such as landfill gas methane.
3) High moisture content shallow soil layers that limit oxygen transport
4) Regional coverage of a high percentage of the ground surface by impervious or near impervious materials, as occurs in major city centers.
5) The special condition of excessively dry soils that do not support sufficient microbial activity.
6) A vadose zone composed solely or principally of bedrock with little or no overlying soils.

Therefore, while these simulations give an indication of the *potential* for oxygen shadow formation under reasonable worst case conditions dominated by diffusive flow, they should not be regarded as actual performance at all field sites.

5. Findings

- The results of these 160 simulations show that the presence or absence of an oxygen shadow is dependent on:
  - Building size
  - Source vapor strength

  - Vadose zone thickness
  - Transport time for oxygen consumption under transient conditions

- At the two lowest source vapor concentrations modeled (10,000 µg/m^3 and 100,000 µg/m^3), an oxygen shadow is not seen even in very large buildings with shallow 1.6 m (5 ft) vadose zones, even after 50 years of simulated transport time.

- At the highest vapor concentration modeled (10,000,000 µg/m^3), quasi-equilibrium conditions are achieved within an year and an oxygen shadow does form under:

  - A small 10 m by 10 m building with a shallow (1.6 m, 5ft) vadose zone OR
  - A modest size 30 m x 30 m building with a moderate thickness vadose zone (4.6 m, 15 ft).

- At intermediate source vapor concentration simulated 1,000,000 µg/m^3, simulations can require a longer transport time to come to quasi-equilibrium. In many of these cases modeled oxygen concentrations are still above the threshold for a period of years but fall below the threshold after decades. We interpret this as flux balance. If diffusion is the dominant transport mechanism, then the following two processes are finely balanced:

  - upward diffusion of hydrocarbons.
  - downward and lateral diffusion of oxygen.

- It is very likely that the modeled results would change significantly if additional processes were modeled, such as high permeability layers beneath building slabs, wind speed/direction variability and bi-directional flow through foundation cracks and penetrations throughout the floor plan. However those factors may be harder to identify during a site screening process then the inputs in the current modeling (such as foundation dimensions and thickness of the vadose zone).

- The depletion of oxygen beneath a rectangular building is controlled primarily by the dimension of the short side of the floor plan.

We believe these results will provide useful guidance for practitioners in identifying situations where the presence of oxygen needed for biodegradation of petroleum hydrocarbons should be confirmed with field measurements, and, conversely, other situations where the presence of oxygen can be reasonably be inferred from site conditions.

6. References

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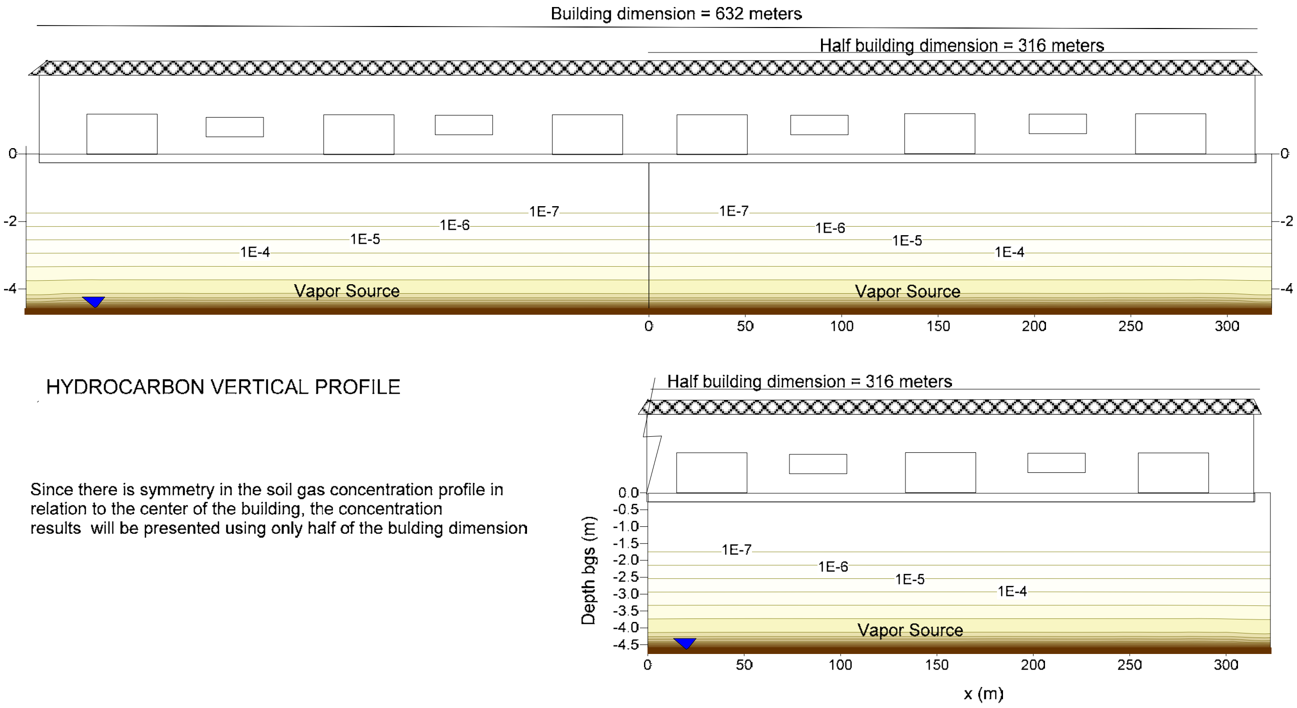
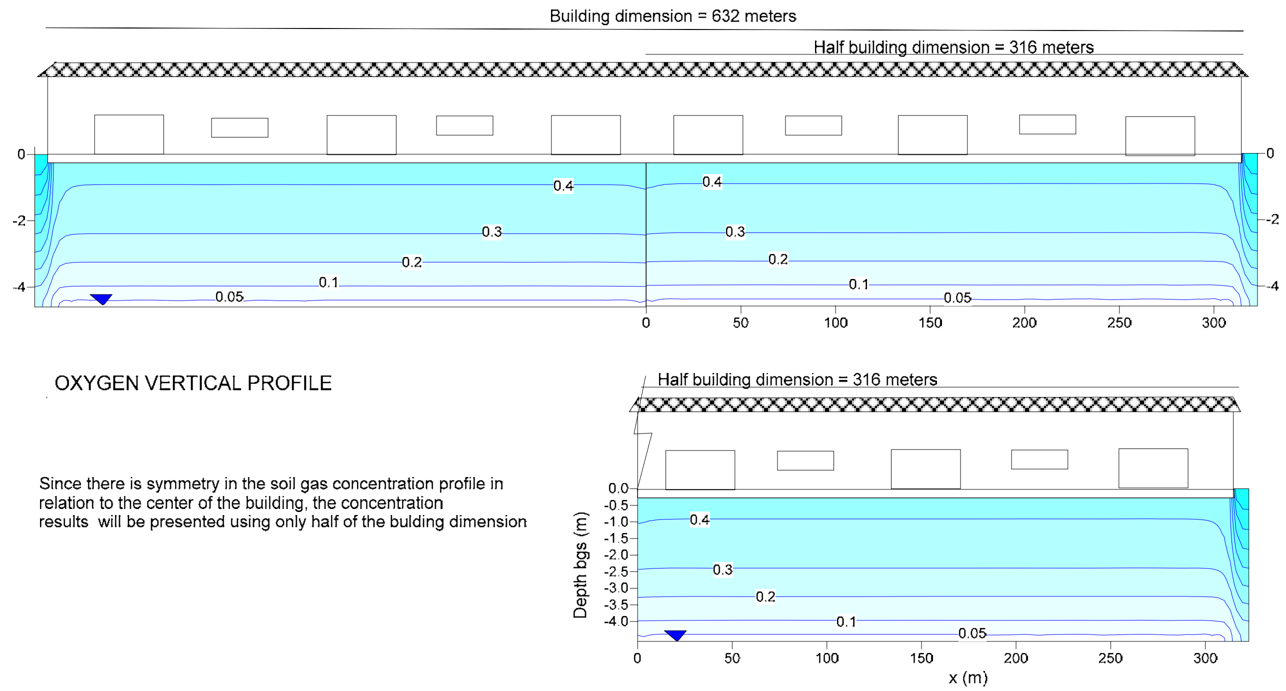
Attachment 1. Figures



HYDROCARBON VERTICAL PROFILE

Since there is symmetry in the soil gas concentration profile in relation to the center of the building, the concentration results will be presented using only half of the bulding dimension

Figure 1A. Example of graphical convention used in presentation of hydrocarbon results, showing full building width at top and at bottom the half building 2d cross section used in other figures



OXYGEN VERTICAL PROFILE

Since there is symmetry in the soil gas concentration profile in relation to the center of the building, the concentration results will be presented using only half of the bulding dimension

Figure 1B. Example of graphical convention used in presentation of oxygen results, showing full building width at top and at bottom the half building 2d cross section used in other figures

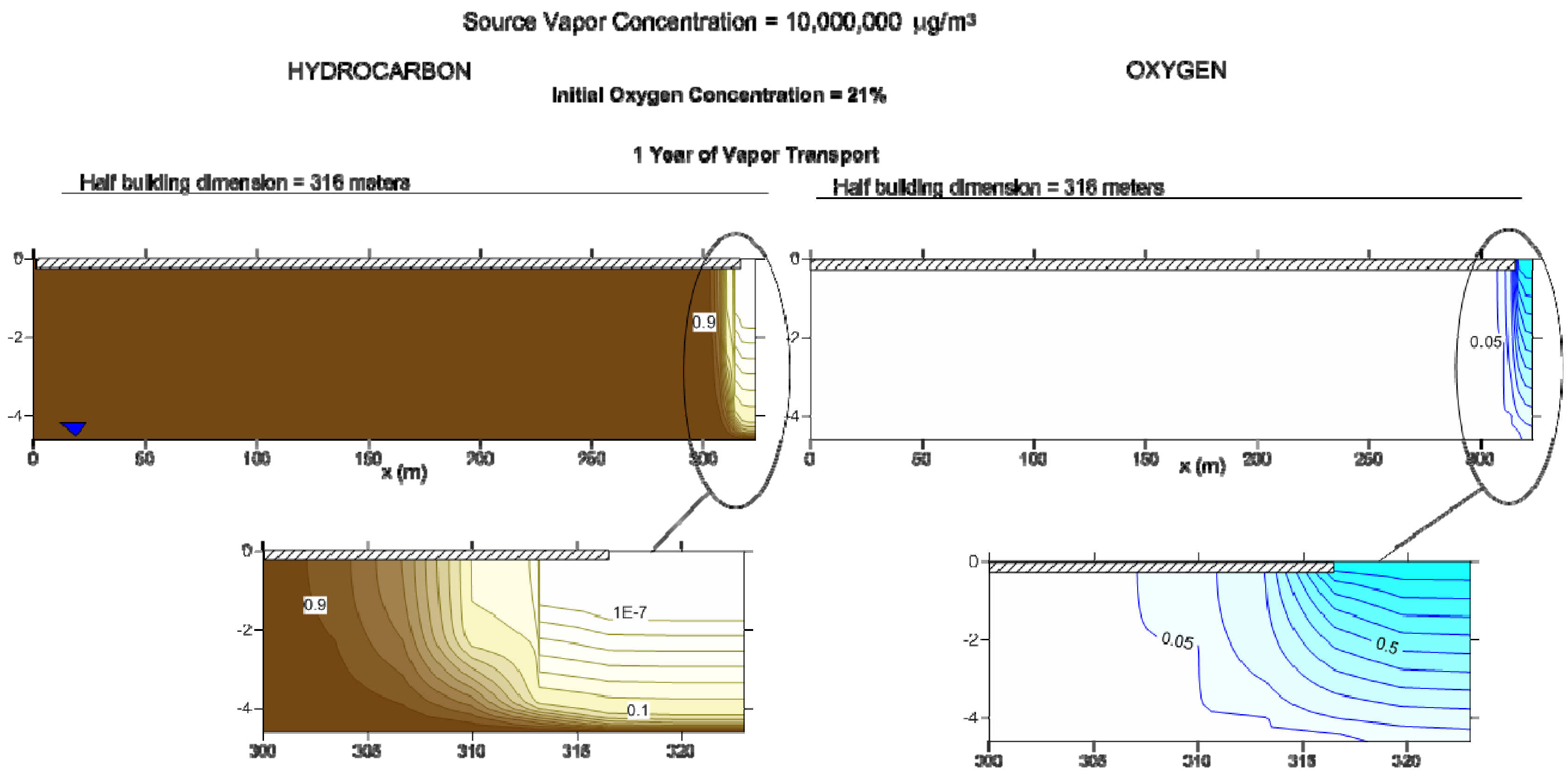
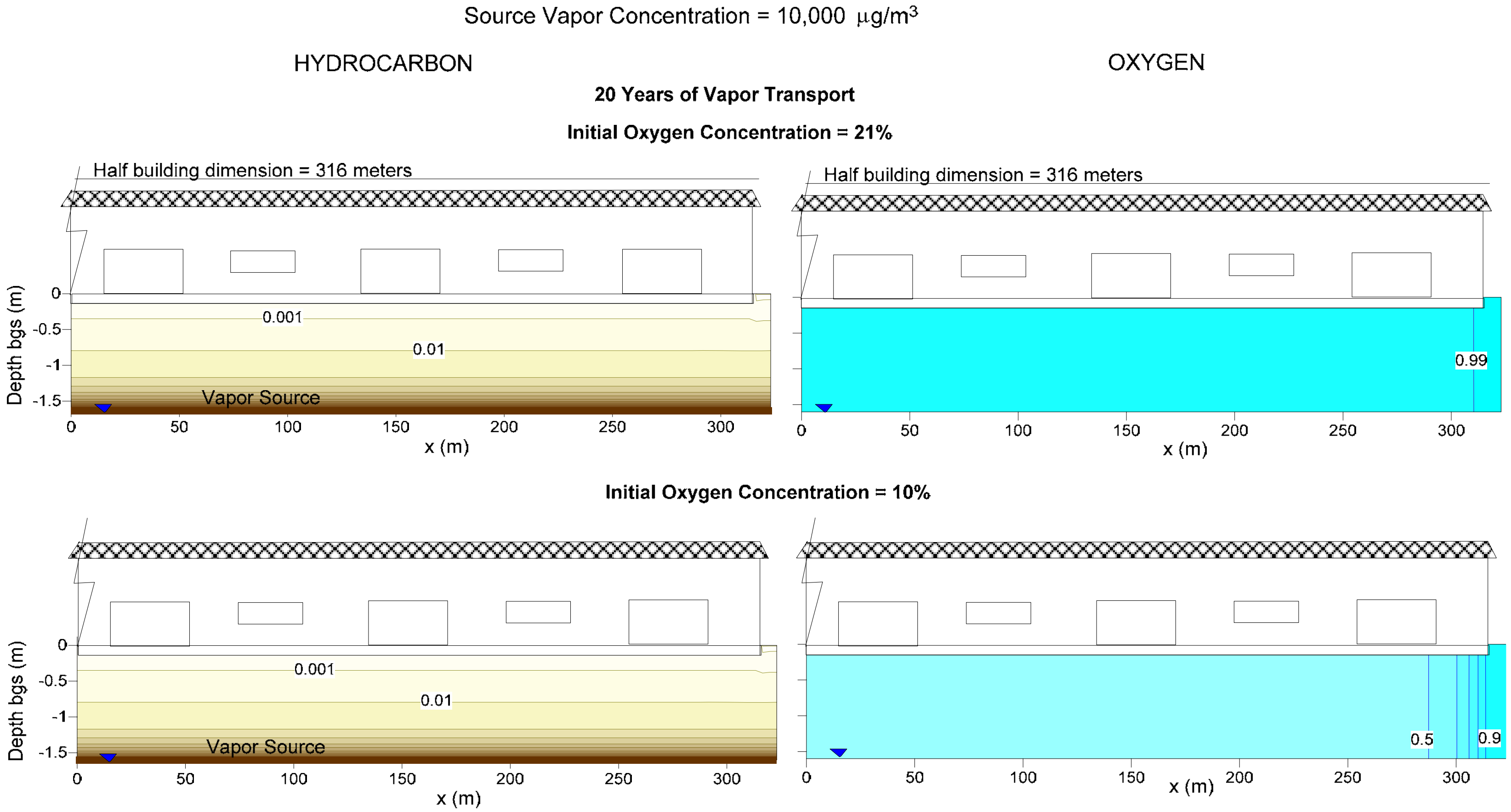


Figure 1C: Expanded view of portion of 7 meter model domain outside the building footprint showing that even under high concentration conditions the model is insensitive to the width of the domain.



Source Vapor Concentration = 10,000 µg/m^3

HYDROCARBON

OXYGEN

20 Years of Vapor Transport

Initial Oxygen Concentration = 21%

Initial Oxygen Concentration = 10%

Figure 2. Concentration results for source vapor concentration of 10,000 µg/m^3 at depth of 1.6 m (5ft) and building size of 632 m by 632 m (total area of 399,424 sq.m). Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape

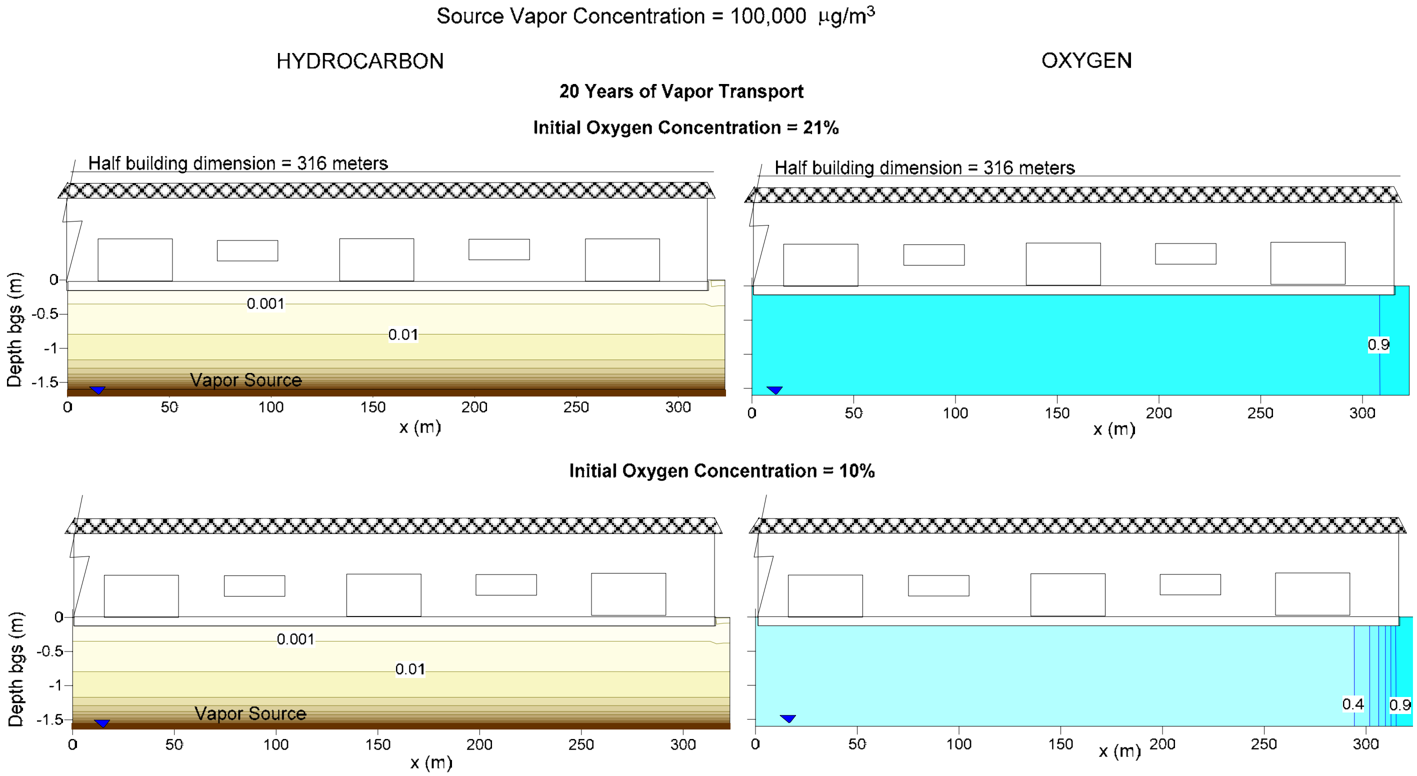


Figure 3. Concentration results for source vapor concentration of 100,000 µg/m^3 at depth of 1.6 m (5ft) and building size of 632 m by 632 m (total area of 399,424 sq.m). Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

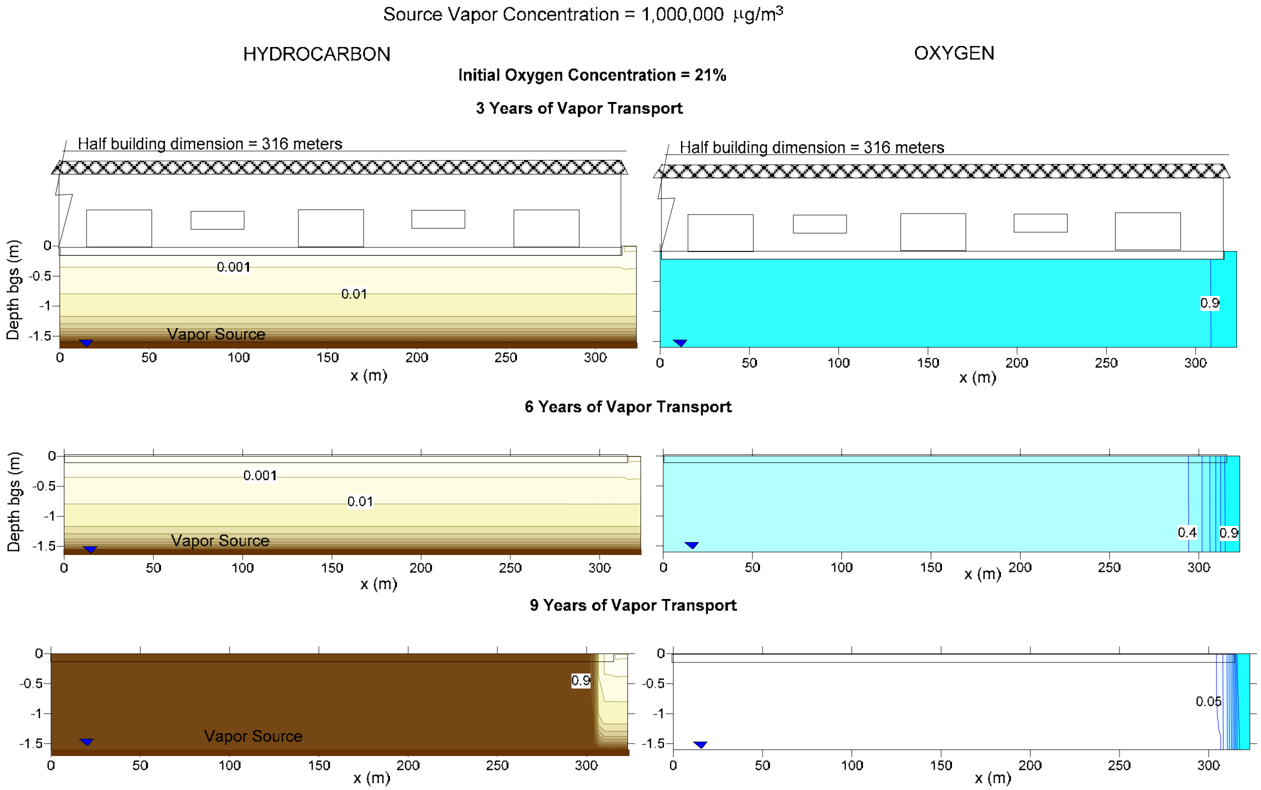


Figure 4. Concentration results for source vapor concentration of 1,000,000 µg/m^3 at depth of 1.6 m (5ft) and building size of 632 m by 632 m (total area of 399,424 sq.m). Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

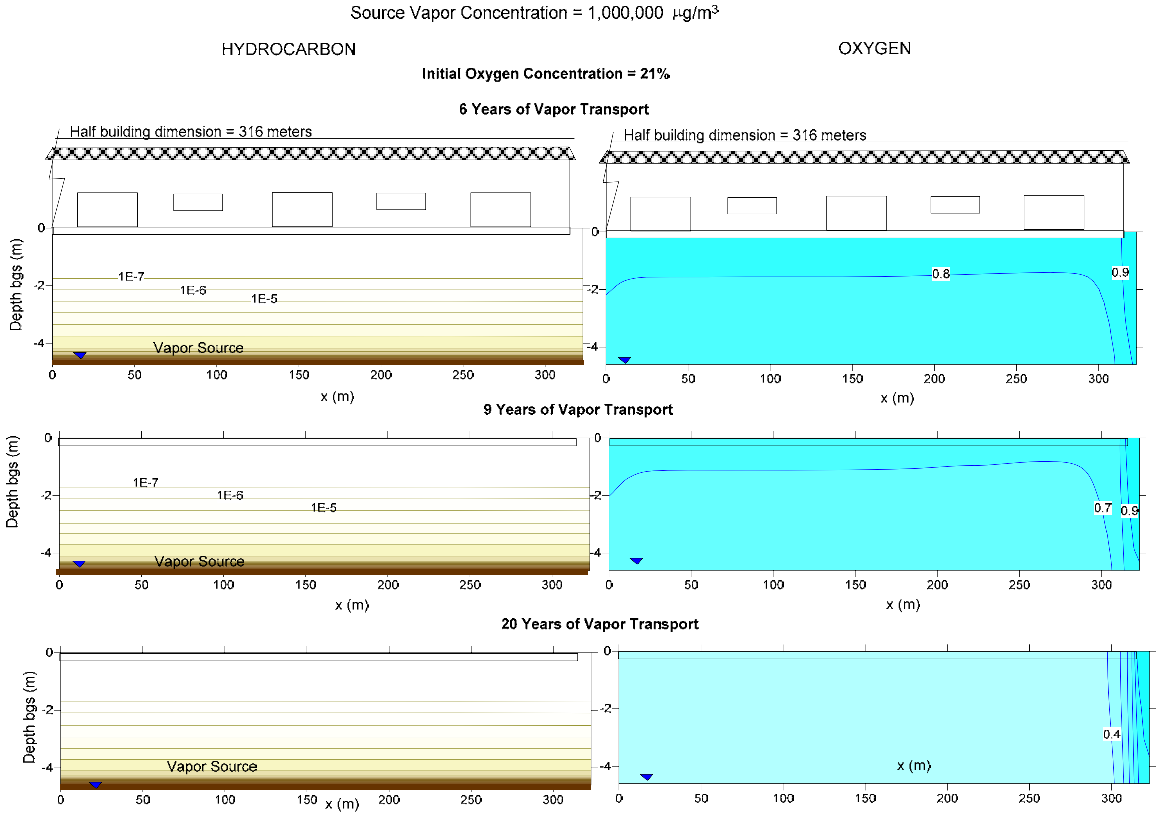


Figure 5. Concentration results for source vapor concentration of 1,000,000 $\mu g/m^3$ at depth of 4.6 m (15ft) and building size of 632 m by 632 m (total area of 399,424 sq.m). Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

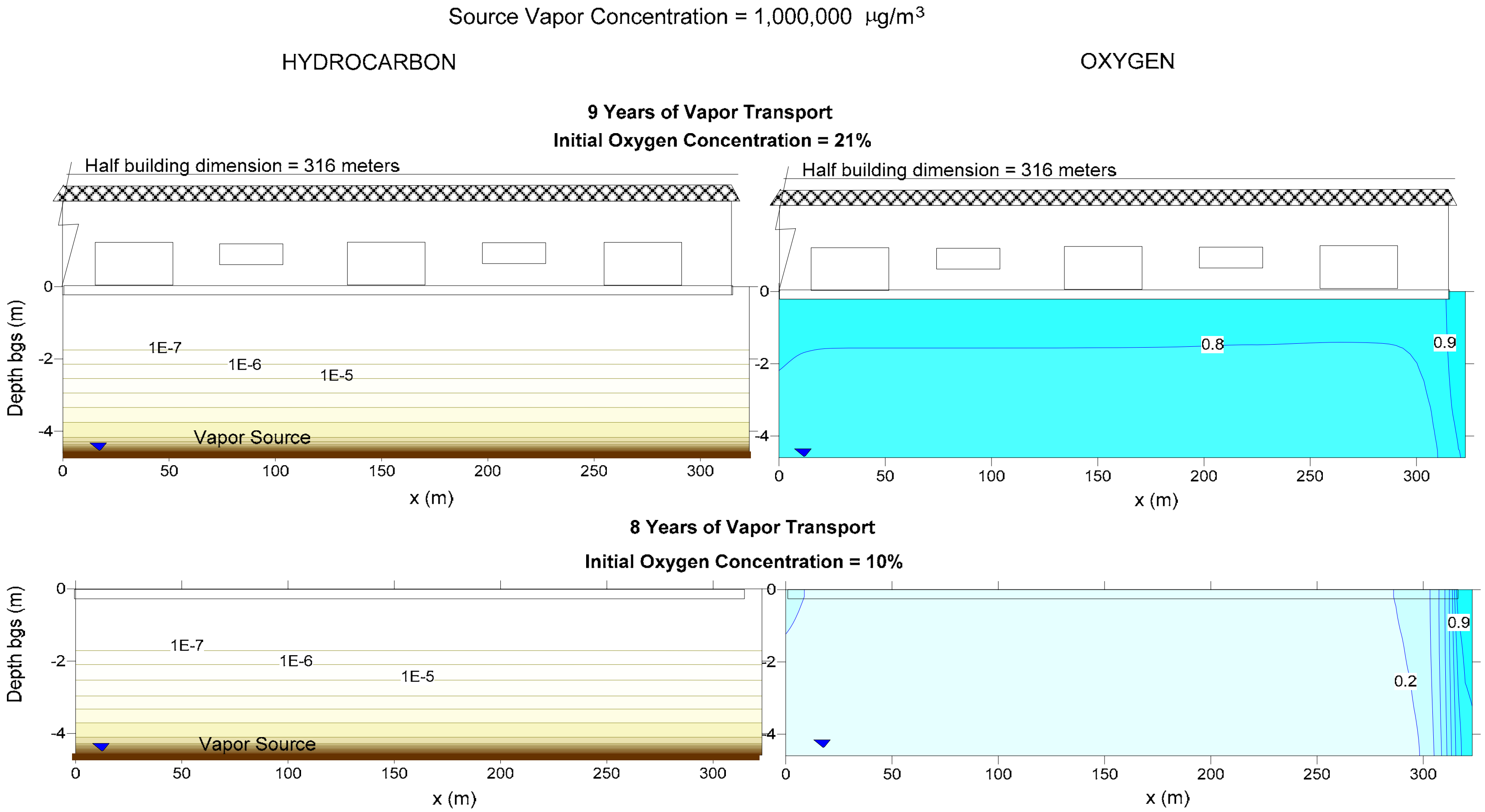


Figure 6. Concentration results for source vapor concentration of 1,000,000 μg/m^3 at depth of 4.6 m (15ft) and building size of 632 m by 632 m (total area of 399,424 sq.m), for an initial concentration of oxygen at 21% and 10%. Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

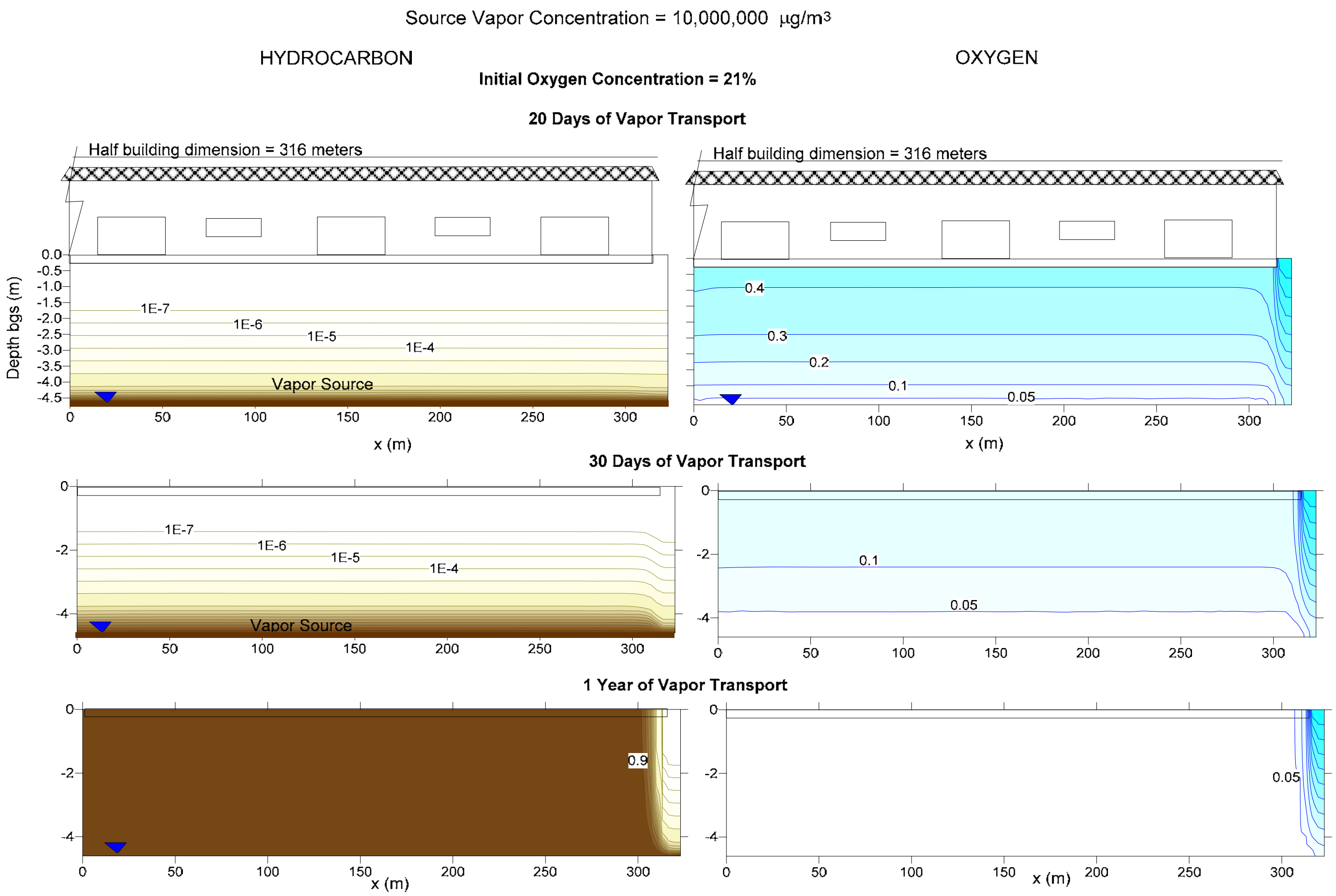


Figure 7. Concentration results for source vapor concentration of 10,000,000 μg/m^3 at depth of 4.6 m (15ft) and building size of 632 m by 632 m (total area of 399,424 sq.m). Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

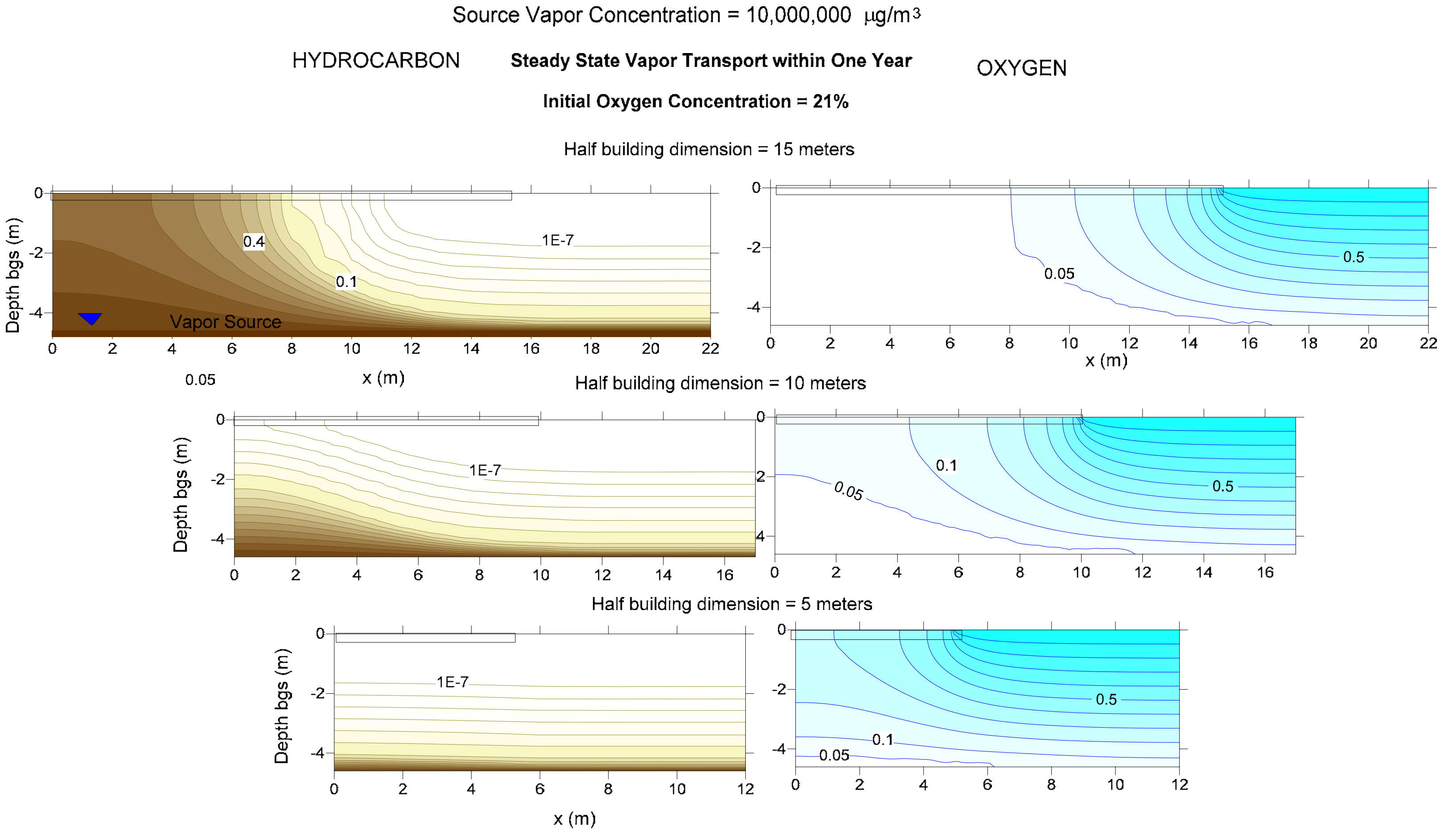


Figure 8. Concentration results for source vapor concentration of 10,000,000 μg/m^3 at depth of 4.6 m (15ft) and three building sizes: 30 m by 30 m, 20 m by 20 m and 10 m by 10 m. Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

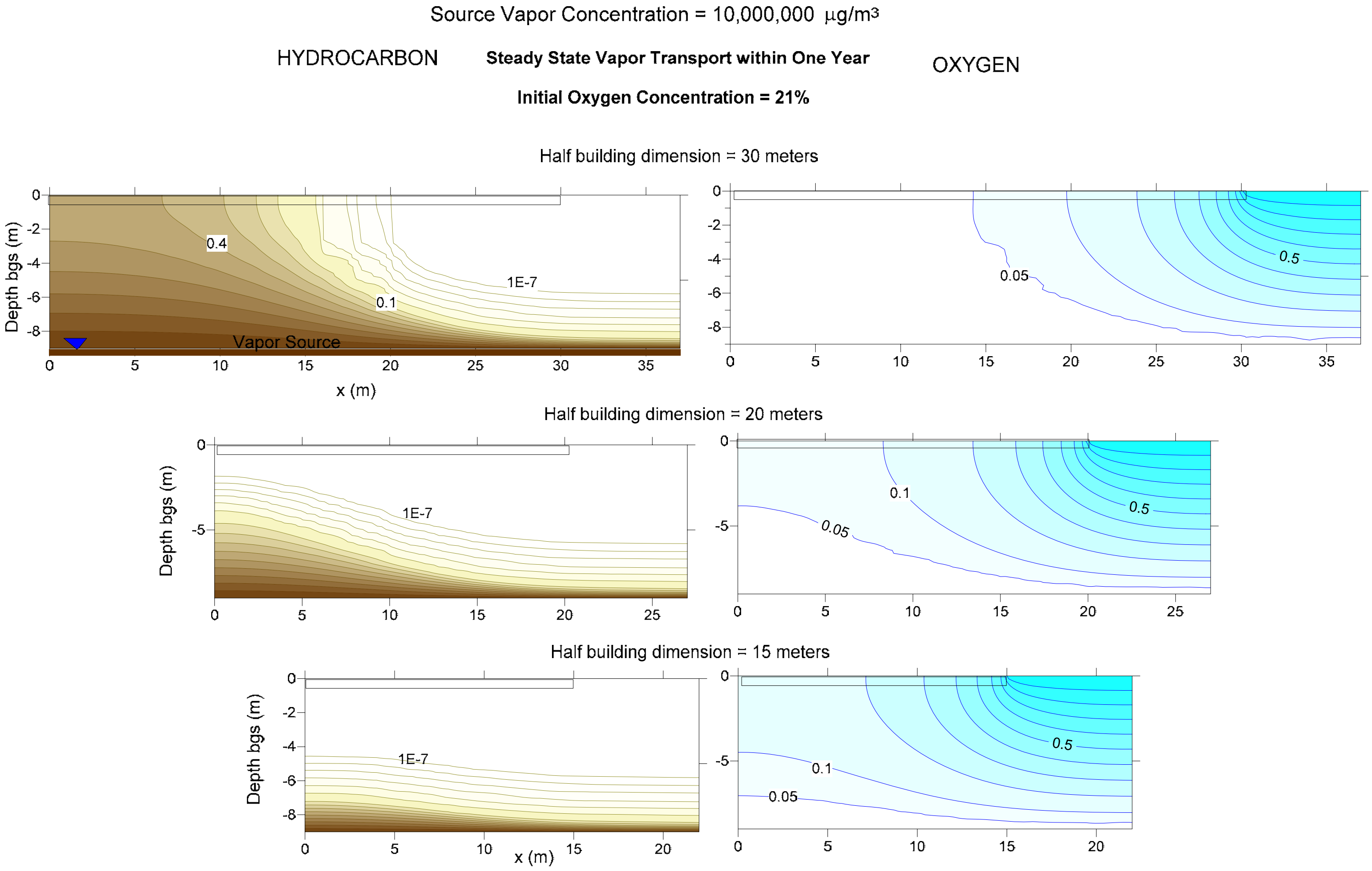


Figure 9. Concentration results for source vapor concentration of 10,000,000 μg/m^3 at depth of 9 m (30 ft) and three building sizes: 60 m by 60 m, 40 m by 40 m and 30 m by 30 m. Hydrocarbon and oxygen concentration profiles are normalized by hydrocarbon source and atmospheric concentration, respectively. Square shape.

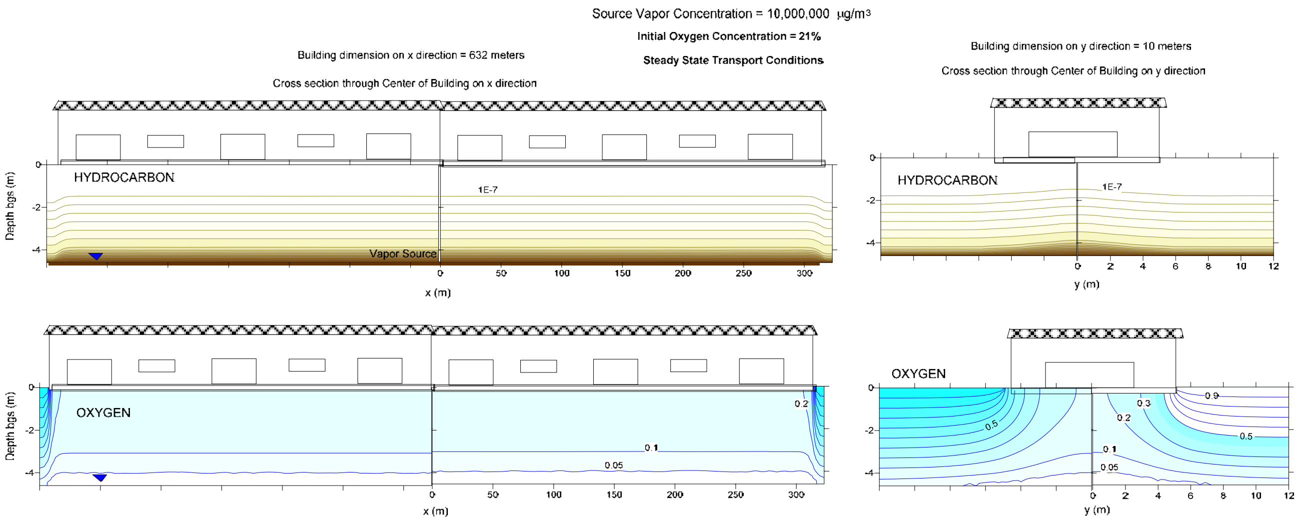


Figure 10. Concentration results for a building with rectangular shape 632 m x 10 m, source vapor concentration of 10,000,000 µg/m^3 at 4.6 m (15 ft), viewed in two perpendicular cross sections

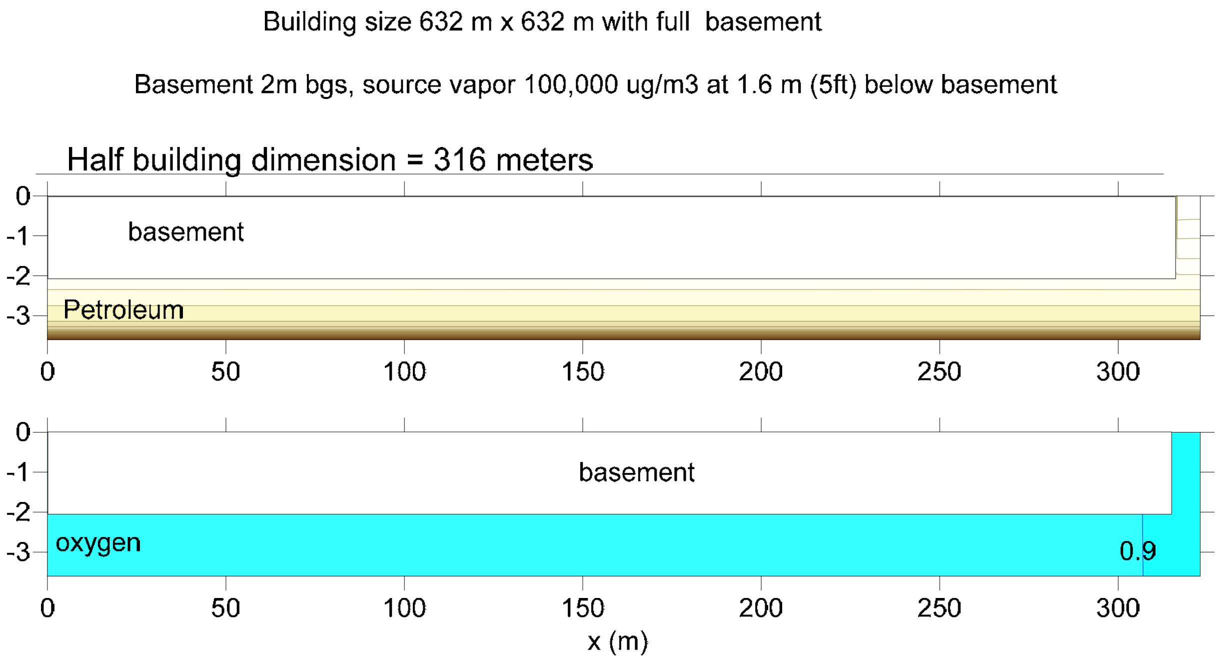


Figure 11: Concentration results for building with basement, transport time 9 years, initial oxygen = 21%

Attachment 2. Tables

Table 1. Matrix Summarizing Simulations Run with Source at 1.6 m (5 ft)

Full Domain Scale (International Units)

Geology: Homogeneous Sand

Slab-on-grade Building Square Shape (meters x meters)

Source Vapor Concentration	Foundation Dimensions (m x m)	Initial Oxygen Concentration (%)	Simulated Transport Time with Biodegradation	Oxygen Shadow?	Minimum Oxygen Concentration Right below Slab		Minimum Oxygen Concentration 1 m (3 ft) below Slab	
$\mu g/m^3$			Years		C/Catm	(%)	C/Catm	(%)
10,000	10 x 10	21	0.5	No	0.99	20.8	0.99	20.8
10,000	10 x 10	21	1	No	0.99	20.8	0.99	20.8
10,000	10 x 10	21	9	No	0.99	20.8	0.99	20.8
10,000	10 x 10	21	50	No	0.99	20.8	0.99	20.8
10,000	90 x 90	21	1	No	0.99	20.8	0.99	20.8
10,000	90 x 90	10.5	1	No	0.50	10.4	0.50	10.4
10,000	90 x 90	21	9	No	0.97	20.4	0.97	20.4
10,000	90 x 90	10.5	9	No	0.48	10.1	0.48	10.1
10,000	90 x 90	21	50	No	0.87	18.3	0.87	18.3
10,000	90 x 90	10.5	50	No	0.48	10.1	0.48	10.1
10,000	120 x 120	21	9	No	0.98	20.6	0.98	20.6
10,000	120 x 120	10.5	9	No	0.49	10.2	0.49	10.2
10,000	120 x 120	21	50	No	0.9	18.9	0.9	18.9
10,000	120 x 120	10.5	50	No	0.44	9.2	0.44	9.2
10,000	240 x 240	21	0.8	No	0.99	20.8	0.99	20.8
10,000	632 x 632	21	9	No	0.99	20.8	0.99	20.8
10,000	632 x 632	21	20	No	0.99	20.7	0.99	20.7
10,000	632 x 632	21	50	No	0.96	20.2	0.96	20.2
10,000	632 x 632	10.5	20	No	0.49	10.2	0.49	10.2
10,000	632 x 632	10.5	50	No	0.46	9.7	0.46	9.7
100,000	10 x 10	21	1	No	0.99	20.8	0.99	20.8
100,000	10 x 10	21	9	No	0.98	20.6	0.98	20.6
100,000	10 x 10	21	50	No	0.98	20.6	0.98	20.6
100,000	90 x 90	21	1	No	0.99	20.7	0.99	20.7
100,000	90 x 90	10.5	1	No	0.48	10.1	0.48	10.1
100,000	90 x 90	21	9	No	0.91	19.2	0.91	19.2
100,000	90 x 90	10.5	9	No	0.42	8.7	0.42	8.7
100,000	90 x 90	21	50	No	0.57	11.9	0.57	11.9
100,000	90 x 90	10.5	50	No	0.17	3.5	0.17	3.5
100,000	120 x 120	21	9	No	0.92	19.3	0.92	19.3
100,000	120 x 120	10.5	9	No	0.42	8.7	0.42	8.7
100,000	120 x 120	21	50	No	0.58	12.1	0.58	12.1
100,000	120 x 120	10.5	50	No	0.11	2.3	0.11	2.3
100,000	632 x 632	21	9	No	0.93	19.6	0.93	19.6
100,000	632 x 632	21	20	No	0.85	17.9	0.85	17.9
100,000	632 x 632	10.5	20	No	0.35	7.2	0.35	7.2
100,000	632 x 632	21	50	No	0.63	13.2	0.63	13.2
100,000	632 x 632	10.5	50	No	0.12	2.5	0.12	2.5
1,000,000	10 x 10	21	1	No	0.93	19.5	0.92	19.3
1,000,000	10 x 10	21	9	No	0.85	17.8	0.85	17.7
1,000,000	10 x 10	21	50	No	0.85	17.8	0.85	17.7
1,000,000	30 x 30	21	9	No	0.59	12.3	0.58	12.2
1,000,000	40 x 40	21	9	No	0.59	12.4	0.59	12.3
1,000,000	40 x 40	10.5	9	**Yes**	0.05	1.0	0.05	1.0
1,000,000	40 x 40	21	20	**Yes**	0.05	1.0	0.05	1.0
1,000,000	60 x 60	21	9	**Yes**	0.05	1.0	0.05	1.0
1,000,000	90 x 90	21	1	No	0.93	19.5	0.93	19.5

Full Domain Scale (International Units)

Geology: Homogeneous Sand

Slab-on-grade Building Square Shape (meters x meters)

Source Vapor Concentration	**Foundation Dimensions (m x m)**	**Initial Oxygen Concentration (%)**	**Simulated Transport Time with Biodegradation**	**Oxygen Shadow?**	**Minimum Oxygen Concentration Right below Slab**		**Minimum Oxygen Concentration 1 m (3 ft) below Slab**	
$\mu g/m^3$			**Years**		**C/Catm**	**(%)**	**C/Catm**	**(%)**
1,000,000	90 x 90	10.5	1	No	0.16	3.4	0.15	3.2
1,000,000	90 x 90	21	9	**Yes**	0.05	0.9	0.05	0.9
1,000,000	90 x 90	10.5	9	**Yes**	0.04	0.9	0.04	0.9
1,000,000	90 x 90	21	50	**Yes**	0.04	0.9	0.04	0.9
1,000,000	90 x 90	10.5	50	**Yes**	0.04	0.9	0.04	0.9
1,000,000	120 x 120	21	9	**Yes**	0.05	1.0	0.05	1.0
1,000,000	120 x 120	10.5	9	**Yes**	0.04	0.8	0.04	0.8
1,000,000	120 x 120	21	50	**Yes**	0.04	0.8	0.04	0.8
1,000,000	120 x 120	10.5	50	**Yes**	0.04	0.8	0.04	0.8
1,000,000	632 x 632	21	1	No	0.93	19.5	0.92	19.4
1,000,000	632 x 632	21	3.0	No	0.78	16.4	0.78	16.3
1,000,000	632 x 632	10.5	3.0	**Yes**	0.05	1.0	0.05	1.0
1,000,000	632 x 632	21	6.0	No	0.56	11.8	0.56	11.7
1,000,000	632 x 632	10.5	6.0	**Yes**	0.05	1.0	0.05	1.0
1,000,000	632 x 632	21	9	**Yes**	0.05	1.0	0.05	1.0
2,000,000	10 x 10	21	0.5	No	0.86	18.1	0.85	17.9
5,000,000	10 x 10	21	0.5	no	0.32	6.7	0.29	6.1
5,000,000	120 x 120	21	0.8	**yes**	0.05	1.0	0.05	1.0
5,000,000	240 x 240	21	0.8	**yes**	0.05	1.0	0.05	1.0
5,000,000	632 x 632	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	10 x 10	21	0.5	**yes**	0.05	1.0	0.05	1.0
10,000,000	20 x 20	21	0.5	**yes (X)**	See simulation with dimensions 10 x 10 above			
10,000,000	30 x 30	21	0.5	**yes (X)**				
10,000,000	90 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
Slab-on-grade Building Rectangular Shape (meters x meters)								
10,000	10 x 90	--	--	no (X)	See simulations with dimensions 90 x 90 above			
10,000	30 x 90	--	--	no (X)				
10,000	60 x 90	--	--	no (X)				
1,000,000	10 x 632	21	6	no	0.78	16.3	0.77	16.2
1,000,000	10 x 632	21	9	no	0.76	15.9	0.75	15.8
1,000,000	10 x 632	21	20	no	0.75	15.6	0.74	15.5
10,000,000	10 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	20 x 90	21	0.8	**yes (X)**	See simulation with dimensions 10 x 90 above			
10,000,000	30 x 90	21	0.8	**yes (X)**				
10,000,000	60 x 90	21	0.8	**yes (X)**				

(X) means the simulation was not run separately, but the qualitative result was obvious by inspection based on other simulations done

Table 2. Matrix Summarizing Simulations Run with Source at 4.6 m (15 ft)

Full Domain Scale (International Units)

Geology: Homogeneous Sand

Slab-on-grade Building Square Shape (meters x meters)

Source Vapor Concentration	**Foundation Dimensions (m x m)**	**Initial Oxygen Concentration (%)**	**Simulated Transport Time with Biodegradation**	**Oxygen Shadow?**	**Minimum Oxygen Concentration Right below Slab**		**Minimum Oxygen Concentration 1 m (3 ft) below Slab**	
µg/m^3			**Years**		**C/Catm**	**(%)**	**C/Catm**	**(%)**
1,000,000	90 x 90	21	9	no	0.59	12.3	0.58	12.3
1,000,000	90 x 90	10.5	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	90 x 90	21	20	no	0.23	4.9	0.23	4.8
1,000,000	90 x 90	21	9	no	0.70	14.7	0.70	14.7
1,000,000	120 x 120	21	20	no	0.34	7.1	0.34	7.1
1,000,000	120 x 120	21	50	**yes**	0.05	1.0	0.05	1.0
1,000,000	200 x 200	10.5	8	no	0.23	4.8	0.22	4.6
1,000,000	200 x 200	21	9	no	0.71	14.9	0.71	14.9
1,000,000	200 x 200	10.5	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	200 x 200	21	20	no	0.36	7.6	0.36	7.6
1,000,000	200 x 200	10.5	20	**yes**	0.04	0.9	0.04	0.9
1,000,000	240 x 240	10.5	8	no	0.22	4.6	0.22	4.6
1,000,000	240 x 240	21	9	no	0.71	14.9	0.71	14.9
1,000,000	240 x 240	10.5	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	240 x 240	21	20	no	0.36	7.6	0.35	7.4
1,000,000	632 x 632	21	6	no	0.81	17.0	0.81	17.0
1,000,000	632 x 632	10.5	8	no	0.20	4.2	0.20	4.2
1,000,000	632 x 632	21	9	no	0.71	14.9	0.71	14.9
1,000,000	632 x 632	10.5	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	632 x 632	21	20	no	0.36	7.6	0.36	7.6
5,000,000	90 x 90	21	9	**yes**	0.05	0.9	0.05	0.9
10,000,000	10 x 10	21	0.5	no	0.29	6.1	0.28	5.9
10,000,000	10 x 10	21	1	no	0.29	6.1	0.28	5.9
10,000,000	10 x 10	21	9	no	0.29	6.1	0.28	5.9
10,000,000	10 x 10	21	50	no	0.29	6.1	0.28	5.9
10,000,000	10 x 10	10.5	50	no	0.29	6.1	0.28	5.9
10,000,000	20 x 20	21	1	no	0.06	1.3	0.06	1.3
10,000,000	20 x 20	21	9	no	0.06	1.3	0.06	1.3
10,000,000	20 x 20	21	20	no	0.06	1.3	0.06	1.3
10,000,000	30 x 30	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	90 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	90 x 90	21	9	**yes**	0.04	0.9	0.04	0.9
10,000,000	632 x 632	21	0.05	no	0.42	8.8	0.42	8.8
10,000,000	632 x 632	21	0.08	no	0.14	2.9	0.13	2.7
10,000,000	632 x 632	21	1	**yes**	0.05	1.0	0.05	1.0
Slab-on-grade Building Rectangular Shape (meters x meters)								
10,000,000	10 x 90	21	0.8	no	0.20	4.1	0.19	3.9
10,000,000	10 x 90	21	9	no	0.19	4.0	0.19	4.0
10,000,000	10 x 90	10.5	20	no	0.19	4.0	0.19	4.0
10,000,000	10 x 90	21	50	no	0.19	4.0	0.19	4.0
10,000,000	20 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	30 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	60 x 90	21	0.8	**yes**	0.05	1.0	0.05	1.0
10,000,000	10 x 632	21	1	no	0.20	4.1	0.20	4.1

Full Domain Scale (International Units) Geology: Homogeneous Sand								
Slab-on-grade Building Square Shape (meters x meters)								
Source Vapor Concentration	**Foundation Dimensions (m x m)**	**Initial Oxygen Concentration (%)**	**Simulated Transport Time with Biodegradation**	**Oxygen Shadow?**	**Minimum Oxygen Concentration Right below Slab**		**Minimum Oxygen Concentration 1 m (3 ft) below Slab**	
$\mu g/m^3$			**Years**		**C/Catm**	**(%)**	**C/Catm**	**(%)**
10,000,000	10 x 632	21	6	no	0.20	4.1	0.20	4.1
10,000,000	10 x 632	21	9	no	0.20	4.1	0.20	4.1
10,000,000	10 x 632	21	20	no	0.20	4.1	0.20	4.1

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Table 3. Matrix Summarizing Simulations Run with Source at 9 m (30 ft)

Full Domain Scale (International Units)

Geology: Homogeneous Sand

Source Vapor Concentration	**Foundation Dimensions (m x m)**	**Initial Oxygen Concentration (%)**	**Simulated Transport Time with Biodegradation**	**Oxygen Shadow?**	**Minimum Oxygen Concentration Right below Slab**		**Minimum Oxygen Concentration 1 m (3 ft) below Slab**	
µg/m^3			**Years**		**C/Catm**	**(%)**	**C/Catm**	**(%)**
Slab-on-grade Building Square Shape (meters x meters)								
10,000,000	30 x 30	21	1	no	0.14	2.9	0.14	2.9
10,000,000	30 x 30	21	6	no	0.14	2.9	0.14	2.9
10,000,000	30 x 30	21	9	no	0.14	2.9	0.14	2.9
10,000,000	30 x 30	21	20	no	0.14	2.9	0.14	2.9
10,000,000	40 x 40	21	1	no	0.062	1.3	0.06	1.3
10,000,000	40 x 40	21	9	no	0.062	1.3	0.06	1.3
10,000,000	40 x 40	21	20	no	0.062	1.3	0.06	1.3
10,000,000	60 x 60	21	1	no	0.06	1.3	0.06	1.3
10,000,000	60 x 60	21	9	no	0.06	1.3	0.06	1.3
Slab-on-grade Building Rectangular Shape (meters x meters)								
10,000,000	10 x 632	21	1	no	0.47	9.9	0.46	9.7
10,000,000	10 x 632	21	6	no	0.47	9.9	0.46	9.7

Table 4. Matrix Summarizing Simulations Run with a Silt Clay Layer on Ground Surface

Full Domain Scale (International Units) **Geology: silt clay on top (1 m thick) and Sand Below**									
Slab-on-grade Building Square Shape (meters x meters)									
Source Vapor Concentration	**Source Depth**	**Foundation Dimensions (m x m)**	**Initial Oxygen Concentration (%)**	**Simulated Transport Time with Biodegradation**	**oxygen shadow?**	**Minimum Oxygen Concentration Right below Slab**		**Minimum Oxygen Concentration 1 m (3 ft) below Slab**	
µg/m^3	**(m)**			**Years**		**C/Catm**	**(%)**	**C/Catm**	**(%)**
100,000	1.6	632 x 632	21	9	no	0.47	9.9	0.47	9.9
100,000	1.6	632 x 632	21	20	**yes**	0.049	1.0	0.05	1.0
1,000,000	1.6	30 x 30	21	1	no	0.44	9.2	0.44	9.2
1,000,000	1.6	30 x 30	21	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	1.6	40 x 40	21	1	no	0.32	6.7	0.32	6.7
1,000,000	1.6	40 x 40	21	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	4.6	120 x 120	21	4	no	0.24	5.0	0.24	5.0
1,000,000	4.6	120 x 120	21	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	4.6	200 x 200	21	4	no	0.24	5.0	0.24	5.0
1,000,000	4.6	200 x 200	21	9	**yes**	0.05	1.0	0.05	1.0
1,000,000	4.6	240 x 240	21	4	no	0.24	5.0	0.24	5.0
1,000,000	4.6	240 x 240	21	9	**yes**	0.05	1.0	0.05	1.0
10,000,000	4.6	632 x 632	21	4	no	0.24	5.0	0.24	5.0
10,000,000	9	30 x 30	21	6	no	0.09	1.9	0.09	1.9
10,000,000	9	30 x 30	21	9	no	0.09	1.9	0.09	1.9
10,000,000	9	40 x 40	21	6	**yes**	0.05	1.0	0.05	1.0
Slab-on-grade Building Rectangular Shape (meters x meters)									
1,000,000	1.6	10 x 632	21	1	no	0.66	13.9	0.65	13.7
1,000,000	1.6	10 x 632	21	9	no	0.53	11.1	0.52	10.9
1,000,000	1.6	10 x 632	21	20	no	0.52	10.9	0.52	10.9
10,000,000	4.6	10 x 60	21	1	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 60	21	9	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 60	21	20	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 90	21	1	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 90	21	9	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 632	21	1	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 632	21	6	no	0.10	2.1	0.10	2.0
10,000,000	4.6	10 x 632	21	9	no	0.10	2.1	0.10	2.0
10,000,000	9	10 x 632	21	1	no	0.33	6.9	0.33	6.9
10,000,000	9	10 x 632	21	9	no	0.33	6.9	0.33	6.9

Table 5. Matrix Summarizing Simulations Run with Source at 1.6 m (5 ft) Below a Basement

Full Domain Scale (International Units)

Geology: Homogeneous Sand

Building With Full Basement Square Shape (meters x meters)
Basement Depth of 2 m bgs

Source Vapor Concentration	Foundation Dimensions (m x m)	Initial Oxygen Concentration (%)	Simulated Transport Time with Biodegradation	oxygen shadow?	Minimum Oxygen Concentration Right below Slab		Minimum Oxygen Concentration 1 m (3 ft) below Slab	
$\mu g/m^3$			Years		C/Catm	(%)	C/Catm	(%)
10,000	632 x 632	21	9	no	0.99	20.8	0.99	20.8
100,000	632 x 632	21	9	no	0.88	18.4	0.88	18.4
1,000,000	632 x 632	21	1.0	no	0.87	18.2	0.86	18.0
1,000,000	632 x 632	21	3.0	no	0.60	12.5	0.59	12.4
1,000,000	632 x 632	21	9	**yes**	0.05	1.0	0.05	1.0

MATRIX OF PEER REVIEW COMMENTS: Draft *3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab.*

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Hers and Jourabchi	General Charge Question 1				The stated purpose in the report "...was to conduct additional three-dimensional (3-D) finite difference vapor transport modeling simulations to systematically assess the oxygen shadow phenomenon in order to evaluate the relationships between building footprint, source strength and depth, and oxygen content in soil vapor beneath a building. These new simulation results are aimed at improving the understanding of the impact of building footprint on the formation of an underlying oxygen shadow, and inform decision making as to whether there is a building footprint above which a long lasting oxygen shadow may form beneath the center of a slab-on-grade building, as one of a suite of site screening criteria." As described in sections below, there are several gaps in reporting (or are at least not clear to the reviewer) that preclude a complete understanding of the model simulations results. Notwithstanding this, a preliminary opinion is provided. The model is considered suitable for the scenarios simulated, which assume a gasoline release and source total petroleum hydrocarbon (TPH) concentrations up to 10 mg/L. For ethanol-blended gasoline or other types of petroleum releases where methane generation may be significant, the model is not appropriate because multi-component transport and pressures associated with methane generation and biodegradation are not included in the model. The main potential limitations in the model runs pertain to assumption of a no-transport boundary for the foundation slab, and apparent limited or no sensitivity analysis for certain parameters.	1 . We have added a more detailed description of the conceptual understanding of vapor intrusion, the 3-D model, and modeling assumptions in Section 2 and described how that understanding relates to the model process assumptions. 2. We are recommending conducting simulations of advection from ethanol releases / methane generation as part of future investigations since they could not be completed within the current funding level. These recommendations are provided in the report transmittal memo. 3. We now more explicitly address the assumption of a no-transport boundary for the foundation slab. We have described in more detail the sensitivity analysis previously performed for biodegradation rate.
Hers and Jourabchi	General Charge Question 2				In principle, it is considered appropriate to develop screening criteria for building dimensions for the purposes of PVI assessment provided that a scientific process is followed for conceptual site model (CSM) and mathematical model development and model simulations. There is precedence for developing screening criteria for other environmental media (e.g., dilution attenuation factors (DAFs) for groundwater contaminant migration); however, the soil vapor intrusion pathway is considered more complex and requires considerable judgment in the application of models. The steps required for a rigorous approach are: i. An appropriate CSM. ii. The mathematical model reasonably approximates the conceptual site model. iii. The mathematical model has been shown to reasonably match field data. iv. Reasonably conservative modeling scenarios and input parameters are used. v. The modeling results are appropriately applied or interpreted with respect to the overall goal (i.e., predicting the potential for unacceptable risks to human health).	Additional material describing the conceptual understanding of vapor intrusion, the 3-D model, and its input parameters has been added in section 2.1, about the mathematical model/scenario used in section 2.2 and what we believe to be reasonably conservative inputs in section 2.3.
Hers and Jourabchi	General Charge Question 2 (cont.)				Our review of the ARCADIS modeling with respect to the above is as follows: **i. CSM:** Our understanding is that gas migration through the foundation slab is not included in the model. This is potentially overly conservative and possibly a significant limitation. There are other factors not considered in the CSM such as wind-induced or barometric gas pumping, but it is acknowledged that modeling such processes is highly complex. Other comments on the CSM are provided below. **ii. Mathematical model:** For the range of TPH concentrations simulated is considered appropriate. **iii. Match to field data:** This issue is not addressed in this modeling study, although there is reference to previous studies where reasonable matches between field and modeled data were obtained. This is a general limitation that pertains to many modeling. **iv. Reasonably conservative modeling scenarios and input:** Based on the available information, it appears that reasonably conservative assumptions were adopted, although the sensitivity of modeling results to biodegradation rate constants and soil gas advection (from building depressurization) should be demonstrated. The modeling results for the basement scenario should also be more fully described. **v. Application of modeling results:** Implicit in the modeling threshold for development of an oxygen shadow (1%) is that this concentration could potentially result in an increased risk for PVI. This may be generally true, but requires acknowledgement and at least some explanation given that the oxygen shadow is predicted below the centre of a building foundation that is a no-transport boundary. The relationship between source concentrations assumed and possible release scenarios (i.e., dissolved versus LNAPL) is not well explained. Some of the discussion is potentially mis-leading, for example, the range of TPH source soil gas concentrations is justified because "it corresponds to a range from 0.01 mg/l to 10 mg/l in dissolved phase hydrocarbon concentration, which is typical for groundwater in equilibrium with LNAPL". The lower threshold for this range would be representative of a dissolved, not LNAPL release scenario. The discussion in Abreu et al. (2009) on dissolved versus LNAPL may be more helpful in this regard; the authors are also referred to DeVaull (2010). It is recommended that either a more thorough discussion of TPH source concentrations for dissolved and LNAPL scenarios be provided (with references), or discussion on this issue be removed. The lack of inclusion of modeling results for higher TPH source concentrations representative of LNAPL sources, but acknowledgment in report that they should be considered, is awkward and limiting.	More information on source strengths used is provided (Section 2.3.2). More information about sensitivity analysis is also provided (Section 2.4). Clarification has been provided that higher source strength scenarios were evaluated in previous studies and those results are discussed more in the revised draft (Section 2.3.2).
Hers and Jourabchi	General Charge Question 3				Likely yes, see response to other questions, although this will depend on biodegradation rate constant used.	No specific response required

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Hers and Jourabchi	General Charge Question 4				The conclusions require clarity with respect to which conditions the findings are based on. For example, the report findings indicate for a source concentration of 10,000,000 ug/m3 and source depth equal to 15 feet, an oxygen shadow formed for a 30 m by 30 m building. Does this conclusion apply to the layered soil, or uniform soil scenario (there does not appear to be a simulation with layered soil for 30 m by 30 m building for 15 ft. depth – this would be an important case to evaluate)? Does it apply to a basement scenario? Further discussion would be helpful as the possible building dimension where no oxygen shadow would be expected.	We have expanded section 2 and the appendicies to to include more detail on assumed soil conditions, building conditions, etc. Buildings much smaller then the 10mx10m standard are unlikely to be a significant part of the available buildings to be assessed and buildings of that particular size were extensively explored in EPA (2012). Below that size only under extreme conditions would a shadow exist. The majority of the simulations were conducted assuming homogeneous sand soil and some simulations had a silt clay layer at the surface. Therefore the conclusions reached do not directly apply for layered soils where there is a lower permeability layer between the slab and the source. Homogeneous sand soil is the base conservative scenario since it allows for the most rapid transport of degradable petroleum hydrocarbons toward the slab. There could be many combinations for layered soil scenarios, not all of which could be explored within the scope of work. We however believe that the scenarios in section 3.5, those with a silty clay layer at the surface overlying a sand layer extending down to the source are the most conservative simple cases. If a clay layer of some thickness was instead postulated to lie between the slab and the source, the oxygen shadow would have been less likely to develop, because the vertical transport of petroleum hydrocarbons to the area immediately below the slab would have been inhibited. The intended application of this work is to develop screening criteria that can be used without extensive stratigraphic borings beneath the building.
Hers and Jourabchi	Specific Charge Question 1				The report is for the most part well written. The normalized concentration plots are an effective means of showing concentration attenuation. The main limitation is that certain assumptions and defaults are not described. These limitations are described below. It is recommended that figures be prepared that plot the oxygen concentration below the building as a function of source depth, source concentration and soil type scenario. This would make results more transparent and easier to understand. The results of EPA (2012) for higher source concentrations should be included. Another way of plotting data is the ratio of building width (or half-width) over source depth versus the source concentration and oxygen concentration below the building.	Extensive additional information about assumptions and defaults have now been provided. We agree that the reviewers suggestions regarding additional figures would improve the document. If funding allows we plan at a later time to include figures that plot the oxygen concentration below the building as a function of source depth, source concentration and soil type scenario, or plot ratio of building width (or half-width) over source depth versus the source concentration and oxygen concentration below the building. We plan to include results from EPA 2012 for higher source concentrations as suggested.
Hers and Jourabchi	Specific Charge Question 2				The report is incomplete with respect to describing the conceptual site model (CSM) upon which the mathematical modeling is based. The CSM assumptions or characteristics that underlie the modeling should be described, including: • Uniform, non-depleting contamination source that extends below the entire building (the conservatism of this assumption increases as the building size increases); • Transport through porous media (not applicable to fractured media); • No significant preferential pathways; • Slab-at-grade or basement building; • Depressurized building (assumed, but not described in the report); • Foundation slab is a no-transport boundary, except for perimeter crack; • No significant methane generation; • Oxygen ingress limited to a perimeter crack and sides of building (conservative because oxygen diffuses through intact concrete and interior cracks in the foundation); • Oxygen transport is limited to diffusion and soil gas advection through building depressurization (soil gas advection assumed, but not described in report); additional mechanisms for oxygen transport, such as advection through wind-loading or barometric pumping is not included. The limitations section describes some of the above CSM considerations. Reference to this section should be made earlier in the report. While it is important to discuss limitations, a CSM section and linkage to model process assumptions is needed.	We have added more detailed description of the conceptual understanding of vapor intrusion, the 3-D model and modeling assumptions in Section 2. We have introduced some of the limitations in section 2.2.2 and discuss other potentially confounding factors in Section 2.5..
Hers and Jourabchi	Specific Charge Question 3				Applicability of modeling results to ethanol-blended gasoline releases.	We have recommend conducting simulations of advection from ethanol releases / methane generation as part of future investigations (see report transmittal memo).
Hers and Jourabchi	Specific Charge Question 4a				The numbers of simulations for the basement scenario were limited and further discussion of this scenario is warranted. Otherwise the simulations appear to be representative of near worst-case conditions.	Text was added to section 3.6 to clarify why only a few simulations with basement were run and to explain the reasons more simulations are not needed because the results of the basement scenarios can be easily inferred from corresponding slab on grade scenarios.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Hers and Jourabchi	Specific Charge Question 4b				Recommend sensitivity analysis for biodegradation rate constants and soil gas advection from depressurization.	A discussion of sensitivity analysis for biodegradation rate constants was added to section 2.3.3. Regarding soil gas advection from depressurization we recommend future work be undertaken as funding is available. However as indicated by Abreu (2005), the effect of building pressurization is limited to a couple of meters around the crack, therefore, for larger buildings and longer distances, oxygen transport is predominantly dominated by diffusion. Thus we expect that such a sensitivy analyzis on pressurization won't show much of an effect in the concentration profiles at larger distances. The reversed flow from the building into the subsurface and potencial "diffusion" through the concrete could be the biggest difference locally to the crack.
Hers and Jourabchi	Specific Charge Question 5				The rate constants are not provided in the report but in Abreu et al. (2009b) rate constants of 0.79 and 2 hr^{-1} are given in Table 1, but it is not clear what was used for this report. Devaull (2011) reports a median aromatic hydrocarbon first-order biodegradation rate of 0.48 hr^{-1}. Hers et al. (2012) estimated a benzene first-order rate of 0.05 hr^{-1} from field data for site in Canada with soil temperature between 5-7^{o}C. The biodegradation model used (e.g., first-order, Monod) is not described. Based on evaluation of Monod kinetic rate constant models, a first-order oxygen limited model is considered a reasonable approximation, for oxygen concentrations greater than 1%. Given that Abreu et al. (2009) indicate the results of model simulations and oxygen depletion is sensitive to the biodegradation rate constant, it is recommended that a sensitivity analysis for the biodegradation rate constant be conducted for this study (a median first-order decay rate of 0.5 hr^{-1} is recommended, and range corresponding to one order of magnitude on either side of the mean).	An extensive discussion of biodegradation rates and the sensitivity thereto has been provided in section 2.3.3 and 2.3.4.
Hers and Jourabchi	Specific Charge Question 6				There is no documentation of the following input parameters: • Soil properties, including water-filled and total-porosity, and fraction organic carbon (f_{oc}); • Building depressurization and soil gas advection; • TPH composition and physical-chemical properties of the TPH, and • Building foundation properties such as crack size. Are all these parameters, including silty clay properties and TPH composition and physical-chemical properties, listed on Table 1, page 107 of Abreu et al. (2009)? (does not appear to be). For transparency, it would nice to include this table. If benzene is used as a surrogate for TPH, how do differences in aliphatic versus aromatic properties affect the results? The aliphatic fraction often represents over 95% of the TPH vapors. How does f_{oc} affect transient simulations and time to quasi-steady state conditions? A sensitivity analysis to evaluate f_{oc} may not be warranted, but underlying certain statements such as "but it took nine years for oxygen to be depleted" are for a specific assumed f_{oc}. Presumably with lower f_{oc}, a shorter time would be predicted, with higher f_{oc}, a longer time would be predicted. Soil gas advection could potentially be significant for shallow contamination scenarios depending on the soil-air permeability and depressurization assumed. But for larger slab-at-grade buildings, the depressurization may be relatively small, reducing the potential for significant soil gas advection.	We have added more detailed description of the conceptual understanding of vapor intrusion, the 3-D model inputs, and modeling assumptions in Section 2.2 and in Appendix A. Tables that provide similar data to the one requested from Abreu 2009 but updated to this work have been provided (Tables 1 and 2). Section 2.3.4 now addresses the question posed regarding alilphatic vs. aromatic rates. Regarding soil gas advection from depressurization, this subject is recommended for future work. However, as indicated by Abreu (2005), the effect of building pressurization is limited to a couple of meters around the crack, therefore, for larger buildings and longer distances, oxygen transport is predominantly dominated by diffusion. Thus we predict that a sensitivy analyzis on pressurization won't show much of an effect in the concentration profiles at larger distances. The reversed flow from the building into the subsurface and potencial "diffusion" through the concrete could be the biggest difference local to the foundation. We added an additional paragraph at the end of section 2.3.6 to describe the expected effect of the fraction of organic carbon on the results.
Hers and Jourabchi	Specific Charge Question 7				This is a critically important question. It appears that the modeling is generally and approximately consistent with the USEPA empirical database results (developed by Golder Associates and RTI International, based in original database by Ms. Robin Davis). For a source concentration of 10,000,000 ug/m^3 (which would be representative of a highly weathered LNAPL gasoline source) and a source-building separation equal to 15 feet, an oxygen shadow is predicted for a 30 m by 30 m building, but not for a 10 m by 10 m building, so it is presumed that the threshold building size would be between these two sizes. Most buildings in the U.S. EPA empirical database are relatively small (less than 30 m by 30 m) and for UST sites with LNAPL sources, the exclusion distance (i.e., distance for attenuation of hydrocarbon vapors to non-significant concentrations) was estimated to be about 15 feet. Therefore, the modeling results do not appear inconsistent with the available data. However, as indicated in previous modeling by Abreu et al. (2009), it is important to also consider higher source concentrations representative of a gasoline LNAPL source (e.g.,100,000,000 ug/m^3) where the modeling indicates greater potential for oxygen depletion for smaller buildings. If this modeling is going to be applied to develop building thresholds, how are these results going to be incorporated, or is a source concentration of 10,000,000 ug/m^3 considered an upper threshold for LNAPL? A proposed novel way to statistically compare the modeling results to empirical data is through binning of the empirical data on either side of the modeling source concentration thresholds, and then plotting the empirical oxygen versus distance data and the modeling results for the three depths considered. In this way, a statistical comparison could be made. Such analysis goes beyond the scope of this review, but could be recommended to the U.S. EPA as separate work scope, once the ARCADIS modeling study has been finalized.	We have included further justification for chosen source conditions drawing on explanatory language from EPA (2012) as well as some new 2013 references, and provided additional references to how source strengths above and below the range simulated have been simulated in previous work or do not require simulation. .

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Hers and Jourabchi	Specific Charge Question 8				See below.	No specific response required
Hers and Jourabchi		1.1	141		“Impervious” is used to describe surface cover beside buildings (e.g., parking lots, sidewalks, roads). A common dictionary definition is “incapable of being penetrated”. The materials that represent surfaces described will have a range of properties with respect to permeability and diffusivity (e.g., some pavements have relatively high permeability). In addition, typically there are cracks and possibly other openings in surfaces that increase overall permeability and diffusivity. Recommend that impervious be qualified or different term be used.	Language has been added in several places in the report to clarify that the building slab is assumed to be a no flow boundary, as a simplifying assumption. The effects of this simplification are discussed. We have also added additional material describing the relative permeability of various exterior paving materials including concrete and asphalt parking lots.
Hers and Jourabchi		2.3	244		“Impervious” is used to describe surface cover beside buildings (e.g., parking lots, sidewalks, roads). A common dictionary definition is “incapable of being penetrated”. The materials that represent surfaces described will have a range of properties with respect to permeability and diffusivity (e.g., some pavements have relatively high permeability). In addition, typically there are cracks and possibly other openings in surfaces that increase overall permeability and diffusivity. Recommend that impervious be qualified or different term be used.	
Hers and Jourabchi		2.1	168		Use consistent terminology for model. *[in lines 168 and 174]*	Text has been revised to "Abreu/Johnson 3-D numerical vapor intrusion model"
Hers and Jourabchi		2.1	174		Use consistent terminology for model. *[in lines 168 and 174]*	Text has been revised to "Abreu/Johnson 3-D numerical vapor intrusion model"
Hers and Jourabchi		2.2	186		Define “building size threshold”.	Revision made in text.
Hers and Jourabchi		2.2	219		Reference is incorrect. Either Abreu *et al.* (2009a or b). Page 12?	recommended correction made in the text
Hers and Jourabchi		2.4	280-282		It appears that simulations were run over different time steps to evaluate whether quasi steady-state conditions were achieved. A more rigorous explanation of the process used to evaluate transient concentration trends is required. How is a quasi-steady state threshold defined? Was a quasi-steady state threshold reached for all simulations? (this was addressed in the Abreu et al. 2009 GWMR paper).	Addressed in edits to section 2.1 of the text.
Hers and Jourabchi		3.2	321		Model domain of 7 m beyond building had no effect on model simulations. How was this verified? Evaluation of the figures suggests differences in the oxygen concentration contours that may provide insight on the influence of the domain on transport, for example, some figures (1C and possibly 7, some figures are quite small) show near horizontal oxygen contour lines at the domain boundary while other figures (4-6 and 11) show nearly vertical contour lines at the domain boundary.	The orginal scale of the figures didn't allow this feature to be clearly seen. Figure 5 was expanded to show it clearly that the concentration at the boundary will not be markedly different as the the lateral boundary distance increases. This was verified in several simulations by Abreu and Johnson (2005, 2006) using a much larger boundary distance. The effect that the reviewer is mentioning on the oxygen is from the depletion below the building and thus this will not change if the lateral boundary distance is increased.
Hers and Jourabchi		3.6	434		Differences between basement and slab-at-grade scenario are described as “slight”. Define “slight”. For one set of comparisons, the difference in oxygen concentrations was 16.3% versus 12.4% (24%).	We have clarified the text in this paragraph to make clear that although the exact predicted percentage oxygen predicted in the two scenarios differ somewhat the differences would not lead to different site management decisions.
Hers and Jourabchi		4	480		Reference other potential sources of methane such as ethanol in ethanol-blended gasoline and biodegradation of petroleum hydrocarbon (e.g., diesel spills).	Made recommended change.
Menatti	General Charge Question 1				Yes	No specific response required
Menatti	General Charge Question 2				The authors modeled several different sizes of buildings that are representative of the real world based on references cited in Section 2.3.	No specific response required
Menatti	General Charge Question 3				The authors used 1% oxygen as the oxygen concentration at which aerobic biodegradation of petroleum hydrocarbons is limited. This number appears to be conservative and is used by Dr. George DeVaull in his BioVapor Model (see BioVapor screen enclosed). On Line 180, the authors mention “kinetic reaction rate parameters” used in the modeling. I assume these are aerobic biodegradation rate constants. In the paper, I didn’t see what numbers they used for these rates so I could not determine if they were conservative. I have enclosed some pages from a presentation given by Dr. George DeVaull in June 2011 in Reno, Nevada that show different aerobic biodegradation rates for aromatic and aliphatic hydrocarbons. It would be helpful if the authors discussed this a little more in the paper.	A more extensive discussion of the biodegradation rate used and the sensitivity of the results to that rate has now been provided as section 2.3.3 along with reference to two DeVaul papers..
Menatti	General Charge Question 4a				Yes.	No specific response required
Menatti	General Charge Question 4b				Yes.	No specific response required

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Menatti	Specific Charge Question 1				Yes.	No specific response required
Menatti	Specific Charge Question 2				Yes.	No specific response required
Menatti	Specific Charge Question 3				See Additional Comments below.	No specific response required
Menatti	Specific Charge Question 4(a)				Yes.	No specific response required
Menatti	Specific Charge Question 5				See my response to General Question No. 3 above.	No specific response required
Menatti	Specific Charge Question 6				No.	No specific response required
Menatti	Specific Charge Question 7				We have two sites at which a groundwater contaminated with petroleum hydrocarbons has migrated under relatively large buildings. The data from these two sites support the conclusions presented in the report. a. Valley Meat Market, Ogden, Utah • Slab-on-grade commercial building: 100 feet by 50 feet (30.3 meters by 15.2 meters). • Groundwater sampled from monitor wells adjacent to the building contained TPH-GRO concentrations from 9 to 15 mg/L and benzene concentrations from 2.2 to 3.8 mg/L. • Depth to groundwater is about 9 to 10 feet bgs. • Vadose zone soil type is silt with clay and occasional sand. • Soil gas sampled from four sub-slab vapor “wells” contained non-detectable concentrations of TPH and benzene, and oxygen concentrations from 13% to 17%. b. Residential Apartments, Salt Lake City, Utah (Tesoro) • Residential apartment building: 55 feet by 40 feet (16.7 meters by 12 meters) with floor about 4 feet bgs. • Groundwater sampled from monitor wells adjacent to the building contained TPH-GRO concentrations from 3 to 67 mg/L and benzene concentrations from 0.01 to 4.4 mg/L. • Depth to groundwater is about 8 to 9 feet bgs (4 to 5 feet below the floor of the building). • Vadose zone soil type is clayey sand and sandy clay. • Soil gas sampled from two sub-slab vapor “wells” contained TPH concentrations of 330 to 440 ug/m3, benzene concentrations of <3.2 to 4.5 ug/m3, and oxygen concentrations from 20% to 22%. I have enclosed a paper that may refute the conclusions in the report: Patterson and Davis, ES&T, Volume 43, No. 3, 2009.	We have reviewed Patterson and Davis (2009) for consistency with study conlusions. They also observed a real O2 shadow under a building overlying a kerosene plume. In their study source concentrations were up to 47,000,000 ug/m3, depth to source 3m, half-width of building 9m. Although we did not simulate those exact conditions we believe that the result observed is reasonably similar to our simulations with input variables similar to those.
Menatti	Specific Charge Question 8				Yes, see below.	No specific response required
Menatti				General Comment	This is very good and important work!	No specific response required
Menatti		1.1	128		Isn’t PVI a sub-category of VI?	Change from category to sub-category has been made as requested.
Menatti		1.1	131-133		I would mention that, due to low odor thresholds, you would probably smell the petroleum hydrocarbons before you would be chronically exposed to them.	This comment cannot be addressed in a rigorous manner Toxicological screening levels are being frequently updated. Odor threholds are difficult to determine and variable between persons and dependent on other conditions. This comment is also tangential to the main focus of the document.
Menatti		2.2	185		In Lines 185 and 192, and throughout the paper, you use metric units sometimes and English units other times. I recommend that throughout the paper you use English units first and in parentheses state the equivalent metric units.	Units have been revised for consistency with common US practice and the previous document on this model. English units have been stated first for building length, building area and depths below ground surface with metric in parantheses. Consistent with the previous document and common US practice concentrations and pressures are stated in metric units.
Menatti		2.2	192		In Lines 185 and 192, and throughout the paper, you use metric units sometimes and English units other times. I recommend that throughout the paper you use English units first and in parentheses state the equivalent metric units.	Units have been revised for consistency with common US practice and the previous document on this model. English units have been stated first for building length, building area and depths below ground surface with metric in parantheses. Consistent with the previous document and common US practice concentrations and pressures are stated in metric units.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Menatti		2.2 & Tables	196-212 & Tables		The importance of this paper to me as a regulator and State Fund manager is to know under what conditions I will need to collect sub-slab soil gas samples under buildings. I base those decisions on groundwater contaminant concentrations in monitor wells located adjacent to buildings. Therefore, it would be helpful if you tied the contaminant source vapor concentrations to the contaminant concentrations in groundwater more clearly in the text. Also add a column to the Tables (to the left of the "Source Vapor Concentration" column) that shows corresponding "Source Groundwater Concentration." For example, from your text, I understand that TPH in groundwater at a concentration of 0.01 mg/L is roughly equivalent to a "Source Vapor Concentration" of about 10,000 ug/m3. I also understand that a TPH concentration in groundwater of about 10 mg/L is about 1,000,000 ug/m3 TPH in soil gas.	We have revised section 2.3.2 to make clearer the relationship between source vapor concentration and groundwater concentration. We have provided two 2013 references to support those statements.
Menatti		2.2	210		Based on my experience, a TPH concentration in groundwater of about 30 mg/L or greater indicates LNAPL (gasoline). You state that TPH concentrations in groundwater of 0.01-10 mg/L are indicative of LNAPL. It would be great if you had a reference for this. I don't have a reference for my 30 mg/L TPH, it's just a SWAG. By the way, we close sites with 10 mg/L TPH in groundwater. This issue is very important to me as I want to be able to use the data that is normally collected at sites (contaminant concentrations in groundwater) to make decisions about whether to collect soil gas or not. I do not want to collect soil gas if I don't have to.	We have provided new citations and revised wording for the 0.01 to 10 mg/L TPH range in section 2.3.2.
Menatti		Tables			The "Simulated Transport Time with Biodegradation" column in the tables was not clear to me. For example, in Table 1, why would it take 50 years for vapors to diffuse up 5 feet in homogeneous sand? Do these numbers combine diffusion transport rates with aerobic biodegradation rates? Are the different transport times due to changing the biodegradation rates? See my comment on General Question No. 3 above.	Additional discussion has been added to clarify that simulation times were varied to assess the sensitivity of the model results to the transport time (see SEction 2.2.1). This was the method we employed for verifying whether quasi-steady conditions have been established. Additional information about the relationship between groundwater concentration and source vapor concentration has been added to the text.
Menatti		4		General Comment on Primary Limitations References	I have enclosed four papers that contain information that could be referenced in the "Primary Limitations" section of the report. • Cross-foundation air flow and source depletion are discussed in Parker, 2003. • Oxygen replenishment under a residential slab is discussed in Lundegard, Johnson, and Dahlen, 2008. • Oxygen depletion under a large building in Australia is discussed in Patterson and Davis, 2009. • Attributes of commercial and industrial buildings that affect vapor intrusion are discussed in Eklund and Burrows, 2009.	We appreciate the reviewer providing these references. Where appropriate citations have been added to the document.
Suuberg	General Charge Question 1				The model has indeed been run as described in the Background statement attached to the reviewer charge. The model runs are suitable. The basic question that remains unanswered is whether they are sufficient- there is a chance that they are not.	No specific response required
Suuberg	General Charge Question 2				It is very appropriate to use modeling results to explore the complexity of the phenomena that are being explored. The basic questions that are being asked, including that regarding the impact of a building footprint size, are appropriate.	No specific response required
Suuberg	General Charge Question 3				Here is where there is a major difficulty with the results as presented. The model inputs are not sufficiently clearly described, and the nature of the calculations is also not entirely clear (see below). The authors have used reasonable inputs, but they are not the only possible inputs.	Addressed via specific comments
Suuberg	General Charge Question 4				The conclusion that an oxygen shadow can exist is well supported. What remains unclear is generality of the conclusions.	Addressed via specific comments
Suuberg	Specific Charge Question 1				Generally no. The authors have relied upon too much material that is presented in other publications. There is no reason not to include a summary of key equations and inputs in this report, and that would greatly enhance the ability of a reader to fully comprehend the scope and limitations of what has been presented (see below).	Substantial additional information has been added in response to this comment, in section 2 and Appendix A.
Suuberg	Specific Charge Question 2				Again, it does demonstrate that under certain plausible (and maybe even arguably "typical" scenarios) the phenomenon of oxygen shadow, and therefore does raise necessary questions regarding the ability of biodegradation to reduce PVI impacts. But it falls far short of a goal of offering general guidance.	The reviewer asks that we "offer general guidance". Such guidance is being prepared by US EPA, based in part of the results of this modeling study and is thus not within the scope of work of this project.
Suuberg	Specific Charge Question 3				There are many issues that are touched upon, but not fully developed in the present work (see below).	Addressed via specific comments
Suuberg	Specific Charge Questions 4(a) and 4(b)				It is unclear that the present calculations truly represent "worst case" scenarios. The sensitivity analyses are not sufficient.	Additional information about the range of concentrations and biodegradation rates considered has been provided in section 2.3.3. Additional discussion of the potential limitation at low moisture is now discussed in sections 2.2.2.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Suuberg	Specific Charge Question 5				This is one of the most unclear aspects of the report. It is not even clear what was used (though reference to previous publications offers a pretty good idea of this). Still, there are so many aspects of this on which the present report is silent, that there are serious issues regarding the generality of its conclusions. A much more complete exploration of the impacts of rate law and kinetic constants is called for.	We have added additional information regarding the rates selected. We have discussed the potential validity of findings for ethanol based fuels in our discussion of methane effects. Additional material explaining that a first order rate law was used and clarifying the source and sensitivity of the rates employed was added in section 2.3.3 in response to this and other similar comments.
Suuberg	Specific Charge Question 6				Some were alluded to by the authors, and others are brought out below. There is significant potential for these to have impacts on conclusions, in the opinion of this reviewer.	Addressed via specific comments
Suuberg	Specific Charge Question 7				Not that can be specifically used to test the conclusions.	No specific response required
Suuberg	Specific Charge Question 8				Detailed comments are offered below.	No specific response required
Suuberg				General Comment	One significant worry regarding the present report and its stated objectives is that while it refers to oxygen shadow, it does not consider the potentially very important “moisture shadow” as well. Will it be clear what is limiting biodegradation in certain situations, if it is not at least acknowledged that water is also a potentially limiting requirement for microbial activity?	An acknowledgement of this possibility and an analysis of this issue has been added in section 2.3.3.
Suuberg				General Comment	This report bases the oxygen shadow concept on the 1% oxygen concentration limit that has been suggested by Abreu and Johnson (2006) and by Roggemans et al. (API, 2002). This is a key parameter, by definition. The Abreu and Johnson paper represented that the results of modeling biodegradation are not particularly sensitive to this choice, and would give the same results if 0% were assumed. Still, since this represents the very basis of the shadow effect, defense of this value should be strengthened, if possible, by showing results to support this choice.	Additional references have been supplied to support the use of this limit. The authors also note that by definition aerobic degradation requires oxygen, and that the difference between 0% and 1% oxygen (as compared to fully oxygenated soil at 21%) is unlikely to be material given: 1) the expected accuracy of this modeling exercise, 2) the expected inaccuracies in field applications. For example field applications will require measurements of source concentration of TPH, which are unlikely to be accurate to better then +/- 30%, given the known performance characteristics of EPA analytical methods.
Suuberg		2.1	174-176		In lines 174-176, there is frequent reference to solving “transient” equations. What was offered in Abreu and Johnson (2006) was steady state model results. So here, there is solution of a different situation? The situation that is being described becomes a bit unclear when considering the tables of results, where there is reference to “Simulated Transport Time with Biodegradation”. The initial conditions need to then be more clearly specified. What is the condition at time zero? Does a plume suddenly appear beneath the site? Some of the domains may be large enough and groundwater flows slow enough that one would then begin to worry about the dynamics of plume spread vs. the speed of the other phenomena involved. But what is transient in the soil gas pressure field (line 175)? Presumably any advective flow resulting from a building pressurization or depressurization would not be affected by the arrival of a plume of NAPL? This whole aspect of the report just cries out for presentation of the exact equations that were solved, and the relevant boundary and initial conditions for their solution. Also, what about the major unknown--the actual biodegradation rate itself??? What was used and how sensitive were the results to this? What kind of HC is this typical of? Granted that a lot of this has appeared in other papers and reports, the questions above show how without this being presented in the report at hand, there will be all sorts of questions regarding interpretation of the results that are presented.	In response to this comment we have described the process for determining when quasi-steady state conditions had been established. We have described the initial conditions in section 2 and Appendix B. The equations solved have been provided here as a new appendix A although they were previously included by citation. A discussion of biodegradation rates and types of hydrocarbons has been included in sections 2.3.3 and 2.3.4.
Suuberg		2.2	192		A trivial point, but in line 192, dimensions are offered in English units, whereas most of the rest of the report deals in SI units. (or shows the equivalence of English and SI).	Units have been revised for consistency with common US practice and the previous document on this model. English units have been stated first for building length, building area and depths below ground surface with metric in parantheses. Consistent with the previous document and common US practice concentrations and pressures are stated in metric units
Suuberg		2.2	196-197		Recognizing that this is given in different pieces of related work elsewhere, it would still be useful to show some very fundamental assumptions regarding stoichiometry. For example, the conclusion in lines 196-7 is clearly based upon a certain assumption regarding the reaction processes and their oxygen consumption. These should be explicitly stated. The discussion by Devaull (2007) is a reasonable model for how this could be approached here. Also, Devaull presents results for full mineralization. Is there a chance that some partial degradation of petroleum products might be of interest? Related to the above point, a sensitivity analysis is presented with respect to initial soil oxygen content. This corresponds to the fact that the baseline oxygen demand of different soils varies, as the authors note through citation to different websites. But what this analysis does not show is the impact of a competition for oxygen between processes. What the oxygen profile might be will be determined by the relative rates of consumption by naturally occurring substrates vs. the petroleum HC. This might at least be worth mention. There is also another issue regarding the realism of the initially reduced oxygen level results, as noted below.	As part of a more detailed detailed description of the conceptual understanding of vapor intrusion, the 3-D model, and assumptions in Section 2 we have described assumptions regarding stoichiometry in section 2.3.6.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Suuberg		2.2	219		While citing to previously published papers is certainly fair and encouraged generally, the citation in line 219 leaves the reader of this report wondering why they did not simply include that short table here, rather than forcing a flipping between the present work and the earlier one.	Table 1 and additional discussion in Section 2.3 has been provided to address the comment.
Suuberg		2.3	224		Out of curiosity, since the numbers in line 224 seemed a bit at odds with what this reviewer is used to, I went back to the cited reference to check. The cited table does not really support the numbers in the text. The maximum in the table is 3000 square feet, rather than 5000. Moreover, the cited data are for floor area, not footprint area, so the values in line 224 overstate by a bit the size of the housing stock.	A correction has been made in section 2.3.1 that addresses this comment.
Suuberg		2.3	243-245		The emphasis on building footprint size minimizes the potential importance of the surrounding impervious surfaces, cited in lines 243-245. Giant parking lots can potentially play an important role in many aspects of SVI. This should probably receive greater emphasis than it does.	Substantial additional information has been added 2.3.1 to address this question.
Suuberg		2.3	252		Where the authors talk about expanding the building size in line 252, is this not equivalent to increasing the building plus impervious paving? To the extent that they are equivalent, the discussion could be more explicit on that point.	A note has been added at the end of the discussion of concrete or asphalt parking lots to address this. "Note that if building A is surrounded by a concrete parking lot it would behave differently than a building B, equivalent in size to building A plus its parking lot. This difference is primarily due to the depressurization of the interior space (5 Pa in these simulations), as well as the enclosure of the interior space."
Suuberg		2.4	270	Last bullet point	It is not really clear that the authors should express the bullet point in line 270 in the way that they do. The thickness of the vadose zone is relevant if the source of the HC is atop (or in) the water table. On the other hand, if there is free product somewhere in the vadose zone, then the vadose zone thickness is not per se important. It is the locus of the contaminant source relative to ground surface that is key. So it is again important to show more explicitly what the assumptions were regarding the location of the source (this goes to the plea above to show the equations, boundary conditions and initial conditions).	Reworded to "decreasing depth of vapor source beneath the building." (Section 2.4, last bullet)
Suuberg		3.2	305-309		Do not the two sentences in lines 305 to 309 repeat the same thought? But there is an important issue regarding the presentation of results. In Figure 3, for example, the 10% oxygen panel shows normalized oxygen concentrations. But are these normalized with respect to atmospheric 21% or to 10%? By the looks of it, it is normalized to atmospheric (21%), but then what is the significance of the calculation? Why would the background consumption of oxygen suddenly halt at the start of the calculation shown? This is not physically realistic, if that is indeed what was done. At best, it is unclear.	The normalization procedure is described in section 3.2 and has been edited to avoid repetition.
Suuberg		Figures	606-618	Figures 1A and 1B	Is the point about an axis of symmetry (Figure 1A and B) really worth a separate figure? Kind of doubtful that it is. But what it does do is to raise an interesting point regarding the building “shadows”. The oxygen shadow is shown in Figure 1B, but there is no corresponding and opposite HC shadow in 1A. The authors’ previous results showed gradients of HC concentration around the edges of buildings. So this must be a low source concentration calculation result. If so, it would be worth pointing out (if the figure is retained).	The reviewer is correct that this is a low source concentration simulation result, Figure 3 is the result of the hydrocarbon and Figure 4 is the corresponding oxygen result - there is no oxygen shadow in Figure 3 and therefore, consistently, there is no hydrocarbon shadow (or build up) in figure 3. This was clarified in the text of section 3.2 as the reviewer suggested.

Commenter	Charge Question	Guidance Section	Line Number	Details	Comment	EPA Resolution
Suuberg		Figures	636-640	Figure 4	Figure 4 calls out for more discussion. The HC gradient beneath the building shown at 3 and 6 years seems to suggest that it is a steady state gradient, but then precipitously, between 6 and 9 years, that gradient is replaced by a high HC concentration field, seemingly because of exhaustion of the oxygen that was there to begin with. That part is what is presented in the text. But here is where knowledge of the reaction stoichiometry and kinetics are essential. Do these results make sense in the context of the full universe of possible reactions and rates? In other words, what is offered is a particular calculation for a particular case, but which offers little confidence that it would apply in any particular real scenario. The authors have effectively demonstrated that a shadow effect can arise under some particular cases. But of how much general value is this to practitioners in the field? Again, this comes back to all sorts of issues such as how much black carbon and humic acid does soil contain? How much moisture? What is the prevailing temperature at the site? Some of these factors are alluded to in Section 4 (along with others). While the above remarks were introduced with regard to Figure 4, they really apply to the majority of results presented.	Figure 8 shows that the change was not abrupt at 3 years - note that the steady gradient at 3 yr and 6 yr is due to the oxygen rich atmosphere through the whole domain and the transport equation with first order kinetics. The change in results from between 6 and 9 yrs is consistent with the change in results between 3 and 6 years. Between 3 and 6 years the change in oxygen normalized concentration was of (0.9-0.4) = 0.5. If between 6 and 9 years, the fluxes (oxygen and HC) had not changed and the model would allow the same change in oxygen concentration, the result would had to be a negative concentration (0.4-0.5 = - 0.1) indicating that there was not enough oxygen available to allow degradation to occur when the transport time gets to 9 years, therefore the model threshold oxygen concentration of 0.05 was reached within the time frame between 6yr and 9yr and biodegradation stopped at the zone of oxygen depletion, changing the flux of HC into the domain where the hydrocarbon concentration built up below the building to a steady state condition. - The scales of the domain should also be noted - the depth of the source is just 1.5 meters while the extension of the building is 632 meters, therefore oxygen replenishments occurs up to 10 meters into the subsurface below the edge of the building. Note that soil type is sand and with relatively low moisture, therefore VOCs may migrate a distance of 1.5 meters in just few days - So, since the source is assumed infinite, the build up in VOCs after oxygen is consumed should be relatively quick. The reviewer is correct that there are more kinetic models that could be applied (e.g., 2nd order monod kinetics, zero order kinetics), atlthough that work was not within the scope of the current contract, capabilities for those kinetic models are built it in the Abreu and Johnson 3D model code. Thus the kinetic model is a user defined input to the code. In this work, the first order kinetic model was chosen because most of the available literature reports the biodegradation rates measured in the field as a first-order kinetic fit for vapor transport in the unsaturated zone. Therefore, it is more practical for a modeling exercise to use the same kinetic model as was used in the reported biodegradation rates from field measurements.
						In our view, the general value of this work for the practicioner in the field is not that the model will perfectly simulate all field conditions. Rather the model will give a starting point in order for the practitioner to make a decision wheather it is necessary to perform a sampling program in place to compare site-specific field results with the modeling results presented here. When a review of existing data on site-specific conditions indicates that they are far from the conditions shown here to form an oxygen shadow, such additional field monitoring could be omitted. However if existing site specific data showed that conditions were within or near the range of paramaters simulated here to form an oxygen shadow then additional monitoring could be merited.
Suuberg				General Comment	The bottom line question might be whether this particular set of calculational results can serve as guidance for field practitioners. There are two aspects to answering this question. First, it has already been noted that there would be a distinct lack of confidence just based upon not knowing exactly what went into the calculational results that are presented. This could be easily addressed by adding a couple of tables showing the actual equations, boundary and initial conditions, and parameter values employed. The second, more basic, problem is one related to the universe of problems that this report explores. Would field practitioners/regulators have the ability from this report to draw definite conclusions about the importance of building footprint size? The answer is probably not, for all of the reasons cited. The report convincingly establishes that under certain conditions, oxygen shadows can develop, and that there are dynamic aspects to the phenomenon. But beyond that, it is unclear that the present results offer any insights that can be used in deciding regulatory, mitigation or remedial actions or designs. For this, a lot more work would need to be done in identifying the key controlling variables, and the sensitivity of results to those variables.	Substantial additional background on the calculations performed has now been provided including the requested tables (see Tables 1 and 2, and Appendix A). Regarding the universe of problems, the discussion in section 2.3 has been considerably expanded to discuss the range of source vapor concentraitons covered in this document, and how the values above and below that range have been adequately covered in previous models. language has been similarly expanded to define the effect of biodegradation rates. Recommendations have also been provided for the requested "a lot more work" (see report transmittal memo). We expect that a regulator or practitioner would be able to compare a set of site specific circumstances to the modeled results here. They would then be able to determine if their results fell within a range: a) where it was highly unlikely to observe an oxygen shadow b) where it was highly likely to observe an oxygen shadow OR c) where the results were sensitive enough that the results were highly sensitve to the assumptions made. For these more borderline cases site specific modeling and/or building specific data collection about oxygen concentrations would be adviseable. The conversion of the results of this document to specific regulatory guidance is beyond the scope of our contract.

The purpose of this project was to conduct additional 3-D finite difference vapor transport modeling simulations to systematically assess the oxygen shadow phenomenon in order to evaluate the relationships between building footprint, source strength and depth, and oxygen content in soil vapor beneath a building. These new simulation results are aimed at improving the understanding of the impact of building footprint size on the formation of an underlying oxygen shadow, and inform decision making by OUST as to whether there is a building footprint above which a permanent oxygen shadow may form beneath the center of a slab-on-grade building as one of a suite of site screening criteria. These scenarios extend the simulations presented in Abreu and Johnson (2005, 2006); Abreu et al. (2009a, b); and U.S. EPA (2012).

Starting from a "base case" model run, subsequent runs were conducted to determine the building size threshold. Subsequent simulations were chosen based on the results of these initial simulations and decreasing or increasing the building size. All other parameters were reasonably representative of typical conditions and were held constant during the modeling runs. Soil properties for the base cases were for a homogeneous sandy soil and the simulation was run for various durations to determine if quasi-steady state conditions had been achieved or to verify the length of time before oxygen is depleted. Additional scenarios were run for a sand soil overlain by a one meter silty clay layer."

2.0 RESPONSE TO PEER REVIEW CHARGE QUESTIONS

The peer review charge questions request opinions and perspectives regarding the following.

1. "Whether the model and model runs are suitable and sufficient for the stated simulation objectives".

The stated purpose in the report "...*was to conduct additional three-dimensional (3-D) finite difference vapor transport modeling simulations to systematically assess the oxygen shadow phenomenon in order to evaluate the relationships between building footprint, source strength and depth, and oxygen content in soil vapor beneath a building. These new simulation results are aimed at improving the understanding of the impact of building footprint on the formation of an underlying oxygen shadow, and inform decision making as to whether there is a building footprint above which a long lasting oxygen shadow may form beneath the center of a slab-on-grade building, as one of a suite of site screening criteria*."

As described in sections below, there are several gaps in reporting (or are at least not clear to the reviewer) that preclude a complete understanding of the model simulations results. Notwithstanding this, a preliminary opinion is provided. The model is considered suitable for the scenarios simulated, which assume a gasoline release and source total petroleum hydrocarbon (TPH) concentrations up to 10 mg/L. For ethanol-blended gasoline or other types of petroleum releases where methane generation may be significant, the model is not appropriate because multi-component transport and pressures associated with methane generation and biodegradation are not included in the model. The main potential limitations in the model runs pertain to assumption of a no-transport boundary for the foundation slab, and apparent limited or no sensitivity analysis for certain parameters.

2. "The scientific appropriateness of using results from a numerical model for developing screening criteria based on the dimensions of a building given the wide possibilities for the footprint of a building that might be impacted by PVI, and given the relatively limited empirical literature relating the dimensions of a building to the possibility for vapor intrusion".

In principle, it is considered appropriate to develop screening criteria for building dimensions for the purposes of PVI assessment provided that a scientific process is followed for conceptual site model (CSM) and mathematical model development and model simulations. There is precedence for developing screening criteria for other environmental media (*e.g.*, dilution attenuation factors (DAFs) for groundwater contaminant migration); however, the soil vapour intrusion pathway is considered more complex and requires considerable judgment in the application of models. The steps required for a rigorous approach are:

i. An appropriate CSM.

ii. The mathematical model reasonably approximates the conceptual site model.

iii. The mathematical model has been shown to reasonably match field data.

iv. Reasonably conservative modeling scenarios and input parameters are used.

v. The modeling results are appropriately applied or interpreted with respect to the overall goal (*i.e.*, predicting the potential for unacceptable risks to human health).

Our review of the ARCADIS modeling with respect to the above is as follows:

i. **CSM**: Our understanding is that gas migration through the foundation slab is not included in the model. This is potentially overly conservative and possibly a significant limitation. There are other factors not considered in the CSM such as wind-induced or barometric gas pumping, but it is acknowledged that modeling such processes is highly complex. Other comments on the CSM are provided below.

ii. **Mathematical model**: For the range of TPH concentrations simulated is considered appropriate.

iii. **Match to field data**: This issue is not addressed in this modeling study, although there is reference to previous studies where reasonable matches between field and modeled data were obtained. This is a general limitation that pertains to many modeling studies and particularly vapour intrusion, and warrants further evaluation (although it is recognized that this may be beyond the scope of this study).

iv. **Reasonably conservative modeling scenarios and input**: Based on the available information, it appears that reasonably conservative assumptions were adopted, although the sensitivity of modeling results to biodegradation rate constants and soil gas advection (from building depressurization) should be demonstrated. The modeling results for the basement scenario should also be more fully described.

v. **Application of modeling results**: Implicit in the modeling threshold for development of an oxygen shadow (1%) is that this concentration could potentially result in an increased risk for PVI. This may be generally true, but requires acknowledgement and at least some explanation given that the oxygen shadow is predicted below the centre of a building foundation that is a no-transport boundary. The relationship between source concentrations assumed and possible release scenarios (*i.e.*, dissolved versus LNAPL) is not well explained. Some of the discussion is potentially mis-leading, for example, the range of TPH source soil gas concentrations is justified because “it corresponds to a range from 0.01 mg/l to 10 mg/l in dissolved phase hydrocarbon concentration, which is typical for groundwater in equilibrium with LNAPL”. The lower threshold for this range would be representative of a dissolved, not LNAPL release scenario. The discussion in Abreu *et al.* (2009) on dissolved versus LNAPL may be more helpful in this regard; the authors are also referred to DeVaull (2010). It is recommended that either a more thorough discussion of TPH source concentrations for dissolved and LNAPL scenarios be provided (with references), or discussion on this issue be removed. The lack of inclusion of modeling results for higher TPH source concentrations representative of LNAPL sources, but acknowledgment in report that they should be considered, is awkward and limiting.

3. “Whether the model inputs are reasonably representative of worst-case conditions for oxygen depletion in the vadose zone immediately underlying a building”.

Likely yes, see response to other questions, although this will depend on biodegradation rate constant used.

4. “Whether the reported conclusions are adequately supported by the simulation results”.

The conclusions require clarity with respect to which conditions the findings are based on. For example, the report findings indicate for a source concentration of 10,000,000 ug/m^3 and source depth equal to 15 feet, an oxygen shadow formed for a 30 m by 30 m building. Does this conclusion apply to the layered soil, or uniform soil scenario (there does not appear to be a simulation with layered soil for 30 m by 30 m building for 15 ft. depth – this would be an important case to evaluate)? Does it apply to a basement scenario? Further discussion would be helpful as the possible building dimension where no oxygen shadow would be expected.

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?”

The report is for the most part well written. The normalized concentration plots are an effective means of showing concentration attenuation. The main limitation is that certain assumptions and defaults are not described. These limitations are described below.

It is recommended that figures be prepared that plot the oxygen concentration below the building as a function of source depth, source concentration and soil type scenario. This would make results more transparent and easier to understand. The results of EPA (2012) for higher source concentrations should be included.

Another way of plotting data is the ratio of building width (or half-width) over source depth versus the source concentration and oxygen concentration below the building.

2. “Does the report satisfy the goal for which it was conducted? If not, please indicate any identified gaps.”

The report is incomplete with respect to describing the conceptual site model (CSM) upon which the mathematical modeling is based. The CSM assumptions or characteristics that underly the modeling should be described, including:

- Uniform, non-depleting contamination source that extends below the entire building (the conservatism of this assumption increases as the building size increases);
- Transport through porous media (not applicable to fractured media);
- No significant preferential pathways;

- Slab-at-grade or basement building;
- Depressurized building (assumed, but not described in the report);
- Foundation slab is a no-transport boundary, except for perimeter crack;
- No significant methane generation;
- Oxygen ingress limited to a perimeter crack and sides of building (conservative because oxygen diffuses through intact concrete and interior cracks in the foundation);
- Oxygen transport is limited to diffusion and soil gas advection through building depressurization (soil gas advection assumed, but not described in report); additional mechanisms for oxygen transport, such as advection through wind-loading or barometric pumping is not included.

The limitations section describes some of the above CSM considerations. Reference to this section should be made earlier in the report. While it is important to discuss limitations, a CSM section and linkage to model process assumptions is needed.

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

Applicability of modeling results to ethanol-blended gasoline releases.

4. a) "Are the simulations sufficiently representative of worst-case subsurface and building conditions for oxygen depletion in the vadose zone immediately underlying a building such that the results can appropriately support OUST's development of screening criteria related to the oxygen shadow beneath buildings?"

The numbers of simulations for the basement scenario were limited and further discussion of this scenario is warranted. Otherwise the simulations appear to be representative of near worst-case conditions.

b) "Are the reported sensitivity analyses representative of worst-case subsurface conditions for oxygen depletion in the vadose zone immediately underlying a building?"

Recommend sensitivity analysis for biodegradation rate constants and soil gas advection from depressurization.

5. "Is the default biodegradation rate, including its dependence upon oxygen content in the vadose zone, scientifically appropriate? Is it representative of the range of toxic, vapor-forming substances found in petroleum fuels (currently or historically) and subsurface conditions that may be encountered in the United States? Do the reported sensitivity analyses for biodegradation rate capture reasonably expected worst-case subsurface conditions for vapor concentration and oxygen depletion in the vadose zone immediately underlying a building?"

The rate constants are not provided in the report but in Abreu *et al.* (2009b) rate constants of 0.79 and 2 hr^{-1} are given in Table 1, but it is not clear what was used for this report. Devaull (2011) reports a median aromatic hydrocarbon first-order biodegradation rate of 0.48 hr^{-1}. Hers *et al.* (2012) estimated a benzene first-order rate of 0.05 hr^{-1} from field data for site in Canada with soil temperature between 5-7^{o}C.

The biodegradation model used (*e.g.*, first-order, Monod) is not described. Based on evaluation of Monod kinetic rate constant models, a first-order oxygen limited model is considered a reasonable approximation, for oxygen concentrations greater than 1%. Given that Abreu *et al.* (2009) indicate the results of model simulations and oxygen depletion is sensitive to the biodegradation rate constant, it is recommended that a sensitivity analysis for the biodegradation rate constant be conducted for this study (a median first-order decay rate of 0.5 hr^{-1} is recommended, and range corresponding to one order of magnitude on either side of the mean).

6. “Are there other factors, or other choices of parameter values, that were not simulated that if included could potentially change the reported conclusions?”

There is no documentation of the following input parameters:

- Soil properties, including water-filled and total-porosity, and fraction organic carbon (f_{oc});
- Building depressurization and soil gas advection;
- TPH composition and physical-chemical properties of the TPH, and
- Building foundation properties such as crack size.

Are all these parameters, including silty clay properties and TPH composition and physical-chemical properties, listed on Table 1, page 107 of Abreu *et al.* (2009)? (does not appear to be). For transparency, it would nice to include this table.

If benzene is used as a surrogate for TPH, how do differences in aliphatic versus aromatic properties affect the results? The aliphatic fraction often represents over 95% of the TPH vapors.

How does f_{oc} affect transient simulations and time to quasi-steady state conditions? A sensitivity analysis to evaluate f_{oc} may not be warranted, but underlying certain statements such as “but it took nine years for oxygen to be depleted” are for a specific assumed f_{oc}. Presumably with lower f_{oc}, a shorter time would be predicted, with higher f_{oc}, a longer time would be predicted.

Soil gas advection could potentially be significant for shallow contamination scenarios depending on the soil-air permeability and depressurization assumed. But for larger slab-at-grade buildings, the depressurization may be relatively small, reducing the potential for significant soil gas advection.

7. “Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?”

This is a critically important question. It appears that the modeling is generally and approximately consistent with the USEPA empirical database results (developed by Golder Associates and RTI International, based in original database by Ms. Robin Davis). For a source concentration of 10,000,000 ug/m^3 (which would be representative of a highly weathered LNAPL gasoline source) and a source-building separation equal to 15 feet, an oxygen shadow is predicted for a 30 m by 30 m building, but not for a 10 m by 10 m building, so it is presumed that the threshold building size would be between these two sizes. Most buildings in the U.S. EPA empirical database are relatively small (less than 30 m by 30 m) and for UST sites with LNAPL sources, the exclusion distance (*i.e*., distance for attenuation of hydrocarbon vapors to non-significant concentrations) was estimated to be about 15 feet. Therefore, the modeling results do not appear inconsistent with the available data. However, as indicated in previous modeling by Abreu *et al.* (2009), it is important to also consider higher source concentrations representative of a gasoline LNAPL source (*e.g.*,100,000,000 ug/m^3) where the modeling indicates greater potential for oxygen depletion for smaller buildings. If this modeling is going to be applied to develop building thresholds, how are these results going to be incorporated, or is a source concentration of 10,000,000 ug/m^3 considered an upper threshold for LNAPL?

A proposed novel way to statistically compare the modeling results to empirical data is through binning of the empirical data on either side of the modeling source concentration thresholds, and then plotting the empirical oxygen versus distance data and the modeling results for the three depths considered. In this way, a statistical comparison could be made. Such analysis goes beyond the scope of this review, but could be recommended to the U.S. EPA as separate work scope, once the ARCADIS modeling study has been finalized.

8. 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.

See below.

3.0 ADDITIONAL COMMENTS

Additional comments are:

1. Line 141 and 244: “Impervious” is used to describe surface cover beside buildings (*e.g.*, parking lots, sidewalks, roads). A common dictionary definition is “incapable of being penetrated”. The materials that represent surfaces described will have a range of properties with respect to permeability and diffusivity (e.g., some pavements have relatively high permeability). In addition, typically there are cracks and possibly other openings in surfaces that increase overall permeability and diffusivity. Recommend that impervious be qualified or different term be used.
2. Line 168 and 174: Use consistent terminology for model.
3. Line 186: Define “building size threshold”.
4. Line 219: Reference is incorrect. Either Abreu *et al.* (2009a or b). Page 12?
5. Line 280-282: It appears that simulations were run over different time steps to evaluate whether quasi steady-state conditions were achieved. A more rigorous explanation of the process used to evaluate transient concentration trends is required. How is a quasi-steady state threshold defined? Was a quasi-steady state threshold reached for all simulations? (this was addressed in the Abreu *et al.* 2009 GWMR paper).
6. Line 321: Model domain of 7 m beyond building had no effect on model simulations. How was this verified? Evaluation of the figures suggests differences in the oxygen concentration contours that may

provide insight on the influence of the domain on transport, for example, some figures (1C and possibly 7, some figures are quite small) show near horizontal oxygen contour lines at the domain boundary while other figures (4-6 and 11) show nearly vertical contour lines at the domain boundary.

7. Line 434: Differences between basement and slab-at-grade scenario are described as “slight”. Define “slight”. For one set of comparisons, the difference in oxygen concentrations was 16.3% versus 12.4% (24%).
8. Line 480: Reference other potential sources of methane such as ethanol in ethanol-blended gasoline and biodegradation of petroleum hydrocarbon (*e.g.*, diesel spills).

4.0 CLOSURE

We appreciate the opportunity to conduct this review. Should you have any questions or require further clarification, please contact either of the undersigned at 604-298-6623.

Yours very truly,

GOLDER ASSOCIATES LTD.

Parisa Jourabchi, Ph.D. Research Scientist	Ian Hers, Ph.D., P.Eng. Principal, Global Vapor Intrusion Practice Leader

PJ/IH/jcc

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5.0 REFERENCES

DeVaull, G.E. 2010. Vapor Intrusion from Subsurface to Indoor Air: Biodegradable Petroleum Vapors versus Recalcitrant Chemicals. Presented at Vapor Intrusion 2010: Air & Waste Management Association (A&WMA) Conference, Chicago, IL. September 29-30.

DeVaull, G.E. 2011. Biodegradation Rates for Petroleum Hydrocarbons in Aerobic Soils: A Summary of Measured Data. Presented at International Symposium on Bioremediation and Sustainable Environmental Technologies, Reno, NV. June 27-30.

Hers, I., P. Jourabchi, M. Lahvis, P. Dahlen., E.H. Luo, P. Johnson, and U. Mayer. 2012. In preparation. Cold Climate Study of Soil Vapor Intrusion at a Residential House above a Petroleum Hydrocarbon Plume.

Golder Associates Ltd. – Burnaby

Education

Ph.D., Civil Engineering (Geoenvironmental), University of British Columbia, Vancouver, BC, 2004

M.A.Sc., Civil Engineering (Geotechnical), University of British Columbia, Vancouver, BC, 1988

B.A.Sc., Civil Engineering, University of British Columbia , Vancouver, BC, 1986

Employment History

Golder Associates Ltd. – Burnaby, BC

Principal, Senior Environmental Engineer (1988 to Present)

World-wide practice Leader for Golder Associates' vapour intrusion services across North America. Provides review, technical advice, and program development planning for industrial and regulatory clients across North America, Australia, and Europe. Has directed research programs, developed guidance, and consulted to numerous federal, provincial and state agencies. Responsible for project direction and technical oversight of multi-disciplinary projects primarily related to site assessment, human health risk assessment, remedial investigations, and remediation feasibility studies and design for a wide range of contaminated sites. Responsible for leading Golder vapour intrusion discipline team. Provides specialist technical advice on assessment and modelling of subsurface chemical fate for groundwater and soil vapour, natural attenuation studies, design of remediation systems for site contaminated with organic chemicals including soil vapour extraction, air sparging, enhanced biodegradation technologies, and design and construction of soil gas extraction and control systems for contaminated sites and landfills. Developed environmental sampling and analysis guidance for regulatory agencies and provides advice on statistical methods for analysis of soil and groundwater data.

British Columbia Institute of Technology – Burnaby, BC

Instructor (1994 to 2005)

Instructor and former member of advisory committee for Bachelor of Environmental Engineering Technology program. Taught "Principles of Environmental Assessments and Audits", "Field Investigation Methods", and "Remediation Technologies". Also been responsible for supervision of several student research term projects.

University of British Columbia – Vancouver, BC

Professional Short Course and Civil Engineering Instructor (1997 to 2006)

Developed and taught several modules of professional development short courses at UBC between 2002 and 2006, including Contaminated Sites Investigation and Management; Impact of New Regulations in BC; and Review of the New Regulatory Regime in BC and the Use of Screening Level Risk Assessments. In 2002 and 2003, co-instructor for Civil 408 Geoenvironmental Engineering. Guest lecturer for courses in civil engineering on risk assessment, fate and transport of chemical and remediation technologies (Civil 411, 567 and 572). Ph.D. research on soil vapour transport and intrusion of VOCs into buildings.

M.A.Sc. Program

(1986 to 1988)

Course work included geotechnics, contaminant and resource hydrogeology and environmental engineering

PROJECT EXPERIENCE – GUIDANCE DEVELOPMENT, APPLIED RESEARCH AND TRAINING COURSES

Shell Global "Cold Climate" Vapor Intrusion Research Project Canada

Project director for research of vapor intrusion in cold climate areas. Together with Arizona State University (ASU) (Dr. Paul Johnson, Dr. Paul Dahlen), designed and then implemented field program at house overlying petroleum fuel contamination at site in Saskatchewan, Canada. High resolution monitoring of subsurface oxygen, pressure, temperature, soil moisture was conducted, and weather data was obtained to evaluate seasonal trends. The field program was supplemented by a modeling study using 1-D analytical models and multi-dimensional numerical model (MIN3P) developed by the University of British Columbia.

Electric Power Research Institute (EPRI) Research Project
US

Dr. Hers is project director for multi-year research project of vapour intrusion at MGP sites. The first phase of the project was a comprehensive review of state of the practice for vapour intrusion, identification of issues for vapour intrusion assessment at MGP sites and development of detailed work plan for field investigation and two sites and complementary laboratory testing program. The second stage is underway and consists of detailed monitoring at two sites and implementation of standard and novel techniques for soil vapour intrusion assessment including passive and active soil gas survey, forensic analyses, detailed monitoring of fate and transport, biodegradation and influence of environmental factors (capping, soil moisture, temperature, etc.) on soil vapour intrusion. The third phase will consist of updating of best practices for assessment of vapour intrusion at MGP sites (2007-2009).

Health Canada – National Vapour Intrusion Guidance and Model
Canada

Project director for development of screening level risk assessment guidance for soil vapour intrusion into buildings for Health Canada. A comprehensive screening framework was developed consisting of preliminary qualitative screening to assess potential risks and identification of low, medium and high risk sites, followed by quantitative screening involving use of vapour attenuation factor charts. Novel adjustments were incorporated in the guidance based on groundwater mass flux, bioattenuation and source depletion. The guidance also included supporting information on partitioning, transport and risk equations, and protocol for soil vapour sampling and analysis. As a follow-up to this project, a computer model was created to implement the Health Canada guidance. Follow-up models for site-specific implementation of Johnson and Ettinger model and bioattenuation are in-progress (2004 to 2007).

Health Canada – National Site Characterisation Guidance Manual
Canada

Project director for comprehensive guidance manual on site characterisation of contaminated sites, to be used across Canada in support under the Federal Contaminated Sites Action Fund (FCSAP). This manual provides state-of-the-science guidance on contaminated site assessment process, conceptual site model development, sampling design, data quality and detailed methods for investigation of different media (soil, groundwater, soil vapour and indoor air). The manual describes requirements for different investigation phases and how to ensure that representative, high quality data is obtained to fulfill relevant objectives (initial site characterization, risk assessment, remediation planning) (2006-2008).

Health Canada – Site Assessment Training Course Canada	Project director for development of two-day training course for Health Canada as part of their mandate to provide expert support under the Federal Contaminated Sites Action Fund (FCSAP). This course targeted to risk assessors and covered the fundamentals of conceptual model development, hydrogeology, contaminant transport and site characterisation methods. (2005)
Health Canada - Physical-Chemical Parameter Database Canada	Project director for database of physical-chemical parameters and toxicity reference values (TRVs). Reviewed and compared physical-chemical properties from a number of different sources and for selected chemicals, conducted more in-depth assessment of issues for selected chemicals including variability in reported physical-chemical properties and reliability of different literature sources (2005).
Health Canada – Evaluation of Particulate Matter in Indoor Air Canada	Project reviewer for literature search and initial evaluation of data on particulate matter in indoor air to support development of guidance on human health risks associated with particulate. Helped develop protocol for evaluation of data based on different indoor environments, particulate matter fractions (*e.g.,* PM10, PM2.5), and methods for characterizing particulate matter. Particulate matter data was compiled and statistical analysis conducted to evaluate trends in data. (2004 to 2005).
U.S. EPA Vapor Intrusion Guidance Washington, D.C.	Dr. Hers was one of three principal authors of the Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway, prepared for U.S. EPA as part of the RCRA Environmental Indicator (EI) program (Draft, Fall 2001). This project included evaluation of available model frameworks, screening-level computer models, and empirical data in support of the development of guidance. In addition, modeling was performed to evaluate volatilization of chemicals from groundwater, develop diffusion and advection parameters, for various U.S. SCS soil texture types, for input into the model (2001-2002). In 2002 and 2003, Dr. Hers helped develop the framework and modeling in support of the vapor attenuation factors ("alpha charts") incorporated in the Draft EPA OSWER Vapor Intrusion Guidance. In 2003, Dr. Hers one of two experts (the other was Dr. Paul Johnson) retained to respond to comments on OWSER guidance. At this time, he also provided input and review of USEPA Superfund Johnson and Ettinger model inputs. Between 2004 and 2008, Dr. Hers provided data analysis and expert review for development of supporting technical documents and databases on vapour intrusion. A significant focus of his work has been the use of empirical attenuation factor data compiled from over 40 sites to improve understanding of this pathway and guidance. Recent activities have included review of conceptual site models, numerical model simulations and background data (2001-2010).
U.S. EPA Vapor Intrusion Workshops San Francisco, Dallas, Atlanta	Dr. Hers was an invited speaker at three training workshops on the USEPA OSWER "One Agency" Subsurface Vapor Intrusion Guidance (follow-up to RCRA). His presentation addressed the estimation of input parameters for soil vapour intrusion modeling purposes, and process and inputs used to derive the semi-site specific attenuation factors in the Guidance. His work was foundational both in terms of developing the approach and attenuation values subsequently adopted. (2002-2003)

Alberta Environment
Alberta

Principal researcher and developer of guidance manual for Alberta Environment on assessment of soil vapour intrusion. This manual will include comprehensive guidance on conceptual model development, field data collection, use of predictive models, indoor air assessments and mitigation systems (2006, ongoing).

Science Advisory Board of British Columbia - Screening Level Risk Assessment Guidance Project
Canada

The Science Advisory Board was established by the BC Ministry of Environment to provide scientific advice on guidance and tools for improving risk assessment in British Columbia. To support this process, screening level risk assessment (SLRA) guidance for the soil vapour intrusion and groundwater migration pathways were developed. The SLRA guidance comprised of two main components, qualitative preliminary screening of sites to identify potential for soil vapour intrusion and classify sites, and quantitative secondary screening based on a multi-step process for site screening based on key characteristics implemented through user-friendly decision matrix and attenuation factor charts. This SLRA guidance included a detailed supporting protocol for calculation of vapour attenuation factors, and well as estimated human health risk based on the predicted indoor air concentrations (2005).

Science Advisory Board of British Columbia - Guidance on Site Characterisation for Evaluation of Soil Vapour Intrusion
Canada

Project director and principal researcher for development of guidance on characterizing sites for evaluation of soil vapour intrusion into buildings. This project focused of providing guidance on soil vapour sampling and analysis, which is emerging in important tool for vapour intrusion evaluation. All facets of soil vapour characterization were addressed including the conceptual site model, vapour sampling design and factors influencing vapour concentrations, soil gas and subslab gas probe installation, sampling methods, and field and analytical procedures (Summa canisters, sorbent tubes, passive samplers). To complement the soil vapour guidance, recommendations for characterization of other media (soil, groundwater and indoor air) were also provided as well as ancillary testing to better evaluate conditions for vapour intrusion (*e.g.,* building conditions) (2005 – 2006, update 2010).

Science Advisory Board of British Columbia - Hydrological Assessment Tools Project
Canada

Project director and principal researcher for project involving development of hydrogeological assessment tools for risk assessment of contaminated sites. This project included three separate components (i) a protocol for evaluating the mobility of light non-aqueous phase liquid (NAPL), (ii) a study on methods and approaches for evaluating the fate and transport of chemicals within the unsaturated zone, and (iii) approaches for evaluating influence of vertical aquitards on contaminant mobility. Each of these projects identified the state of the science pertaining to the technical issue (theory, models and practice), followed by practical guidance on how concepts could be used by practitioners to better assess contaminant fate and transport, as part of a site specific risk assessment process (2005 and 2006).

Science Advisory Board of British Columbia - CSST Matrix Standards Review Project
Canada

Project director and principal researcher (human health pathways) for project involving review of protocol used to develop matrix soil standards in British Columbia. The matrix soil standards for British Columbia involve consideration of human health and ecological pathways, and were initially developed in 1996. This project involved a 10-year review of the standards, with the aim of identifying new scientific advancements for existing pathway standards, and identifying new exposure and receptors that should be considered. Highlights of the project included evaluation of the four-compartment groundwater model (leaching, unsaturated zone transport, mixing and saturated zone transport), and in particular, methods for evaluating metals partitioning and transport (leaching tests, geochemical modeling), (ii) review of recent developments for assessment of soil vapour intrusion and recommendation of a modeling approach to development generic and semi site-specific standards, (iii) development of a framework and preliminary protocol for deriving standards for two new land uses (high density urban and wild lands) and (iv) updating of the input assumptions and protocol for estimating dose rate and risks for ingestion, dermal contact and dust pathways (2005).

Ontario Ministry of Environment
Ontario

Project reviewer and advisor for state-of-the-science guidance on soil vapour and indoor air testing developed for Ontario Ministry of Environment. The conceptual site model, process, methods and interpretation of results were discussed in detail. Supporting data on such aspects as site conditions and environmental factors influencing soil vapour, and building conditions and background sources influencing indoor air quality were included. Review of models for prediction of vapour intrusion from soil, groundwater and soil vapour sources. Development of screening level modeling approach incorporating bioattenuation reduction factors for petroleum hydrocarbon compounds. Review of Ontario MoE Tier 1 and 2 process including soil depletion multiplier model and groundwater model (2005-2009).

New Jersey Department of Environmental Protection
New Jersey

Dr. Hers is the principal researcher for a multi-year research project of subsurface vapour intrusion into buildings for the New Jersey Department of Environment Protection. This project has involved detailed testing of media concentrations and building properties to assess vapour intrusion at four sites (two petroleum hydrocarbon and two chlorinated solvent sites). Extensive and innovative testing procedures involved the use of tracers, cross-slab pressure monitoring devices, multi-level probes for profiling, subslab probes and groundwater monitoring using geoprobe and diffusion bag sampling. Through this work, better knowledge was obtained in the following areas: (1) vapor attenuation factors for different sites and contaminants, (2) volatilization from the water table and influence of fresh-water lens and capillary fringe, (3) bioattenuation of petroleum hydrocarbon vapours and kinetics for different compounds, (4) subslab vapor sampling, (5) influence of building conditions on vapour intrusion and monitoring methods. The practical outcomes of this work were data and methods that were used to help support the development of the New Jersey vapor intrusion guidance (2002-2006). Dr. Hers was also an invited reviewer of the New Jersey Vapor Intrusion Guidance.

Canada Mortgage and Housing Corporation Vancouver, BC	Director for research program for CMHC involving evaluation of potential soil gas intrusion into a building constructed above residual coal tar contamination and dust migration into residences at a metals-contaminated site. The coal-tar site monitoring scope included testing of sump water, groundwater, soil gas, sump air and indoor air samples, and monitoring of building depressurization. Golder also developed and then implemented an innovative tracer test using helium to measure soil gas flow rates. The study concluded that the risk assessment findings were valid based on follow-up monitoring (2002-2003).
BC Environment Training Courses British Columbia	Co-director and coordinator of comprehensive two-day and four-day courses were developed for BC Environment staff. The objective of the course was to provide participants with fundamental principles, concepts and methods for the characterization and remediation of contaminated sites. The course included a one-day field component where various field methods (drilling, well installation, groundwater sampling, vapour sampling, air sampling) were demonstrated. (2004).
Michigan Environmental Science Board Lansing, MI	Provided expert testimony to the Michigan Environmental Science Board on the use of the vapour intrusion models to predict indoor air quality. The testimony scope included use of the Johnson and Ettinger model, and appropriate input parameters (2000).
State of Michigan Industry Group Michigan	Expert review of issues pertaining to vapour intrusion pathway including validation and use of vapor intrusion models, review of empirical data on vapour intrusion, evaluation of regulatory frameworks and models used by different regulatory jurisdictions, and recommendations for assessment and regulation of this pathway conducted for a consortium of four large companies in the State of Michigan (2000 and 2001).
UK Environmental Agency – Soil Gas Models United Kingdom	Advisor for research and guidance development project for evaluation of soil gas intrusion models. Reviewed ten different soil gas models (Johnson-Ettinger, Jury, VAPEX3, Unocal, GSI, BC, VOLASOIL, BPRISC, Ferguson model) and conducted sensitivity analysis and provided recommendations on models for use in UK regulatory environment. (1999-2001)

PROJECT EXPERIENCE – RISK ASSESSMENT AND VAPOUR INTRUSION ASSESSMENT

Health Canada and DND – Valcartier Vapour Intrusion Study Québec	Project director for evaluation of soil vapour intrusion at site with large chlorinated solvent plume. Reviewed existing data, conducted predictive modeling and developed work plan. Provided oversight of all field monitoring activities, quality control, and data validation and interpretation (2006-2009).
IBM Vapour Intrusion Assessment San Jose, CA	Expert advisor and reviewer for design of soil vapour monitoring study to evaluate potential vapour intrusion risks from chlorinated solvent plume at former industrial site. Developed protocol for quality control testing and soil gas performance testing, including evaluation of methods for evaluating soil-air permeability (2006).

Vapour Intrusion and Air Quality Assessment Calgary, AB	Expert advisor and reviewer for comprehensive study of indoor air quality in homes above large chlorinated solvent plume in groundwater. Responsible for review of hydrogeological data, evaluation of soil vapour fate and transport and predictive modeling, and design of soil vapour and indoor air monitoring program including all quality assurance/quality control aspects. Developed criteria for indoor air assessment and risk management measures. Coordinated input from other consultants on the technical review team and presented findings to senior management and regulatory agencies. Senior reviewer for evaluation of vapour mitigation measures, design of sub-slab depressurization (SSD) systems installed in a large number of buildings, and diagnostic testing program and data interpretation (2002 - 2005).
Law Firm United States	Retained by legal council to provide expert review of exposure and health risk arising from potential vapor intrusion into planned future building at site contaminated with chlorinated solvent compounds. Conducted hydrogeological evaluation and assessment of chemical transport in groundwater in fractured bedrock setting, and reviewed predictive modeling of soil vapor transport and intrusion in building. Conducted comprehensive review of exposure factors and compared deterministic risk assessment results to probabilistic assessment using Monte Carlo simulation and Crystal Ball. Reviewed soil vapor sampling and analysis methods and results (2002).
Confidential Client Groundwater and Soil Vapor Assessment United States	Project manager and technical reviewer for soil gas risk assessment conducted at industrial research facility. Releases of a wide-range of chlorinated solvent compounds have affected soil and groundwater concentrations below and adjacent to buildings at the site, which included a large generator room and nearby offices. Using available soil and groundwater data, a site-specific risk assessment was conducted, and risk-based screening criteria were developed. The geological setting consists of residuum underlain by groundwater, and is complicated by sub-surface utilities and foundations. Through appropriate use of a screening level model for predicting indoor air concentrations and careful consideration of soil properties, characteristics for different buildings, and receptor characteristics, it was shown that risks to workers in the building would likely be acceptable (2002).
Confidential Client Calgary, AB	Conducted expert review of soil gas assessment conducted at large infilled industrial site with elevated methane levels proposed for re-development. Subsequently implemented field investigation program to evaluate possible sources of methane, which included site fills, underlying bedrock and adjacent landfills. Field program included multi-level soil gas sampling and dissolved gas testing and stable carbon isotope testing to help identify methane sources. Evaluation of conceptual remediation measures to address possible gas control measures. (2003-2004).
Alberta Environmental Protection Calgary, AB	Retained to conduct expert third-party review of site assessment, risk assessment and remedial options for the Lynnview Ridge site in Calgary, Alberta. Several hundred houses were constructed on a former refinery site and thus site characterization (soil vapour sampling), estimation of potential vapour intrusion into houses, indoor air testing and vapour intrusion mitigation were important issues for this site. (2003-2004).

BC Hydro
Hazelton, BC

Technical advisor for evaluation of vapour intrusion issues for houses located above a diesel contaminated groundwater. Designed soil vapour sampling program, which included the collection of split samples using Summa canisters (EPA Method TO-15) and sorbent tubes. Responsible for predictive modeling of potential vapour intrusion into indoor air (2001).

CN Rail
Richmond Hill, ON

Technical reviewer of site characterization report and risk assessment for light oil spill that had migrated below a townhouse complex. At several units, oil had migrated into building drains. Reviewed potential mechanisms for vapour intrusion and results of indoor air monitoring. Provided recommended mitigative strategies for addressing vapour intrusion pathway (2001).

Yukon Pipe Line
Whitehorse, YK

Project manager for development of risk-based remediation standards for 40 hectare former tank farm site contaminated with gasoline and diesel from approximately 32 large above-ground tanks that leaked. Residential development is planned for this site. Following remediation of shallow contaminated soil, risk-based standards were used to identify requirements for deeper contamination with the primary potential exposure pathway of concern being vapour intrusion. Extensive monitoring of soil vapour was conducted at this site, which included testing to evaluate lateral and vertical vapour attenuation from hydrocarbon sources, and seasonal variation in vapour concentrations. Predictive modeling was conducted to evaluate vapour fate and transport, and potential intrusion into buildings. Risk based standards were developed for vapour and soil for both individual chemicals (BTEX and naphthalene) and TPH fractions. The risk based standards approach was to identify safe off-set distances for residential development and identify areas of the site that could be developed without further in situ remediation (2000-2001).

Shell Oy
Kokkola, Finland

Prepared risk-based remediation plan for site contaminated with light fuel oil and diesel. Residual hydrocarbon had migrated below a rail yard, and the dissolved hydrocarbon plume was near to a park and daycare centre. Evaluated site characterization data, conducted groundwater modeling (BIOSCREEN), soil vapor transport and intrusion modeling, and evaluated natural attenuation mechanisms. Developed risk based cleanup levels for the source zone, and a protocol for evaluating natural attenuation mechanisms at this site (2000).

ADI Footscray
Victoria, Australia

Evaluated soil vapour fate and transport, and conducted predictive modeling for site contaminated with chlorinated solvents (TCE, DCE, VC), for which residential land use was planned. Site geology consists of thin veneer of fill and unconsolidated soil deposits above basalt deposits. Soil vapor data suggested that barometric pumping was resulting in relatively high advective flux of soil gas and hence vapor transport rates. Assisted with the conceptual design of engineering controls (capping, ventilation) to address potential vapor intrusion risks (1997).

BC Environment, AEP, API, CPPI
British Columbia

Project manager for research project involving experimental design, implementation, and modelling conducted to assess predictive model of soil gas VOC transport and intrusion into buildings, required to validate risk based methods for the soil gas to indoor and outdoor air pathways. Developed methods for soil gas analysis, construction, and testing of flux chambers and testing of experimental building. (1996-1997).

IBI Group Vancouver, BC	Project manager for remediation planning, human health and ecological risk assessment for two industrial sites. Former land uses included railway yard and foundry. The risk assessment involved a Problem Formulation followed by quantitative risk estimation for the soil ingestion, dermal adsorption, and inhalation (dust and volatiles) pathways. The remedial plan included a Special Waste Reduction Plan in which remedial technologies were evaluated in terms of feasibility and cost (1996).
Human Health Screening Risk Assessment Burnaby, BC	Advisor for project involving a screening-level human health risk assessment at a commercial site where chlorinated solvents were encountered in soil and groundwater. A soil gas infiltration model was used to estimate outdoor and indoor exposure to vinyl chloride in air, and lifetime cancer risks were estimated for a commercial receptor. Responsible for design of indoor air sampling program (1995).
Chinese Merchants Association - Murrin Site Vancouver, BC	Task leader for a quantitative human health risk assessment for inhalation exposure at a coal tar contaminated site. The assessment consisted of a deterministic screening risk assessment and a detailed probabilistic risk assessment for benzene, which was the contaminant of primary concern. To mitigate risks, an impermeable liner and soil vapour ventilation system were subsequently designed and installed. (1994)
Chatterton Petrochemical Delta, BC	Task leader for soil gas and hydrogeological modelling of BTEX migration and attenuation at a former petrochemical site. Subsequently, risk-based remediation criteria (RBRC) were developed. The RBRCs were based on protection of human health and environment (aquatic) for several potential exposure pathways and included a quantitative risk assessment. (1995)
Mid-Van Developments Ltd. Vancouver, BC	Assisted in conducting a risk assessment for a site contaminated with fuel oil leaking from a UST. Project Manager for the design and installation of a vapour management system (VMS). (1995)
Telesat Canada Vancouver, BC	Project manager for a supplementary investigation and human health and ecological risk assessment for an industrial site in Vancouver, BC. (1995-1996)
Canada Mortgage and Housing Corporation Canada	Technical advisor for project involving an assessment of the practice of site-specific human health risk assessment for contaminated sites. Assisted in preparation and evaluation of (i) questionnaire sent to risk assessment practitioners and (ii) round-robin hypothetical case study. Assessed risk assessment methodology and conducted statistical evaluation of results. (1996)
Development of Risk-Based Remediation Criteria British Columbia	Assisted in the development of framework and protocol for derivation of risk-based remediation criteria for petroleum hydrocarbons protective of human health and the environment. Reviewed existing regulations, analytical methods, petroleum composition and toxicology, and environmental fate and transport models for petroleum hydrocarbons, including models for soil vapour intrusion into buildings and outdoor air. Helped develop framework for establishing new matrix soil quality criteria for BC Environment (1995).

GVRD - Coquitlam Landfill Risk Assessment Coquitlam, BC	Project manager for human health and ecological risk assessment for the Coquitlam Landfill, which included detailed site investigation, fate and transport modeling for leachate from fly ash, bottom ash, biosolids and refuse, quantitative human health risk assessment and development of risk management measures (1995 and 2001)
Manufacturing Site Richmond, BC	Conducted review of VOC data and human health risk assessment for site used for manufacturing of airplane components. Review of vapour management system (VMS) used to mitigate VOC migration. (1995-1996)
Manufacturing Site Burnaby, BC	Project advisor for risk assessment of former manufacturing site contaminated with chlorinated solvents. Designed and implemented field program, and conducted exposure modelling for soil gas modelling. Assessed natural attenuation mechanism for chlorinated solvents in groundwater, and provided recommended risk management measures. (1997)
GVRD - Biosolids Assessment Coquitlam, BC	Project manager for assessment of leaching potential of a biosolid and soil landfill cover, and potential effects on adjacent creek. (1997)
City of North Vancouver North Vancouver, BC	Project manager for focussed risk assessment of potential effects of hydrocarbon-contaminated soil on aquatic life in creek. Involved hydrological modelling, steamflow assessment, and assessment of potential ecological risk through narcosis approach. (1997)

PROJECT EXPERIENCE – SOIL GAS/LANDFILL GAS ASSESSMENT AND MITIGATION

Major Pipeline Company Alberta	Project advisor for assessment of possible sources of soil gas emissions observed along pipeline in bog area. The assessment consisted of collection and analysis of gas samples obtained from the pipeline, shallow probes, and surface emission flux chambers, and analysis for fixed gases and stable carbon isotopes through University of Alberta. Evaluated possible biogenic versus thermogenic sources of gas through fixed gas ratios and stable carbon isotope ratios. Concluded that the likely source of gas observed was shallow bog deposits (biogenic source) and not from the pipeline (2010).
Arbour Lake School District Calgary, Alberta	Project director for project involved assessment and conceptual design of mitigation measures for fill site with methane impacts. The site had historically been used for disposal of fills containing manure and organic material. The assessment consisted of a detailed soil gas survey, measurement of gas pressures and gas flow rates. Gas Screening Values were estimated (based on UK guidance) using methane concentrations and soil gas flow data to determine semi-quantitative estimate of risk. The site area was divided into different areas based on risk classification and conceptual evaluation of passive/active mitigation was completed (2009-2010).

Major Oil Company
Alberta

Project director for assessment of potential risks associated with abandonned wells and potential soil gas issues at two sites. The work included review of existing data on forensics and potential sources of gases present, conducting shallow soil gas surveys, development of conceptual site model, assessment of well mitigation strategies and gas generation rates, mathematical modeling of subsurface gas migration below and above water table using multiphase reactive transport numerical model (COMPFLOW), coupling of predicted fluxes with air dispersion model (2009-2010).

Gateway Program (Ministry of Transportation) Gas Controls and Fire Protection Management Plan
Delta, BC

Technical director for major project involving construction of highway and large weigh scales through five demolition, land clearing and construction (DLC) landfills and peat bog deposits as part of the South Fraser Perimeter Road in Delta, BC. Responsible for the design of the landfill gas investigation program, assessment and prediction of gas generation and design of passive and active gas controls. Given that the landfills are constructed of woodwaste and major excavations are planned, an important component was preparation of a plan for fire prevention, preparation, monitoring and mitigation (2009).

Whistler Athlete's Village Gas Mitigation System
Whistler, BC

Project director for design of gas mitigation system for portion of athlete's village located next to a former municipal solid waste landfill. The buildings that were mitigated were a lodge and townhouses. A passive venting system and barrier was designed with a monitoring system that included alarms in the basement and crawlspaces of buildings. Due to the numerous utility penetrations and non-uniform foundation, a flexible geomembrane (30 mil PVC) was chosen as the barrier layer. Golder was responsible for construction quality control testing and post-construction performance monitoring (2008-2009).

Orica-Goodman Development Site, Botany Bay
Sydney, Australia

Project advisor and reviewer for soil gas review and conceptual design of mitigation for major commercial development (about 18 buildings and warehouses) at a site with extensive filling in a low-lying peaty area, which was also highly contaminated with chlorinated solvent chemicals. Vapour intrusion modeling of buildings with various types of mitigation systems was initially conducted. Next, a number of different mitigation strategies were evaluated as to feasibility and effectiveness including passive venting system, wind-turbine assisted venting systems and active venting systems. Several different geomembranes were evaluated as to their constructibility and vapour transmission properties. Through the engineering options analysis, a venting design involving use of low energy requirement fans was chosen since it provided for more reliable performance than a wind-turbine system or passive system, and also pipe spacing to be increased (2008-2009).

Large Distribution Warehouse and Office Complex
Surrey, BC

Project director for site assessment, design, inspection and post-construction monitoring at site with extensive woodwaste and peat deposits and biogas (methane) production. Designed liner system consisting of liquid-boot spray-applied membrane below office building and 15 mil polyolefin (taped) liner below warehouse, which was appropriate for warehouse area given high ventilation and dilution in this large warehouse structure. Vents were connected to 12 wind turbines. Post-construction monitoring indicated that the system was working with relatively low methane concentrations below the building (2008-2009).

Pacific Place Condominium (former Expo 86 Site) Vancouver, BC	Project director for health and safety monitoring and gas mitigation at site along False Creek in Vancouver, BC. During site development excavations, strong hydrogen sulphide odours were noted, which emanated from marine deposits under reducing conditions where hydrogen sulphide was being generated. Golder was retained to conduct monitoring program and develop health and safety protocols, and then design mitigation measures for the condo. The measures were a passive (but provisionally active) venting system below a sealed foundation slab. In areas where there were penetrations of the slab (sumps, utilities), special sealing provisions were specified including geomembranes in local areas (2008).
Cedar Grove Development Site Victoria, BC	Project director for review of existing site assessments, gap analysis, soil gas monitoring program, and design of passive mitigation system with geomembrane barrier for fill site underlain by peat deposits developed for commercial development (2008).
Petroleum Contaminated Site Melbourne, Australia	Reviewer of active venting system and barrier system for building to be constructed at site with extensive petroleum contamination. Helped create computer program for soil venting design (2006).
GVRD - Coquitlam Landfill Gas GVRD - Coquitlam Landfill Gas	Project manager/director for multi-year project involving landfill gas monitoring program, shallow soil gas survey and assessment of methane landfill gas emissions for input into human health risk assessment, landfill gas generation study, assessment of existing landfill gas extraction system, design and construction oversight for upgraded active landfill gas extraction system (20 new wells and header), design of passive methane collection system below road and perimeter landfill gas monitoring network (1995 - 2006)
Andy Livingstone Park – Methane Venting and Control System Andy Livingstone Park – Methane Venting and Control System	Advisor and reviewer of active methane venting system constructed below existing building constructed above extensive woodwaste and creosote contaminated soils. Design of piping, blower, monitoring and instrumentation system (2004 to 2005).
Large Fill Site – Methane Evaluation Calgary, AB	Project manager for evaluation of elevated methane levels at large site with extensive organic fill deposits where residential development is proposed. Reviewed site characterization, biological methane potential tests, gas production and pressure data. Implemented additional program of testing and analysis (dissolved gases, isotopes) to identify potential biogenic and thermogenic methane sources (fill, underlying bedrock, adjacent landfill). As part of preliminary feasibility study, identified possible remedial strategies based on proposed development (2003).
Discovery Park - Methane Venting and Control System Vancouver, BC	Reviewer of design of methane control system for site constructed above organic silts and peats. Design is for passive venting that can be converted to active system and partial geosynthetic barrier. Reviewed design of piping system below and through building and soil gas monitoring system (2001).

CMA Murrin Site Vancouver, BC	Project manager/director for soil vapour assessment, human health risk assessment, design and construction management of soil gas venting system, and on-going monitoring at site with high levels of coal-tar contamination developed for commercial use (1993-2006).
Pemcor Developments - Methane Venting and Control System Vancouver, BC	Project engineer for design for subsurface soil gas venting and control system installed below building construction at former industrial landfill in Vancouver, BC. (1995)
City of Burnaby - Methane Venting and Control System Burnaby, BC	Project engineer for subsurface soil gas venting and control system installed below building constructed adjacent to a former Stride Avenue landfill in Burnaby, BC. (1995)
Mid-Van Developments - Methane Venting and Control System Vancouver, BC	Project engineer for subsurface soil gas venting and control system installed below building constructed on peat soil deposits. (1995)
Truck Manufacturing Site Burnaby, BC	Soil gas survey used to assess petroleum hydrocarbon and solvent contamination at a former truck manufacturing site. (1995)
Gas Station Site Kelowna, BC	Project reviewer for soil gas survey conducted at service station site in Kelowna, BC. (1994)
BC Environment – Pacific Place Site Vancouver, BC	Task leader for design and implementation of soil gas surveys for delineation of the extent of contamination and input into soil gas modeling and human health risk assessment (1993).
Solvent Sites Vancouver, BC	Soil gas survey at two TCE and PCE contaminated sites in Vancouver, BC. (1992-1993)

PROJECT EXPERIENCE – ENVIRONMENTAL RESTORATION

Chinese Merchants Association - Coal-Tar Site Vancouver, BC	Project engineer/manager for site remediation at a former coal gasification plant (“Murrin site”). Project components consisted of conceptual remedial planning, final remedial design, geotechnical design, costing, contract preparation, tendering, and site remediation implementation. Designed and conducted pilot tests, and prepared full-scale design for an active sub-slab soil vapour control system, geomembrane cap, and groundwater and product recovery systems. Assisted with groundwater extraction modeling. Conducted bench-scale and pilot-scale investigation to evaluate methods to stabilize hydrocarbon contaminated soils. Currently managing operation, maintenance and monitoring of system. Responsible for managing all Golder Associates staff, and for liaison with owner, architect, construction manager, and regulatory agencies. (1993-2001)

Major Wood-Preserving Facility (Creosote and Chlorophenol) British Columbia	Prepared remediation plan for large major wood products manufacturing site contaminated with creosote and chlorophenols, which is located along the Fraser River. Coal-tar DNAPL has migrated to significant depths (over 20 m) in some areas, and there is an extensive dissolved hydrocarbon plume. Responsible for evaluation and integration of hydrogeological and contamination assessment, product recovery system, groundwater pump-and-treat system, human and ecological risk assessment, site monitoring and development of risk-based remediation plan. (1997-2000)
Multi-national Waste Management Company Delta, BC	Project manager for design and implementation of soil vapour extraction and bioventing system for varsol contamination. Responsible for SVE/airflow modelling. (1996)
BC Environment-Pacific Place Site (Large Industrial Site) Vancouver, BC	Assisted in the screening of remedial options, preparation of remedial plans, and preparation of excavation and soils management plans at the former Expo '86 site (Pacific Place). The site covers 200 acres of former railway, saw mill, metal shops, coal gasification plants, and dump sites. (1988-1992)
Juker Holdings Ltd. – PCB Remediation Delta, BC	Task leader for design of remedial investigation program used to delineate the extent of PCB Special Waste in soil. Responsible for program implementation and monitoring quality control. (1996)
Ex situ Bioremediation British Columbia	Project manager for landfarming bioremediation at four petroleum hydrocarbon sites and one coal-tar site. Designed treatment and monitoring programs and evaluated treatability studies. Conducted treatability study for coal-tar contaminated soils evaluating effectiveness of different nutrient amendments including surfactants. Responsible for permitting, regulatory liaison, and on-going soil monitoring. Soil volumes ranged from 200 m3 to 1,000 m3. Project manager for bioremediation treatability study conducted for coal-tar contaminated site in Surrey, BC. (1991-2000)
Vancouver International Airport Authority – Ex situ Bioremediation Guidance Document Richmond, BC	Prepared Bioremediation Guidance document for construction and operation of ex situ bioremediation facility. (1996)
Contaminated Soil Storage and Treatment Facility Projects British Columbia	Provided design and construction monitoring for contaminated soil storage and treatment facilities including Special Waste contaminated soils. Designed liners, caps, leachate collection systems and sumps, and prepared contract documents. Specific projects include five facilities lined with polyvinyl chloride (PVC) ranging in size from 200 m2 to 1,200 m2 and two facilities lined with high density polyethylene (HDPE) ranging in size from 2,300 m2 to 2,800 m2. Preparation of Monitoring and Contingency Plans for Special Waste treatment facilities. (1991-1996)
City of Vancouver "Block 17" Site Vancouver, BC	Prepared specification for handling, testing, and disposal of contaminated soil and groundwater for inclusion in site development tender. (1996)

Product Recovery Projects
Vancouver, BC

Designed hydrocarbon product recovery wells and trenches and evaluated product recovery systems for a LNAPL site (floating waste oil contaminated with PCB) and DNAPL site (coal-tar). (1993-1994)

Contaminated Soil Excavation and Disposal and UST Decommissioning
British Columbia

Completed design, planning, contract specification, contract administration and monitoring of remedial excavations, UST decommissioning, stockpile and excavation sampling programs, contaminated soil disposal, groundwater control, air monitoring at over 25 petroleum hydrocarbon facilities and industrial sites. Six project examples are listed below:

1. Imperial Oil Refinery Site, Port Moody, BC
Prepared contract and managed field monitoring program for remedial excavations at lead laydown and separator sludge disposal area. Monitoring of backfilling and compaction of excavation. (1990)
2. City of North Vancouver, North Vancouver, BC
Project manager for remedial investigation of former service station, preparation of contract and specifications for UST decommissioning, and contaminated soil remediation. (1997)
3. Sawmill Site, Victoria, BC
Reviewed Phase II investigation data and prepared remediation sampling and excavation plan for chlorophenol contaminated site. (1993)
4. UST Site, Burnaby, BC
Project manager for UST removal and excavation program at site with eight USTs containing a diverse range of fuel products and solvents. (1994)
5. Fertilizer Plant, Abbotsford, BC
Review of contract specifications for remedial excavation and landfill disposal of metals contaminated soils and sediments in ditches. (1994)
6. Hazco Environmental Services Ltd., Richmond, BC
Project manager for monitoring program conducted at three UST sites at a former car rental facility at Vancouver International Airport. (1996)

In situ Treatment Technologies
British Columbia

Completed over 20 projects involving evaluation, design, implementation and monitoring of groundwater extraction, product recovery, soil vapour extraction (SVE), bioventing, air sparging and bio-sparging systems for in situ treatment of hydrocarbon-contaminated soil and groundwater. Seven project examples are listed below:

1. Dual-Phase High Vacuum Extraction – UST Site, Burnaby, BC
Task leader for design and implementation of high vacuum dual-phase soil vapour extraction pilot test for relatively deep glacial drift soil deposits contaminated with gasoline. Conducted pilot test that included monitoring of soil gas flow rates and soil vacuum, used to estimated soil-air permeability and radius-of-influence for soil-air flow. Designed full-scale remediation system that included 20 extraction wells and 25 HP high-vacuum dual-phase extraction system, and catalytic oxidation air treatment. Assisted with the preparation of contract specifications, tendering, bid evaluation, system commissioning and monitoring. (1996-2000)
2. Soil Vapour Extraction – Service Station Sites, Grand Forks, BC
Project manager for soil vapour extraction remediation project for hydrocarbon contamination at two adjacent service station sites. Specific responsibilities were assessment of pilot test data, design of piping system, building and soil vapour extraction equipment (*i.e.,* blowers and related equipment), permitting, design of monitoring program, preparation of contract documents, tendering, construction monitoring, and performance monitoring. Also responsible for on-going groundwater monitoring of the hydrocarbon plume and for evaluation of natural attenuation of hydrocarbon. (1993-1999)
3. Diesel Spill Site, Hazelton, BC
Technical advisor for pilot testing (respiration testing) and design of in situ treatment for large diesel spill at hydrogeologically complex site with deep water table. Proposed design includes groundwater and product recovery, air sparging to increase product recovery rates and biosparging and bioventing (2001-2004).
4. Gasoline and Diesel Spill Site, Skagway, AK
Task leader for design of proposed in situ treatment system for extensive gasoline and diesel spill. Site is along harbour and subject to large tidal fluctuations. Remediation design includes SVE, bioventing and sparging, operated on cyclic basis. Responsible for design of well field (38 wells), civil works including piping design, process equipment and controls and contractor oversight (2001-2003)
5. SVE/Air Sparging/Bioventing – Petro-Chemical Plant, Delta, BC
Task leader for concept design, final design, and procurement of an in situ remediation system for an extensive benzene and toluene spill at a former petro-chemical plant. The proposed remediation system consists of soil vapour extraction system for vadose zone contamination, and air and biosparging for contamination below the water table. Responsible for SVE computer modelling (AIRFLOW/SVE), and biosparging assessment and design. (1995-1996)
6. Trans Mountain Pipeline Ltd. - Bioventing, Richmond, BC
Assisted in design and construction monitoring for bioventing system to remediate jet-fuel contamination at tank farm site. Evaluated fertilizer and irrigation requirements to optimize biodegradation. Water discharge permitting and sampling for water generated during construction dewatering. (1993)
7. Railyard Site, Revelstoke, BC
Project director for design of product recovery program, site monitoring and assessment of monitored natural attenuation (2003 - Ongoing).

PROJECT EXPERIENCE – ENVIRONMENTAL ASSESSMENT

BC Environment-Pacific Place Site Vancouver, BC	Participated in the contamination assessment at the former Expo '86 site (Pacific Place) conducted for BC Environment. The Pacific Place site covers 200 acres of former railway, saw mill, metal shops, coal gasification plants, and in-filled dump areas. Specific responsibilities included conducting and managing field programs, database management, and quality control/quality assurance review of environmental data. (1988-1992)
Coal Gasification Sites (Murrin and Pacific Place) Vancouver, BC	Project manager for assessment of soil, groundwater, and soil gas at Murrin site, which is the location of a former coal gasification plant. Included an assessment of LNAPL and DNAPL extent and transport through soils at the site. Assisted in quantitative human health risk assessment conducted for inhalation (soil gas) exposure. Project engineer for the investigation of soil and groundwater contamination at two former coal gasification plants at the Pacific Place site. (1993-1994)
BC Assessment Authority New Westminster, BC	Conducted an independent review of an environmental site assessment report for an industrial site in New Westminster, BC. The purpose of the review was to assess the adequacy of the ESA, evaluate remedial alternatives, and prepare a remediation cost estimate in support of an evaluation of property value for tax assessment purposes. Provided expert witness services as part of Assessment Appeal Board Hearing. (1996 and 1998)
Wood-Preserving Facility British Columbia	Project engineer for remedial investigation at major wood products manufacturing site primarily impacted with creosote and chlorophenols. Assisted in design of innovative field program including cone penetration test, UV Fluorescence testing, mini piezometers, and hydropunch water sampling. Responsible for cost control. (1996)
Dry Cleaner British Columbia	Project director for investigation at dry cleaner where staged program, consisting of soil vapour survey followed by drilling program was used to delineate perchloroethylene release. The results of this assessment indicated that contaminant migration was largely controlled by site utilities.

Petroleum Distribution/Storage Sites British Columbia	Managed or conducted field investigation programs for the evaluation of soil and groundwater contamination at over forty underground storage tank (UST), pipeline, tank farm, or refinery sites in BC (1990-1997). Five project examples are listed below: 1. Refinery Site, Port Moody, BC Project engineer for investigation of soil and groundwater contamination at lead laydown area, separator sludge disposal area, and several tank lots. (1990-1991) 2. Pipeline Site, Burnaby, BC Project manager for investigation of soil and groundwater contamination resulting from pipeline leak adjacent to sensitive creek. On-going monitoring of natural in situ hydrocarbon degradation. (1991-1993) 3. Oil and Scraper Pit Site, Hinton, AB Project manager for investigation of soil contamination at location of pipeline oil and scraper pits near Hinton, Alberta. (1994) 4. UST Site, Powell River, BC Project engineer for phased investigation at four separate UST facilities located at mill. Consisted of soil gas survey followed by investigation of soil and groundwater contamination. (1990-1991) 5. BC Transit Garage, Vancouver, BC Technical advisor for investigation at former BC Transit garage that included waste oil USTs, fuel USTs, and garage. Designed assessment program and wrote report. (1997)
GVRD-Coquitlam Landfill Site Assessment Coquitlam, BC	Task leader for review of existing data, preparation of sampling and analysis plans, and implementation of site characterization program undertaken as part of a human health and ecological risk assessment for the Coquitlam Landfill. Included installation of shallow and deep wells to characterize hydrogeological regime, and a soil gas survey that included use of SUMMA™ evacuated canisters. (1995)
Terra Nova Municipal Landfill Coquitlam, BC	Project engineer for installation of monitoring wells, groundwater and surface water sampling, and hydrogeological assessment of contamination at municipal ("Terra Nova") landfill. (1991)
Industrial Landfill Sites British Columbia	Managed field program, consisting of installation of monitoring wells, sampling of soil, groundwater, surface water and/or soil gas, at industrial landfill sites in Burnaby and Surrey, BC (1991-1992)
Whitepass Whitehorse, YT	Technical advisor for statistically based design of soil sampling program for large fill site.
Worksyard Sites Coquitlam, BC	Managed field program for assessment of soil and groundwater contamination at four municipal worksyard sites located in Coquitlam (current), Richmond (former), and North Vancouver, BC (current and former). Areas of environmental concern that were investigated include USTs, garages, solvent and pesticide storage areas, material storage areas, and landfill. (1993-1997)
Truck Manufacturing Site Burnaby, BC	Project manager for environmental assessment of former truck manufacturing site contaminated with solvents and petroleum hydrocarbons. (1995)

City of Vancouver “Block 17” Site Vancouver, BC	Managed environmental site assessment and conducted remedial planning for former industrial (light manufacturing) and commercial property located near False Creek in Vancouver, BC. (1994)
Former Pipe Coating Plant Surrey, BC	Project manager for comprehensive Phase I and II assessments of former plant where large diameter pipe was coated with coal-tar. Involved review of production process, historical use of coal-tar solvents and other chemicals, generation of wastes, and implementation of a field program to investigate soil, groundwater, and surface water quality. (1997)

PROJECT EXPERIENCE – GEOTECHNICAL ENGINEERING

Imperial Oil Waste Containment Port Moody, BC	Conducted site investigation, performed slope stability analysis for waste containment facility for refinery. (1990)
BC Tel Lightguide Kamloops, BC	Provided field monitoring and reporting for directional drilling program. (1988)
Light Industrial/Commercial Sites British Columbia	Conducted site investigation and assisted in foundation design for several light industrial projects in Lower Mainland of BC. (1988-1992)
Remedial Excavation Projects British Columbia	Completed the excavation and backfill design for remedial excavation projects in BC. (1992-1996)
Greater Vancovuer Regional District-Coquitlam Landfill Coquitlam, BC	Project manager for design of cap for monocells containing fly-ash at Coquitlam, BC. Involved evaluation of performance- based requirements for cap, preliminary evaluation of cost, and slope stability analysis. (1997)
Federated Co-op Vanderhoof, BC	Project engineer for design of drainage works for tank farm and card-lock facility. (1997)

PROFESSIONAL AFFILIATIONS

Registered Professional Engineer, Association of Professional Engineers and Geoscientists of British Columbia

Roster of Professional Experts, BC Ministry of Environment

Director of the Board, Science Advisory Board for Contaminated Sites in BC

Member, Association of Groundwater Scientists and Engineers

National Ground Water Association

PUBLICATIONS

Other

Hers, I., Roushorne, M., Petrovic, S., Lacoste, C. and M. Richardson. 2006. Overview of the State of Science on Soil Vapour Intrusion – Input to Health Canada Guidance. Proceedings of the First Canadian Federal Contaminated Sites National Workshop, Ottawa, March 7-9.

Sanders, P. and Hers, I. 2006. Vapor Intrusion in Homes over Gasoline-Contaminated Ground Water in Stafford, New Jersey. Ground Water Monitoring and Remediation, Winter.

Hers, I., Li, L. and Hannam, S. 2004. Evaluation of soil gas sampling and analysis techniques at a former petrochemical plant site. Environmental Technology, 25: 847-860.

Hers, I., Zapf-Gilje, R., Li, L. and Atwater, J. 2004. Measurement of BTX vapour intrusion into an experimental building. In-progress technical paper. To be submitted to ES&T.

Hers, I., Zapf-Gilje, R., Johnson, P.C. and Li, L. 2003d. Evaluation of the Johnson and Ettinger model for prediction of indoor air quality. Ground Water Monitoring and Remediation, Summer 2003.

Hers, I., Evans, D, Zapf-Gilje, R. and Li, L. 2002. Comparison, Validation and Use of Models for Predicting Indoor Air Quality from Soil and Groundwater Contamination. Journal of Soil and Sediment Contamination, 11 (4): 491-527.

Hers, I., Zapf-Gilje, Li, L. and Atwater, J. 2001. The use of indoor air measurements to evaluate exposure and risk from subsurface VOCs. J. Air & Waste Manage. Assoc. 51: 174-185.

Hers, I., Atwater, J., Li, L. and Zapf-Gilje, R. 2000a. Evaluation of vadose zone biodegradation of BTX vapours. Journal of Contaminant Hydrology, 46, 233-264.

Hers, I., Zapf-Gilje, R., Li, L. and Atwater, J. 2000b. Measurement of in situ gas-phase diffusion coefficient. Environmental Technology. 21, 631-640.

Hers, I., Zapf-Gilje, R., Li, Loretta, and Atwater, J., 1999. Canadian Consortium Research Project-Evaluation of Vadose Zone BTX Biodegradation. Proc. of In situ and On-Site Bioremediation – The Fifth International Symposium, April 19-22, 1999. In. Natural Attenuation of Chlorinated Solvents, Petroleum Hydrocarbons and Other Organic Compounds, Eds. Bruce C. Alleman and Andrea Leeson, 5(1), Batelle Press.

Hers, I. and Zapf-Gilje, R., 1998a. Canadian consortium research project – Field validation of soil gas transport to indoor air pathway. Proceedings of 1998 Petroleum Hydrocarbon and Organic Chemicals in Ground Water, API/NGWA, Houston, Texas, November 11-13, 1998, 251-266.

Hers, I., Zapf-Gilje, R. 1998b. Canadian consortium research project – Evaluation of predictive models for the soil gas transport to indoor air pathway. Report submitted to project Steering and Advisory Committee (not published). October 1998.

Hers, I., Zapf-Gilje, R., Petrovic, R., Macfarlane, M., and McLenehan, R. 1997. Prediction of Risk-Based Screening Levels for Infiltration of Volatile Sub-surface Contaminants into Buildings. Environ. Tox. and Risk Assessment (6th Vol.), ASTM STP 1317, Eds: F. J. Dwyer, T. Doane, and M. L. Hinman.

Rankin, M., Hers, I., Petrovic, S., Kim M., Zapf-Gilje R. 1996, “Human Health and Ecological Risk Assessment for Coquitlam Landfill Redevelopment”, Proceedings SWANA, 12th Annual Pacific Northwest Regional Symposium, April.

Hers, I., Zapf-Gilje, R., Petrovic, S., Macfarlane, M., McLenehan, R. 1996, “Prediction of Human Health Risks resulting from Infiltration of Volatile Subsurface Contaminants into Buildings”, Proceedings 6th ASTM Symposium on Environmental Toxicology and Risk Assessment, April.

Hers, I., Zapf-Gilje, R. and Boyle, B. 1994, 1995, 1996, “Remediation of Contaminated Sites in BC”, Proceedings of Fundamentals of Environmental Law and Management, The Canadian Institute Conference, Vancouver, BC, October.

Hers, I., Hamilton, G. and Patrick, G.C. 1993, “Remedial Technologies for Groundwater”, Proceedings Seminar on Management of Underground Storage Tanks, Technical University of Nova Scotia, September 14, 1993.

Zapf-Gilje, R., Hers, I., Boyle, B. and Ord, R. 1993, “Sampling Strategies and Statistical Methods for Interpretation of Soil Contamination”, Proceedings Conference on Remediation of Contaminated Sites, Insight Information Inc., May.

Hers, I. and Zapf-Gilje, R. 1991, “The Use of Statistics for Interpretation of Soil Contamination at the Former Expo '86 Site”, Preprints, 44th Canadian Geotechnical Conference, Calgary.

Conlin, B.H., Hers, I. and Robertson, D. 1990, “Characterization of Former Railway Lands at the Pacific Place Site”, Proceedings, Vancouver Geotechnical Society 5th Annual Symposium, May.

Zapf-Gilje, R., Schlender, M.H., and Hers, I. 1990, “The Role of Field Methods for Detection and Characterization of Hydrocarbons-Five Illustrated Cases”, Proceedings Western Canadian Hazardous Waste Management and Liability in the 1990s, The Canadian Institute, Calgary, Alberta, September.

Invited Speaker to AEHS 16th Annual West Coast Conference, Vapor Intrusion Workshop, San Diego, March 19, 2006. Presented talk on “Status of USEPA Generic Screening Levels – Update on Empirical Attenuation Factors”.

Invited Speaker to Air and Waste Management Association Speciality Conference on “Soil Vapor Intrusion – The Next Great Environmental Challenge”, Philadelphia, Pennsylvania, January 25 to 27, 2006. Presented talk on “A Review of Empirical Attenuation Factors from Multiple Sites”.

Invited Speaker to AEHS 14th Annual West Coast Conference, Vapor Intrusion Workshop, San Diego, March 15, 2004.

Presentation at 2nd International Conference on Remediation of Contaminated Sediments, Venice, Italy September 30 to October 3, 2003 “Modeling Studying of In Situ Cap for Creosote Contaminated Marine Sediments”.

Invited Speaker to U.S. EPA Workshops on OSWER Subsurface Vapor Intrusion Guidance, San Francisco December 2002, Dallas January 2003 and Atlanta February 2003.

Co-Developer and Presenter, One-day Professional Development Seminars on “Investigation and Management of Contaminated Sites” and “Contaminated Sites Case Studies and Implications of Proposed Changes to Regulations in B.C.”, Sponsored by University of British Columbia, Vancouver, B.C., May 28, 2002 and February 19 and 20, 2003.

Invited Speaker to U.S. EPA National RCRA Meeting, Workshop on Soil Vapor to Indoor Air Issues, Washington, D.C., January 17, 2002.

Presentation on “Soil Vapour Screening Techniques”, invited speaker at training course for B.C. Ministry of Environment, Lands and Parks, March 27, 2001.

Presentation of paper on “Validation of Johnson and Ettinger model for prediction of indoor air quality using field data from petroleum hydrocarbon and chlorinated solvent site” at 2000 Petroleum Hydrocarbon and Organic Chemicals in Ground Water conference, API/NGWA, Anaheim, California, November 16, 2000.

Invited Speaker to U.S. EPA National RCRA Meeting, Workshop on Soil Vapor to Indoor Air Issues, Washington, D.C., August 15, 2000.

Presentation of “Comparison, Validation and Use of Models for Predicting Indoor Air Quality from Soil and Groundwater Contamination” at Hearing of State of Michigan Environmental Science Board, Indoor Air Panel, Lansing, Michigan, May 4, 2000.

Presentation of “Field Characterization Techniques for Contaminated Sites” at Training Course for Health Canada, Calgary, Alberta, November 1999.

Presentation of “Field Validation of Soil Vapour Transport to Indoor Air Pathway” at 15th Annual International Conference on Contaminated Soils and Water, Indoor Air Workshop, University of Massachusetts, Amherst, Mass., October 18, 1999.

Presentation of “Importance of Advection on Intrusion of Soil Gas into Buildings” Workshop on Soil Vapour Transport to Indoor Air Pathway, Sponsored by BP and University of Texas, University of Texas, Austin, Texas, March 1 and 2, 1999.

Presentation of paper on “Canadian consortium research project-Evaluation of Vadose Zone BTX Biodegradation” at On-Site Bioremediation – The Fifth International Symposium, San Diego, California, April 19-22.

Presentation of paper on “Canadian consortium research project – field validation of soil gas transport to indoor air pathway” at 1998 Petroleum Hydrocarbon and Organic Chemicals in Ground Water conference, API/NGWA, Houston, Texas, November 11-13, 1998.

Presentation on “Soil Gas Building Intrusion Field Validation Project”, Petroleum Environmental Research Forum (PERF) (U.S.), Soil Vapor to Indoor Air Workshop, February 6 and 7, Brea, California.

Presentation on “Canadian Consortium Soil Gas Building Intrusion Research Study”, Invited Speaker at Petroleum Environmental Research Forum (PERF) Workshop, Brea, California, February 6 and 7, 1997.

Presentation on “Remediation of the CMA Murrin Former Coal-Gasification Plant-Case Study”, Guest Lecturer, University of British Columbia, Civil Engineering, Civil 411.

Presentation on “Risk-Based Remediation Approach for Effective Management of Petroleum Contaminated Sites in BC”, Symposium on Environmental Site Assessment and Remediation, Calgary, April 30, 1996.

Presentation on “Environmental Site Assessments”, Guest Lecturer, Environmental Technology Program, Kwantlen College, 1994-1997.

Presentation on “Soil Gas Survey Methods”, Invited Speaker at Training Conference for BC Environment Staff, November 1993.

Please scan [illegible]

Peer Reviewer Conflict of Interest Certification

Peer Review: ***3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab***

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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? ☑ 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 Helped review U.S. EPA VI CSM document that considered 3.D modeling but not directly
- 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

Limited comment on need for 3D modeling but no direct analysis

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Signature June 26/2012 Date ☐ Check here if any explanation is attached

Ian Hers.
Printed Name

Golder Associates Ltd. – Burnaby

Education

Geochemistry Ph.D., Utrecht University, The Netherlands, 2007

Geophysics M.Sc., University of British Columbia, Vancouver, BC, 2001

Engineering Physics B.A.Sc., University of British Columbia, Vancouver, BC, 1995

Languages

English – Fluent

Persian – Fluent

Employment History

Golder Associates – Burnaby, BC

Environmental Scientist (2010 to Present)

Environmental scientist conducting soil vapour modelling and risk assessments. Involved in the preparation of human health risk assessments using the Health Canada spreadsheet tool. Scientist with specialized expertise in the use of a three-dimensional numerical model of reactive transport and flow in variably-saturated porous media (MIN3P) for soil vapour simulations for a variety of contaminated sites applications.

Scientist involved in the numerical model configuration assessments including the evaluation of the effect of capping on hydrocarbon fate and transport; evaluation of hydrocarbon vapour intrusion into a building as part of a cold climate study on vapour biodegradation and transport; evaluation of trench design for the interception of methane gas on the perimeters of a shopping centre; effect of ethanol on gasoline biodegradation and methane oxidation and transport in the vadose zone.

The University of British Columbia - Department of Earth & Ocean Sciences – Vancouver, BC

Visiting Scholar (2007 to 2007)

Researcher for the development of a process-based model of CO_2 emissions from forest soils.

Utrecht University - Geochemistry Department – The Netherlands

Research Assistant (2002 to 2007)

Research assistant responsible for the development and application of a reaction-transport model specific to the simulation of pH distribution and its role as an indicator of biogeochemical transformations in aquatic sediments.
This model was applied to extract information on organic carbon deposition and reactivity, as well as calcite dynamics in marine sediments.
Also responsible for the application of a mechanistic model of sediment compaction to a number of porosity data in order to derive mechanical properties of sediments (elastic response and hydraulic conductivity), and explore the role of mineral dissolution in compaction.

The University of British Columbia - Department of Earth & Ocean Sciences – Vancouver, BC

Research Assistant (1999 to 2001)

Researched the use of nuclear magnetic resonance (NMR) for the quantification of residual hydrocarbon contaminants in porous geologic materials. Developed a new theoretical model to relate the relaxation time of pore water protons to the thickness of residual oil coatings.

The University of British Columbia - Department of Earth & Ocean Sciences – Vancouver, BC

Research Assistant (1998 to 1998)

Conducted laboratory measurements of dielectric constants of geologic materials and an evaluation of the instrument.

Automed Corporation – Richmond, BC

Software Developer (1996 to 1998)

Worked as part of a team to manage software performance for real-time control of medical laboratory equipment, and to design a new modular and object oriented software package.

PROJECT EXPERIENCE – SOIL VAPOUR ASSESSMENT AND MODELLING

Roger's Pass Maintenance Compound Glacier National Park, BC	Assisted in the completion of a preliminary qualitative human health risk assessment and conducted soil vapour modelling for Roger's Pass Maintenance Compound located in Glacier National Park. Project involved screening the various metals, PAHs, and other petroleum hydrocarbons detected in soil and groundwater samples against appropriate federal and regional criteria. Risk estimates for human receptors were calculated for various metals and organic contaminants using applicable exposure scenarios.
Legacy Park Lands, Ltd. Richmond, BC	Conducted soil vapour modelling from available soil and groundwater data to assess possible risk to future residents, where the primary contaminants of concern were volatile hydrocarbons. Also participated in risk assessment to support an application for a Certificate of Compliance for the site.
Science Advisory Board for Contaminated Sites (SABCS) BC, Canada	Research scientist responsible for a modelling study to evaluate the effect of soil moisture on soil vapour transport.
Alberta Environment (AENV) Calgary, AB	Participated in human health risk assessment of contaminants related to creosote from historical wood-preserving operations. The primary exposure pathway of concern was soil vapour intrusion into buildings and utility trenches.
British Columbia Ministry of Environment BC, Canada	Participated in the derivation of high density residential soil and vapour quality standards for use under Contaminated Sites Regulation. Tasks included review of documents, literature search, and preparation of summaries.
Science Advisory Board for Contaminated Sites (SABCS) BC, Canada	Research scientist responsible for a modelling study to help improve soil vapour probe design and sampling methodology through an understanding of probe construction and site conditions on soil vapour concentrations. The VapourT numerical computer model was used to evaluate the chemical concentrations in soil vapour that would be predicted during sampling from a soil vapour probe for different probe construction and site condition scenarios. The modelling scenarios were designed to evaluate the effect of varying probe depths, sampling flow rates, proximity of the probe to the contaminant source zone, and probe construction and surface sealing methods (i.e., annular leakage and surface seal).
Shell Cold Climate Research Study Saskatchewan, Canada	Research scientist responsible for the modelling aspects of a study focused on soil vapour intrusion in a cold climate setting and the effects of seasonal temperature and moisture variations. A numerical model, MIN3P was used in a preliminary and on-going study of soil vapour processes below a building with spatially variable contaminant sources of petroleum hydrocarbons at depth. The two-dimensional simulations accounted for variable soil types and positively, neutral, and negatively pressurized crawlspace.

Electric Power Research Institute (EPRI) Wisconsin, USA	Research scientist responsible for a modelling study of soil vapour processes at a former manufactured gas plant site to evaluate the effect of oxygen-limited hydrocarbon degradation and vapour transport for different capping boundary conditions. The three-dimensional numerical model MIN3P was configured and used to simulation the fate and transport of hydrocarbons and methane source in variably saturated porous media.
Stockland Shopping Centre Merrylands Merrylands, Australia	Research scientist responsible for a modelling study to evaluate the effectiveness of selected methane interception system configurations to aid in the design of a landfill gas management system. The modelling focused on passive systems but also included active extraction and passive systems with ventilation for some configurations. The study was conducted using a three-dimensional reactive transport numerical model, MIN3P, which includes gas trasport through advection and diffusion and was configured for variable soil features and trench designs. The model was used to estimate methane concentrations and flux for thirteen different scenarios, based on which a configuration with suitable performance was chosen and recommended by Golder to the client.

PROFESSIONAL AFFILIATIONS

Member of the American Geophysical Union

PUBLICATIONS

Conference Proceedings

Hers, Ian, Jim Lingle, Frank Dombrowski, Ed Murphy, Tod Rees, Parisa Jourabchi and K. Ulrich Mayer. 2010. *EPRI Soil Vapor Intrusion Field Research Program – Evaluation of soil vapor attenuation above residual MPG impacts at a site in Wisconsin*. Air Waste Management Association (AWMA) Vapor Intrusion, September. Chicago, IL.

Refereed Journal Articles

Jourabchi, Parisa, Ivan L'Heureux, Christof Meile and Philippe Van Cappellen. Physical and chemical steady-state compaction. *Geochimica et Cosmochimica Acta*, 74 (2010), 3494–3513.

Jourabchi, Parisa, Christof Meile, Leonard R. Pasion and Philippe Van Cappellen. Quantitative interpretation of pore water O2 and pH. *Geochimica et Cosmochimica Acta*, 72 (2008), 1350–1364.

Canavan, Richard W., Caroline P. Slomp, Parisa Jourabchi, Philippe Van Cappellen, Anniet M. Laverman and Gerard A. van den Berg. Organic matter mineralization in sediment of a coastal. *Geochimica et Cosmochimica Acta*, 70 (2006), 2836–2855.

Jourabchi, Parisa, Philippe Van Cappellen and Pierre Regnier. Quantitative interpretation of pH distributions in aquatic sediments: a reaction-transport modeling approach. *American Journal of Science*, 305 (2005), 919–956.

Aguilera, David R., Parisa Jourabchi, Claudette Spiteri and Pierre Regnier. A knowledge-based reactive transport approach for the. *Geochemistry Geophysics Geosystems*, 6 (2005)

Peer Reviewer Conflict of Interest Certification

Peer Review: ***3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab***

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- Have you made any public statements (written or oral) on the issue? ☑ No ☐ Yes
- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? ☑ No ☐ Yes
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Signature July 26/2012 Date ☐ Check here if any explanation is attached

Parisa Jourabchi
Printed Name

Golder Associates Ltd.
Affiliation/Organization

Peer Review and Response to Charge Questions

July 21, 2012

John Menatti
Manager, Petroleum Storage Tank Trust Fund
Division of Environmental Response and Remediation
Utah Department of Environmental Quality
195 North 1950 West
P.O. Box 144840
Salt Lake City, Utah 84114-4840

Report Reviewed

Revised Draft Final Report: 3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab dated June 5, 2012 prepared by ARCADIS

Responses to General Questions

1. Whether the model and model runs are suitable and sufficient for the stated simulation objectives.

   Yes.

2. The scientific appropriateness of using results from a numerical model for developing screening criteria based on the dimensions of a building given the wide possibilities for the footprint of a building that might be impacted by PVI, and given the relatively limited empirical literature relating the dimensions of a building to the possibility for vapor intrusion.

   The authors modeled several different sizes of buildings that are representative of the real world based on references cited in Section 2.3.

3. Whether the model inputs are reasonably representative of worst-case conditions for oxygen depletion in the vadose zone immediately underlying a building.

   The authors used 1% oxygen as the oxygen concentration at which aerobic biodegradation of petroleum hydrocarbons is limited. This number appears to be conservative and is used by Dr. George DeVaull in his BioVapor Model (see BioVapor screen enclosed).

   On Line 180, the authors mention "kinetic reaction rate parameters" used in the modeling. I assume these are aerobic biodegradation rate constants. In the paper, I didn't see what numbers they used for these rates so I could not determine if they were conservative.

I have enclosed some pages from a presentation given by Dr. George DeVaull in June 2011 in Reno, Nevada that show different aerobic biodegradation rates for aromatic and aliphatic hydrocarbons. It would be helpful if the authors discussed this a little more in the paper.

4. Whether the reported conclusions are adequately supported by the simulation results.

   Yes.

<u>Responses to Specific Questions</u>

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

   Yes.

2. Does the report satisfy the goal for which it was conducted? If not, please indicate any identified gaps.

   Yes.

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

   See Additional Comments below.

4. a) Are the simulations sufficiently representative of worst-case subsurface and building conditions for oxygen depletion in the vadose zone immediately underlying a building such that the results can appropriately support OUST's development of screening criteria related to the oxygen shadow beneath buildings?

   Yes.

   b) Are the reported sensitivity analyses representative of worst-case subsurface conditions for oxygen depletion in the vadose zone immediately underlying a building?

   Yes.

5. Is the default biodegradation rate, including its dependence upon oxygen content in the vadose zone, scientifically appropriate? Is it representative of the range of toxic, vapor-forming substances found in petroleum fuels (currently or historically) and subsurface conditions that may be encountered in the United States? Do the reported sensitivity analyses for biodegradation rate capture reasonably expected worst-case subsurface conditions for vapor concentration and oxygen depletion in the vadose zone immediately underlying a building?

   See my response to General Question No. 3 above.

6. Are there other factors, or other choices of parameter values, that were not simulated that if included could potentially change the reported conclusions?

   No.

7. Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?

   We have two sites at which a groundwater contaminated with petroleum hydrocarbons has migrated under relatively large buildings. The data from these two sites support the conclusions presented in the report.

   a. Valley Meat Market, Ogden, Utah
   - ***Slab-on-grade commercial building: 100 feet by 50 feet (30.3 meters by 15.2 meters).***
   - ***Groundwater sampled from monitor wells adjacent to the building contained TPH-GRO concentrations from 9 to 15 mg/L and benzene concentrations from 2.2 to 3.8 mg/L.***
   - ***Depth to groundwater is about 9 to 10 feet bgs.***
   - ***Vadose zone soil type is silt with clay and occasional sand.***
   - ***Soil gas sampled from four sub-slab vapor "wells" contained non-detectable concentrations of TPH and benzene, and oxygen concentrations from 13% to 17%.***

   b. Residential Apartments, Salt Lake City, Utah (Tesoro)
   - ***Residential apartment building: 55 feet by 40 feet (16.7 meters by 12 meters) <u>with floor about 4 feet bgs.</u>***
   - ***Groundwater sampled from monitor wells adjacent to the building contained TPH-GRO concentrations from 3 to 67 mg/L and benzene concentrations from 0.01 to 4.4 mg/L.***
   - ***Depth to groundwater is about 8 to 9 feet bgs (<u>4 to 5 feet below the floor of the building</u>).***
   - ***Vadose zone soil type is clayey sand and sandy clay.***

- ***Soil gas sampled from two sub-slab vapor "wells" contained TPH concentrations of 330 to 440 ug/m3, benzene concentrations of <3.2 to 4.5 ug/m3, and oxygen concentrations from 20% to 22%.***

I have enclosed a paper that may refute the conclusions in the report: Patterson and Davis, ES&T, Volume 43, No. 3, 2009.

8. 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.

   Yes, see below.

Additional Comments

1. ***This is very good and important work !***

2. ***Line 128: Isn't PVI a sub-category of VI.***

3. ***Lines 131-133: I would mention that, due to low odor thresholds, you would probably smell the petroleum hydrocarbons before you would be chronically exposed to them.***

4. ***In Lines 185 and 192, and throughout the paper, you use metric units sometimes and English units other times. I recommend that throughout the paper you use English units first and in parentheses state the equivalent metric units.***

5. ***Lines 196-212 and Tables: The importance of this paper to me as a regulator and State Fund manager is to know under what conditions I will need to collect sub-slab soil gas samples under buildings. I base those decisions on groundwater contaminant concentrations in monitor wells located adjacent to buildings. Therefore, it would be helpful if you tied the contaminant source vapor concentrations to the contaminant concentrations in groundwater more clearly in the text. Also add a column to the Tables (to the left of the "Source Vapor Concentration" column) that shows corresponding "Source Groundwater Concentration." For example, from your text, I understand that TPH in groundwater at a concentration of 0.01 mg/L is roughly equivalent to a "Source Vapor Concentration" of about 10,000 ug/m3. I also understand that a TPH concentration in groundwater of about 10 mg/L is about 1,000,000 ug/m3 TPH in soil gas.***

   Line 210: Based on my experience, a TPH concentration in groundwater of about 30 mg/L or greater indicates LNAPL (gasoline). You state that TPH concentrations in groundwater of 0.01-10 mg/L are indicative of LNAPL. It would be great if you had a

reference for this. I don't have a reference for my 30 mg/L TPH, it's just a SWAG. By the way, we close sites with 10 mg/L TPH in groundwater.

This issue is very important to me as I want to be able to use the data that is normally collected at sites (contaminant concentrations in groundwater) to make decisions about whether to collect soil gas or not. I do not want to collect soil gas if I don't have to.

6. ***The "Simulated Transport Time with Biodegradation" column in the tables was not clear to me. For example, in Table 1, why would it take 50 years for vapors to diffuse up 5 feet in homogeneous sand? Do these numbers combine diffusion transport rates with aerobic biodegradation rates? Are the different transport times due to changing the biodegradation rates? See my comment on General Question No. 3 above.***

7. ***I have enclosed four papers that contain information that could be referenced in the "Primary Limitations" section of the report.***

    - ***Cross-foundation air flow and source depletion are discussed in Parker, 2003.***

    - ***Oxygen replenishment under a residential slab is discussed in Lundegard, Johnson, and Dahlen, 2008.***

    - ***Oxygen depletion under a large building in Australia is discussed in Patterson and Davis, 2009.***

    - ***Attributes of commercial and industrial buildings that affect vapor intrusion are discussed in Eklund and Burrows, 2009.***

JOHN A. MENATTI

384 East 6210 South
Murray, Utah 84107
Office: (801) 536-4159
Cell: (801) 554-6560
E-Mail: jmenatti@utah.gov

Professional Experience

- Over 24 years of experience in environmental work that includes program management, project management, regulatory interaction, Phase I and II site assessments, remediation projects, contaminant fate & transport/risk assessments, and emergency response.

- Worked for two national environmental consulting firms (Woodward-Clyde Consultants and PRC Environmental Management).

- Worked for two environmental regulatory agencies (San Diego County Site Assessment & Mitigation Division and the Utah Division of Environmental Response & Remediation).

- Worked for a national law firm (Luce, Forward, Hamilton & Scripps).

- Owned and operated my own environmental consulting firm in Utah (JLM Environmental Consulting).

Employment History

Manager	Petroleum Storage Tank Trust Fund Division of Environmental Response and Remediation Department of Environmental Quality 195 North 1950 West Salt Lake City, Utah 84114-4840 2003 - Present
Environmental Scientist	Leaking Underground Storage Tank Remedial Assistance Section Division of Environmental Response and Remediation Department of Environmental Quality Salt Lake City, Utah 1999 - 2003
Principal-Scientist	JLM Environmental Consulting Murray, Utah 1998 - 1999

Senior Scientist	Luce, Forward, Hamilton & Scripps LLP, Attorneys at Law San Diego, California 1995 - 1998
Senior Soil Scientist	PRC Environmental Management, Inc. San Diego, California 1994 - 1995
Supervising Hazardous Materials Specialist & Emergency Responder	San Diego County Department of Environmental Health Site Assessment and Mitigation Division San Diego, California 1988 - 1994
Senior Hazardous Waste Specialist	Woodward-Clyde Consultants San Diego, California 1986 - 1988

Education

Master of Science & Technology (2007)
Environmental Science
University of Utah
Salt Lake City, Utah

Professional Certificate (1994)
Site Assessment and Remediation
University of California San Diego Extension
San Diego, California

Professional Certificate (1990)
Hazardous Materials Management
University of California San Diego Extension
San Diego, California

Bachelor of Science (1980)
Soil Science
California Polytechnic State University
San Luis Obispo, California

Registrations

Utah Professional Geologist No. 5359488-2250

Utah-Certified Consultant No. CC-120 (inactive). Utah Department of Environmental Quality

Utah-Certified Soil and Groundwater Sampler No. GS-1173. Utah Department of Environmental Quality

Certified Professional Soil Scientist No. 6380 (inactive). ARCPACS Federation of Certifying Boards in Agriculture, Biology, and Earth & Environmental Sciences

Publications

McHugh, T., R. Davis, G. DeVaull, H. Hopkins, J. Menatti, and T. Peargin. 2010. Evaluation of Vapor Attenuation at Petroleum Hydrocarbon Sites: Considerations for Site Screening and Investigation. Soil and Sediment Contamination: An International Journal, October 2010, Volume 19, No. 6, pages 725-745.

Menatti, J., and E. Fall. 2003. A Comparison of Surface Emission Flux Chamber Measurements to Modeled Emissions from Subsurface Contamination. Proceedings of the National Ground Water Association/American Petroleum Institute's 2003 Petroleum Hydrocarbons and Organic Chemicals in Groundwater Conference, August 19-22, 2003, Costa Mesa, California.

Menatti, J. 2001. Shallow Groundwater. Utah Tank News – Fall 2001.

Menatti, J. 2000. The Salt Lake Valley Groundwater Protection Coalition. Utah Tank News – Fall 2000.

McDonald, S., and J. Menatti. 1997. Regulatory Limbo: Water Board Resolutions Open to Wide Interpretation. Los Angeles Daily Journal - June 13, 1997.

Menatti, J., D. Marrin, and A. Donan. 1997. Fate and Transport Modeling of Diesel Fuel Contamination in the Vadose Zone via SESOIL. SESOIL in Environmental Fate and Risk Modeling, Amherst Scientific Publishers, Amherst, Massachusetts.

Odermatt, J.R., and J. Menatti. 1996. Methodology for Using Contaminated Soil Leachability Testing to Determine Soil Cleanup Levels at Contaminated Petroleum Underground Storage Tank (UST) Sites. Journal of Soil Contamination, Volume 5, Number 2, April 1996. CRC Press, Inc., Boca Raton, Florida.

Menatti, J., D. Marrin, and A. Donan. 1994. Fate and Transport Modeling of Diesel Fuel Contamination in the Vadose Zone. Hydrocarbon Contaminated Soils and Groundwater, Volume IV, 1994. Association for the Environmental Health of Soils (AEHS), Amherst, Massachusetts.

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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? ☒ No ☐ Yes
- Have you had any previous involvement with the review document(s) under consideration? ☒ No ☐ Yes
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- Have you made any public statements that would indicate to an observer that you have taken a position on the issue under consideration? ☒ No ☐ Yes
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John A Menatti 7-5-12 ☐ Check here if any explanation is attached

Signature Date

JOHN A. MENATTI

Printed Name

UTAH DEPT. OF ENVIRONMENTAL Quality

Affiliation/Organization

Peer Review Charge Questions:

- whether the model and model runs are suitable and sufficient for the stated simulation objectives;

The model has indeed been run as described in the Background statement attached to the reviewer charge. The model runs are suitable. The basic question that remains unanswered is whether they are sufficient- there is a chance that they are not.

- the scientific appropriateness of using results from a numerical model for developing screening criteria based on the dimensions of a building given the wide possibilities for the footprint of a building that might be impacted by PVI, and given the relatively limited empirical literature relating the dimensions of a building to the possibility for vapor intrusion;

It is very appropriate to use modeling results to explore the complexity of the phenomena that are being explored. The basic questions that are being asked, including that regarding the impact of a building footprint size, are appropriate.

- whether the model inputs are reasonably representative of worst-case conditions for oxygen depletion in the vadose zone immediately underlying a building;

Here is where there is a major difficulty with the results as presented. The model inputs are not sufficiently clearly described, and the nature of the calculations is also not entirely clear (see below). The authors have used reasonable inputs, but they are not the only possible inputs.

- whether the reported conclusions are adequately supported by the simulation results.

The conclusion that an oxygen shadow can exist is well supported. What remains unclear is generality of the conclusions.

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?

Generally no. The authors have relied upon too much material that is presented in other publications. There is no reason not to include a summary of key equations and inputs in this report, and that would greatly enhance the ability of a reader to fully comprehend the scope and limitations of what has been presented (see below).

2. Does the report satisfy the goal for which it was conducted? If not, please indicate any identified gaps.

Again, it does demonstrate that under certain plausible (and maybe even arguably “typical” scenarios) the phenomenon of oxygen shadow, and therefore does raise necessary questions regarding the ability of biodegradation to reduce PVI impacts. But it falls far short of a goal of offering general guidance.

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

There are many issues that are touched upon, but not fully developed in the present work (see below).

4. a) Are the simulations sufficiently representative of worst-case subsurface and building conditions for oxygen depletion in the vadose zone immediately underlying a building such that the results can appropriately support OUST's development of screening criteria related to the oxygen shadow beneath buildings? b) Are the reported sensitivity analyses representative of worst-case subsurface conditions for oxygen depletion in the vadose zone immediately underlying a building?

It is unclear that the present calculations truly represent "worst case" scenarios. The sensitivity analyses are not sufficient.

5. Is the default biodegradation rate, including its dependence upon oxygen content in the vadose zone, scientifically appropriate? Is it representative of the range of toxic, vapor-forming substances found in petroleum fuels (currently or historically) and subsurface conditions that may be encountered in the United States? Do the reported sensitivity analyses for biodegradation rate capture reasonably expected worst-case subsurface conditions for vapor concentration and oxygen depletion in the vadose zone immediately underlying a building?

This is one of the most unclear aspects of the report. It is not even clear what was used (though reference to previous publications offers a pretty good idea of this). Still, there are so many aspects of this on which the present report is silent, that there are serious issues regarding the generality of its conclusions. A much more complete exploration of the impacts of rate law and kinetic constants is called for.

6. Are there other factors, or other choices of parameter values, that were not simulated that if included could potentially change the reported conclusions?

Some were alluded to by the authors, and others are brought out below. There is significant potential for these to have impacts on conclusions, in the opinion of this reviewer.

7. Are you aware of documented field studies, not mentioned in the report, that either support or refute the conclusions presented in the report?

Not that can be specifically used to test the conclusions.

8. 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.

Detailed comments are offered below.

Detailed Comments

One significant worry regarding the present report and its stated objectives is that while it refers to oxygen shadow, it does not consider the potentially very important “moisture shadow” as well. Will it be clear what is limiting biodegradation in certain situations, if it is not at least acknowledged that water is also a potentially limiting requirement for microbial activity?

This report bases the oxygen shadow concept on the 1% oxygen concentration limit that has been suggested by Abreu and Johnson (2006) and by Roggemans et al. (API, 2002). This is a key parameter, by definition. The Abreu and Johnson paper represented that the results of modeling biodegradation are not particularly sensitive to this choice, and would give the same results if 0% were assumed. Still, since this represents the very basis of the shadow effect, defense of this value should be strengthened, if possible, by showing results to support this choice.

In lines 174-176, there is frequent reference to solving “transient” equations. What was offered in Abreu and Johnson (2006) was steady state model results. So here, there is solution of a different situation? The situation that is being described becomes a bit unclear when considering the tables of results, where there is reference to “Simulated Transport Time with Biodegradation”. The initial conditions need to then be more clearly specified. What is the condition at time zero? Does a plume suddenly appear beneath the site? Some of the domains may be large enough and groundwater flows slow enough that one would then begin to worry about the dynamics of plume spread vs. the speed of the other phenomena involved. But what is transient in the soil gas pressure field (line 175)? Presumably any advective flow resulting from a building pressurization or depressurization would not be affected by the arrival of a plume of NAPL? This whole aspect of the report just cries out for presentation of the exact equations that were solved, and the relevant boundary and initial conditions for their solution. Also, what about the major unknown- the actual biodegradation rate itself??? What was used and how sensitive were the results to this? What kind of HC is this typical of?
Granted that a lot of this has appeared in other papers and reports, the question above show how without this being presented in the report at hand, there will be all sorts of questions regarding interpretation of the results that are presented.

A trivial point, but in line 192, dimensions are offered in English units, whereas most of the rest of the report deals in SI units. (or shows the equivalence of English and SI).

Recognizing that this is given in different pieces of related work elsewhere, it would still be useful to show some very fundamental assumptions regarding stoichiometry. For example, the conclusion in lines 196-7 is clearly based upon a certain assumption regarding the reaction processes and their oxygen consumption. These should be explicitly stated. The discussion by Devaull (2007) is a reasonable model for how this could be approached here Also, Devaull presents results for full mineralization. Is there a chance that some partial degradation of petroleum products might be of interest?

Related to the above point, a sensitivity analysis is presented with respect to initial soil oxygen content. This corresponds to the fact that the baseline oxygen demand of different soils varies, as the authors note through citation to different websites. But what this analysis does not show is the impact of a competition for oxygen between processes. What the oxygen profile might be will be determined by the relative rates of consumption by naturally occurring substrates vs. the petroleum HC. This might at least be worth mention. There is also another issue regarding the realism of the initially reduced oxygen level results, as noted below.

While citing to previously published papers is certainly fair and encouraged generally, the citation in line 219 leaves the reader of this report wondering wh they did not simply include that short table here, rather than forcing a flipping between the present work and the earlier one.

Out of curiosity, since the numbers in line 224 seemed a bit at odds with what this reviewer is used to, I went back to the cited reference to check. The cited table does not really support the numbers in the text. The maximum in the table is 3000 square feet, rather than 5000. Moreover, the cited data are for floor area, not footprint area, so the values in line 224 overstate by a bit the size of the housing stock.

The emphasis on building footprint size minimizes the potential importance of the surrounding impervious surfaces, cited in lines 243-245. Giant parking lots can potentially play an important role in many aspects of SVI. This should probably receive greater emphasis than it does. Where the authors talk about expanding the building size in line 252, is this not equivalent to increasing the building plus impervious paving? To the extent that they are equivalent, the discussion could be more explicit on that point.

It is not really clear that the authors should express the bullet point in line 270 in the way that they do. The thickness of the vadose zone is relevant if the source of the HC is atop (or in) the water table. On the other hand, if there is free product somewhere in the vadose zone, then the vadose zone thickness is not per se important. It is the locus of the contaminant source relative to ground surface that is key. So it is again important to show more explicitly what the assumptions were regarding the location of the source (this goes to the plea above to show the equations, boundary conditions and initial conditions).

Do not the two sentences in lines 305 to 309 repeat the same thought? But there is an important issue regarding the presentation of results. In Figure 3, for example, the 10% oxygen panel shows normalized oxygen concentrations. But are these normalized with respect to atmospheric 21% or to 10%? By the looks of it, it is normalized to atmospheric (21%), but then what is the significance of the calculation? Why would the background consumption of oxygen suddenly halt at the start of the calculation shown? This is not physically realistic, if that is indeed what was done. At best, it is unclear.

Is the point about an axis of symmetry (Figure 1A and B) really worth a separate figure? Kind of doubtful that it is. But what it does do is to raise an interesting point regarding the building “shadows”. The oxygen shadow is shown in Figure 1B, but there is no corresponding and opposite HC shadow in 1A. The authors’ previous results showed gradients of HC concentration around the edges of buildings. So this must be a low source concentration calculation result. If so, it would be worth pointing out (if the figure is retained).

Figure 4 calls out for more discussion. The HC gradient beneath the building shown at 3 and 6 years seems to suggest that it is a steady state gradient, but then precipitously, between 6 and 9 years, that gradient is replaced by a high HC concentration field, seemingly because of exhaustion of the oxygen that was there to begin with. That part is what is presented in the text. But here is where knowledge of the reaction stoichiometry and kinetics are essential. Do these results make sense in the context of the full universe of possible reactions and rates? In other words, what is offered is a particular calculation for a particular case, but which offers little confidence that it would apply in any particular real scenario. The authors have effectively demonstrated that a shadow effect can arise under some particular cases. But of how much general value is this to practitioners in the field? Again, this comes back to all sorts of issues such as how much black carbon and humic acid does soil contain? How much moisture? What is the prevailing temperature at the site? Some of these factors are alluded to in Section 4 (along with others). While the above remarks were introduced with regard to Figure 4, they really apply to the majority of results presented.

The bottom line question might be whether this particular set of calculational results can serve as guidance for field practitioners. There are two aspects to answering this question. First, it has already been noted that there would be a distinct lack of confidence just based upon not knowing exactly what went into the calculational results that are presented. This could be easily addressed by adding a couple of tables showing the actual equations, boundary and initial conditions, and parameter values employed. The second, more basic, problem is one related to the universe of problems that this report explores. Would field practitioners/regulators have the ability from this report to draw definite conclusions about the importance of building footprint size? The answer is probably not, for all of the reasons cited. The report convincingly establishes that under certain conditions, oxygen shadows can develop, and that there are dynamic aspects to the phenomenon. But beyond that, it is unclear that the present results offer any insights that can be used in deciding regulatory, mitigation or remedial actions or designs. For this, a lot more work would need to be done in identifying the key controlling variables, and the sensitivity of results to those variables.

Curriculum Vitae

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Education

Sc. D., Chemical Engineering, M.I.T., 1978
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Professional Appointments

Associate Dean of Engineering, 2011- present
Associate Director, Brown Superfund Program, 2005- present
Co-Director, Program in Innovation Management and Entrepreneurship (PRIME) 2005-present
Associate Dean of the Faculty 2003-2005
Interim Chair, Department of Psychology, 2004-2005
Professor of Engineering, Brown University, 1990-present
Visiting Professor of Engineering, Tallinn Technical University, Summer 2002
Fulbright Scholar, Tallinn Technical University, Spring, 2001
Visiting Professor, University of Newcastle, Australia, January. 2001
Vice Chancellor's Research Best Practice Fellow, University of Newcastle, Australia, Summer, 1995
Associate Professor of Engineering, Brown University, 1984-1990
Visiting Scientist, CNRS, Mulhouse, France, Spring 1988
Assistant Professor of Engineering, Brown University, 1981-1984
Assistant Professor of Chemical Engineering, Carnegie-Mellon University, 1977-1981

Publications

Chapters in Books

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Selected Service To the Profession

- Chairman, American Chemical Society Division of Fuel Chemistry Storch Award Selection Committee, November 2008- present.
- Trustee, Division of Fuel Chemistry, American Chemical Society, 2002-present.
- Symposium Co-organizer, Fuel Chemistry Division, American Chemical Society Meeting, March, 2009.
- Advisory Board, Priority Research Center on Energy, University of Newcastle, Australia, 2007-present.
- Co-organizer, New England Waste Management Officials Organization, workshops on vapor intrusion, June 2007, September 2008.
- Co-organizer, Continuing Legal Education Course on Health Effects of Environmental Contamination- 100 attorneys at Brown, March 2010.
- Co-organizer, Continuing Legal Education Course on Vapor Intrusion (Superfund Grant)- 200 attorneys at Brown, March 2007.
- Co-organizer, Workshop on Sediment Remediation (Superfund Grant), February 2007
- Symposium Co-organizer, Environmental Chemistry Division, American Chemical Society Meeting, August, 2007.
- Symposium Co-organizer, Fuel Chemistry Division, American Chemical Society Meeting, August, 2007.
- Meeting Co-organizer, Carbon 2004, at Brown University, July 2004.
- Symposium Organizer, Fall 2002 National Meeting of the American Chemical Society.
- Department of Energy Advisory Panel Workshop, October, 2002.
- Symposium Co-organizer, 24th Biennial Conference on Carbon, July, 1999.
- Symposium Co-organizer, 1999 International Ash Utilization Symposium, Oct. 1999.
- Symposium Co-organizer, American Chemical Society National Meeting, March, 1999.
- Symposium Co-organizer, Workshop on Biomass Pyrolysis, Innsbruck, Austria, 2000.

- Symposium Co-organizer, American Chemical Society National Meeting, August, 1998.
- Director-at Large, American Chemical Society Division of Fuel Chemistry (1995-1997).
- Member of Review Panel, Coal Research Proposals, Illinois Clean Coal Institute, 1997.
- Chair, Public Policy Subcommittee, American Chemical Society Division of Fuel Chemistry, 1992.
- Chairman of the American Chemical Society, Division of Fuel Chemistry (1991, Chairman-Elect, 1990).
- Program Subcommittee coal topic area chair, 24th International Symposium on Combustion (1991).
- Program subcommittee member, 19th through 26th Symposia on Combustion (1981-1996).
- Program Chair, Combustion Programming, AIChE, 1988-89.
- Session Chair, Biennial Conference on Carbon, 1987.
- Program Chairman and Executive Board Member, Division of Fuel Chemistry, American Chemical Society (1983-87).
- Session Chair, Gordon Research Conference (1985).

Academic Honors

- Fellow of the American Chemical Society, 2011.
- Invited to join the Editorial Board of the journal Oil Shale 2009-
- Invited to join the Editorial Board of the journal Greenhouse Gas Measurement and Management, 2010-
- Awarded an honorary doctorate by Tallinn University of Technology in Estonia, September 2008
- Invited member of the Advisory Board, Priority Research Center for Energy, University of Newcastle, Australia 2007- present.
- Fulbright Scholar, 2000-2001.
- Named Americas Editor of the journal *Fuel*, as of January, 2000- present.
- Recipient of the 1999 H.H. Storch Award for Research in Fuels Chemistry, American Chemical Society.
- Invited to re-join the editorial board, *Energy and Fuels*, 1997-1999.
- Invited Lecturer in Japan, Monbusho, December 1997
- Selected as one of the first Vice Chancellor's Research Best Practice Fellows, University of Newcastle (Australia), Summer 1995

Selected Teaching Highlights

- Co-founded the Brown University Chemical Engineering Program (with J. Calo)- 1981.
- Started new course (together with J. Calo) on Pollution Prevention- 1996
- Started new course (together with G. Crawford) on Entrepreneurship (EN 193, 194) – 1999
- Participated in launching the new Commerce, Organizations and Entrepreneurship Concentration, 2005-2006 – worked on committee designing the program and curriculum.
- Participated in launching the new PRIME program (Program in Innovation Management and Entrepreneurship) in Engineering, 2006-2007. Designed curriculum and program with G. Crawford.

Peer Reviewer Conflict of Interest Certification

Peer Review: ***3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration below the Slab***

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

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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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Eric Suuberg

June 27, 2012

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