

# CANADIAN CONSORTIUM RESEARCH PROJECT - FIELD VALIDATION OF SOIL GAS TRANSPORT TO INDOOR AIR PATHWAY

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## ABSTRACT

Consideration of potential risk in the remediation of petroleum-contaminated sites is now commonplace. At many sites, an important exposure pathway is soil gas intrusion into buildings and indoor air inhalation. Relatively simple screening-level models are often used to quantify potential exposure and risk. These risk models are thought to incorporate conservative assumptions; however, little field data is currently available to test model validity. To address this limitation, a comprehensive research program was recently implemented under the sponsorship of a consortium of governmental, industry, and consulting groups at a former petrochemical plant site impacted by benzene, toluene and xylene releases, located near Vancouver, B.C. The study objectives were to further a fundamental understanding of vadose zone and building intrusion processes, and to facilitate comparison between model predicted and measured hydrocarbon migration. The objectives were achieved through monitoring of hydrocarbon fate and transport in the vadose zone, and intrusion over an approximate one-year period.

The study methods included extensive delineation of the residual non-aqueous phase liquid (NAPL) hydrocarbon concentrations at source, detailed vertical profiling of soil properties (e.g., moisture content, air permeability) and vadose zone hydrocarbon, oxygen, carbon dioxide and methane concentrations in soil gas. Regular monitoring was used to assess the effect of seasonal changes on soil gas fate and transport. To facilitate measurement of soil gas intrusion, a small building with controlled building envelope features (edge crack and service penetrations) was constructed. Near-continuous monitoring of oxygen levels below the building floor slab and differential pressure between subsoils, building and ambient was implemented. Soil gas hydrocarbon intrusion rates were estimated using a flux chamber, and indirectly through air and soil gas monitoring. Soil gas monitoring and intrusion evaluation was conducted for both static and induced building underpressurization (-30 Pascals) conditions.

The results indicate that processes affecting hydrocarbon fate and transport at this site are relatively complex, but nevertheless, relatively consistent under static (i.e., no building underpressurization) conditions over the monitoring duration. Vadose zone processes under static conditions occur within three vertical zones: a deeper zone where diffusion is the dominant process, a relatively thin zone (about 0.3m) where biodegradation is dominant, and shallow zone where a combination of advective, diffusive and biodegradation processes occur. Biodegradation rates are inferred to be very high with a 3 order-of magnitude decrease in hydrocarbon concentrations observed. Within shallow soils below the floor slab, oxygen and pressure monitoring has demonstrated that barometric pumping is occurring. The vadose zone hydrocarbon profile under induced underpressurization indicated an increased depth-of-influence for advective transport. For the static case, the model-predicted hydrocarbon intrusion based on the Johnson and Ettinger (1991) framework is about two orders-of-magnitude greater than that measured. For the induced underpressurization (advection) case, there is less of a difference between the predicted and measured soil gas intrusion. Additional testing is on going to assess the effect of varying underpressurization and building envelope properties on soil gas behavior and intrusion rates for advection dominated conditions.

## INTRODUCTION

Consideration of potential risk in the remediation of sites impacted by volatile organic compounds (VOCs) is now commonplace. At many sites, the soil gas transport to indoor air pathway is an important potential exposure pathway. Relatively simple screening-level models are often used to quantify potential exposure and risk. These models are thought to incorporate conservative assumptions; however, little field data is currently available to test model accuracy. To address this limitation, a comprehensive research program is currently being conducted under the sponsorship of a consortium of governmental and industry partners at a former petrochemical plant site impacted by benzene, toluene and xylene releases, located near Vancouver, B.C. The project research objectives are to further fundamental understanding of vadose zone fate and transport of VOCs and VOC intrusion into buildings, and contribute to the process of model validation and development through comparison of measured and predicted intrusion at the test site. The project approach consists of evaluating fate and transport of VOCs in both the vadose zone, and through the building envelope (a small building has been constructed). To-date, monitoring data over an approximately one-year period has been collected.

This paper begins with a review of background information, and presents a conceptual model for this pathway based on our current understanding of soil gas transport. Next, the results of vadose zone monitoring, and monitoring of soil gas and VOC flux through the building envelope is presented. The paper concludes with a comparison of measured and model predicted VOC intrusion. Due to the extensive and on-going nature of this project, results presented are limited to an overview; additional details will be presented in other publications.

## BACKGROUND

Predictive models commonly used for the soil gas transport to indoor air pathway are limited to one-dimensional steady-state analytical or semi-analytical models based on the Johnson and Ettinger (1991) framework, or one-dimensional transient analytical models based on the Jury *et al.* (1990) framework. Examples of such "screening-level" models include the *ASTM Tool Kit*, a software program based on ASTM ES-1739 and distributed by Groundwater Services Inc., the *VOLASOIL* model developed by the Dutch Ministry of Environment, the *VAPEX* model developed by Environmental Systems and Technologies, Inc., and a model developed Golder Associates Ltd. (Hers *et al.*, 1997). Significant uncertainty surrounds the accuracy of these models.

Integrated studies of vadose zone fate and transport of VOCs combined with measurement of VOC intrusion into buildings remain limited. Two studies conducted by the University of California at Berkeley in conjunction with the Lawrence Berkeley laboratory (Garbesi *et al.*, 1988; Fisher *et al.*, 1996) have consisted of field-based evaluations of soil gas VOC intrusion into buildings. The Garbesi *et al.* (1988) study included measurement of landfill-related VOC intrusion into a house while the Fischer *et al.* (1996) study involved measurement of gasoline-related VOC intrusion (*i.e.*, BTEX and other gases) into an at-grade building. Monitoring conducted by Fischer *et al.* (1996) indicated that soil gas hydrocarbon concentrations decreased sharply over a small vertical depth interval (0.1 m to 0.7 m below ground surface) within sand fill present at the site. It was postulated that a partial physical barrier to vertical transport (*i.e.*, higher moisture content zone) combined with biodegradation can account for the steep gradient. In contrast, a recent study documented by Laubacher *et al.* (1997) indicated the presence of elevated hydrocarbon concentrations in soil gas and low oxygen levels (*i.e.*, below one percent) directly below a basement slab at a gasoline-contaminated site. Soil gas hydrocarbon concentrations adjacent to the basement (*i.e.*, at the same depth) were about two orders-of-magnitude lower and oxygen levels were about 14 %. Soils at this site consisted of uniform sand with occasional silty or clayey lenses with the water table located about 5.8 m below ground surface.

## CONCEPTUAL MODEL

Research to-date indicates that vadose zone fate and transport of VOCs and intrusion into buildings is a complex phenomena. Processes within both the vadose zone and building envelope compartment affect this pathway, and are highly dependent on site specific conditions such as contaminant type and distribution (*e.g.*, is NAPL present above water table?), depth to contamination, soil properties and building characteristics. Within the vadose zone, diffusion, sorption, and in some cases, biodegradation, are generally thought to have the most significant effect on VOC fate and transport. Key factors affecting these vadose zone processes include moisture content, organic carbon and, in the case of biodegradation, the presence of indigenous microbes capable of degrading the hydrocarbon, and conditions favourable for biostimulation (for example oxygen levels). In some cases, soil gas advection through shallow soil near the building envelope, as influenced by building underpressurization and/or barometric pumping, could have a significant effect on VOC intrusion. Key factors affecting soil gas advection and building intrusion include the permeability of the subslab soil and building envelope, and potential preferential pathways (*e.g.*, utility corridors). Depending on site conditions, soil gas advection will be either primarily controlled by resistance to flow through soil, or resistance due to the building envelope.

The relative importance of various processes will depend on site specific conditions. In the case of deeper contamination, diffusion and natural attenuation processes within the vadose zone compartment are expected, in most cases, to control the overall VOC intrusion rate into a building. In the case of shallow contamination, advection and hence properties of the subslab soil (*e.g.*, permeability) and building envelope (*e.g.*, cracks) may be of greater importance.

## SITE DESCRIPTION AND METHOD OVERVIEW

The field site is the former Chatterton petrochemical plant located near Delta, B.C. The plant manufactured benzoic acid, phenol and meta-toluic acid. Raw products included toluene and m&p-xylene while by-products included benzene. Near surface soils in the plant area consist of approximately 3.5 m of dredged river sand underlain by native silt. The depth to the water table generally ranges from 1.5 m to 2.5 m depth below ground surface (bgs). Release of benzene, toluene and m&p-xylene (BTX) have resulted in a laterally extensive zone of residual non-aqueous phase liquid (NAPL) (*i.e.*, smear zone) corresponding to the approximate water table fluctuation (except in source areas). Average annual precipitation at a nearby weather station (*i.e.*, 7 km from site), considered to approximate site conditions, is 1240 mm (Richmond Nature Park).

The study methods included extensive delineation of the residual NAPL concentrations at source, detailed vertical profiling of soil properties (*e.g.*, moisture content, porosity, *in situ* diffusion coefficients) and vadose zone BTX, oxygen, carbon dioxide and methane concentrations in soil gas. Regular monitoring was used to assess the effect of seasonal changes on soil gas fate and transport with vadose zone monitoring conducted between March 1997 and August 1998. To facilitate measurement of soil gas intrusion, a small building (greenhouse) with controlled building envelope features (edge crack and service penetrations) was constructed in August 1997. The greenhouse was fastened to a 6.1 m by 9.3 m concrete slab of 100 mm nominal thickness. Near-continuous monitoring of oxygen levels below the building floor slab and differential pressure between subsoils, building and ambient was implemented. Soil gas hydrocarbon intrusion rates were estimated using a flux chamber, and indirectly through air and soil gas monitoring. Soil gas monitoring and intrusion evaluation was conducted for both static and induced building underpressurization (-10 and -30 Pascals (Pa)) conditions.

## VADOSE ZONE FATE AND TRANSPORT

### Baseline Soil Characterization

Baseline soil conditions were characterized at two locations designated as Sites A and B (Figure 1). Soils consist of a thin (0.1 to 0.3 m) laterally discontinuous soil layer consisting of sandy silt to fine sand containing some silt (henceforth referred to as "silt and fine sand crust") underlain by a medium sand fill (the ground surface is lightly vegetated with grasses). Prior to constructing the greenhouse, the silt and fine sand crust was removed to a depth of 0.3 m and replaced with 0.2 m of imported sand fill compacted to approximately 90% Modified Proctor maximum dry density (ASTM D1557). Grain size, estimated organic carbon and nutrient test results are presented in Table 1. Variability in grain size and organic carbon content was low indicating a relatively uniform sand deposit. For example, the silt content in eight samples collected from a single soil core at Site B ranged from 1.7 to 5.5 %. Grain size and organic carbon data for a vertical soil profile below the approximate centre of the greenhouse is presented in Table 2.

TABLE 1

Soil Type	Mean Grain Size, Organic Carbon and Soil Nutrient Properties						
	D <sub>50</sub> (50 % by weight passing) (mm)	Percent finer than U.S.S. #200 sieve (silt)	Estimated Organic Carbon <sup>3</sup> (%)	Ammonia Nitrogen (mg/kg)	Nitrate Nitrogen (mg/kg)	Total Nitrogen (%)	Total Phosphate (mg/kg)
Silt to fine sand crust <sup>1</sup>	N/A	41	-	5.0	1.9	0.050	9.4
Sand fill <sup>2</sup>	0.33	2.5	0.63	5.4	1.1	0.014	4.4

<sup>1</sup> Arithmetic mean based on one to four samples. <sup>2</sup> Arithmetic mean based on five to thirteen samples.

<sup>3</sup> Estimated from organic matter content (i.e., loss on ignition) using Van Bemmelen factor of 1.724 (Page et al., 1982).

Water retention (field capacity), total porosity, air-entry tension, bulk density and saturated hydraulic conductivity were estimated using disturbed soil samples re-compacted to various densities (Table 3). Samples re-compacted to Standard Proctor and Modified Proctor density (Lambe, 1951) likely represent the range of *in situ* density for the sand, except for near surface soil. The sand field capacity values were relatively low (about 6.8 % by volume, on average) indicating the sand will drain relatively quickly to fairly low moisture contents. Air-entry tensions were also low indicating that continuous air-filled pores will form at relatively low matric suctions. Gas-phase diffusion becomes significant at matric suctions above the air-entry tension.

Soil air permeability was measured at soil gas probes below the centre of the greenhouse according to the method described in Garbesi *et al.* (1996). This test measures soil air permeability within a small radius of the probe tip (0.1 m is suggested by Fischer *et al.* (1996)). Tests were conducted using a range of flow rates (3.1 to 12.6 cm<sup>3</sup>/sec) and pressures (43 to 160 Pa) with results presented in Table 2. Mean soil air permeability was, as expected, highest in low moisture content soils below the slab, and increased with depth. Soil air permeability at a given depth varied somewhat depending on probe pressure (between 30 to 60 %). When corrected for density and gas slippage (Klinkenberg) effects, the variation in permeability decreased slightly.

Soil samples were analyzed for benzene, toluene, ethylbenzene, xylenes (BTEX), and light hydrocarbons. The results indicate the BTX constitute essentially all hydrocarbons in soil. BTX concentrations in soil were relatively low above 1.2 m depth, but increased significantly at about 1.5 m depth indicating the presence of residual NAPL (Figure 2). At Site B, the relative proportions of individual components to total BTX were, on average, 10 % for benzene, 82 % for toluene and 8 % for m&p-xylene. The proportions did not vary significantly with depth, although data points were limited within 0.6 m of ground surface since concentrations, in many cases, were below the detection limit. Similar results were obtained for Sites A and B.

**TABLE 2**  
**Summary of Selected Soil Physical Properties Below Greenhouse**

Soil Gas Probe Depth (m)	Measured Soil Air Permeability <sup>1</sup> (Darcy)	Measured Effective Diffusivity (cm <sup>2</sup> /sec)	Soil Sample Depth Range (m)	Measured Silt Content (%)	Estimated Organic Carbon (%)
0.15	27	-	0.085 - 0.235	1.7	-
0.3	-	0.071	0.19 - 0.34	2.5	-
0.45	6.3	0.028	0.345 - 0.495	4.4	0.52
0.58	7.6	0.024	0.5 - 0.65	2.6	0.52
0.75	-	0.013	0.65 - 0.8	3.8	0.72
0.9	9.5	0.037	0.8 - 0.95	1.8	0.71
-	-	-	0.95 - 1.1	2.2	0.69
1.2	5.6	-	1.1 - 1.25	1.9	0.68
-	-	-	1.25 - 1.4	-	0.70
1.5	8.6	-	1.4 - 1.55	-	0.65
-	-	-	1.55 - 1.85	5.5	0.51

<sup>1</sup> Mean values for tests conducted at varying pressures, tests conducted in November and December 1997.

**TABLE 3**

Sample Preparation	Mean Soil Physical Properties <sup>1</sup>				
	Field Capacity (33 J/kg) Volumetric Water Content (% by Vol)	Total Porosity (%)	Air Entry Tension (J/kg)	Bulk Density (kg/m <sup>3</sup> )	Saturated Hydraulic Conductivity (m/s)
1/2 Standard Proctor	12.2	37.7	0.5	1620	7.7E-04
Standard Proctor	6.8	35.6	0.8	1645	8.1E-04
Modified Proctor	6.9	35.6	1.9	1685	6.7E-04

<sup>1</sup> Arithmetic mean values based on analysis of two to three composite sand fill samples for each density.

#### *Soil Moisture*

Soil moisture content was measured in soil cores from below the approximate middle of the greenhouse, and in soil cores obtained prior to greenhouse construction or adjacent to the greenhouse (Figure 3). Soil moisture contents below the greenhouse are at moderate levels and correspond to air-filled porosities between about 15 and 27 %. On average, the moisture contents appear to be highest between about 0.6 and 0.9 m depth. No physically-based mechanism for the increase in moisture content appears plausible since the grain size distribution is relatively constant with depth.

Moisture content monitoring below the greenhouse has only been conducted over a one-year period and therefore is not indicative of long-term trends. To further investigate long-term trends, a soil core was obtained from below a nearby on site building constructed in the 1960's. Residual NAPL is present below the building starting at about 1.6 m depth below ground surface. Within 1 m of slab surface, the moisture content

below the “old” building is consistently lower than that measured below the greenhouse and likely reflects long-term drying of soil. The lowest moisture content below the old building (2.6 %) is likely just above the soil wilting point, estimated to be on the order of 1 to 2.5 % based on tests conducted on soil from below the greenhouse. The soil wilting point is defined as the moisture content at a matric suction of 1500 J/kg. Bioventing studies suggest that biodegradation rates are significantly reduced for soil moisture contents close to the soil wilting point (Zwick *et al.*, 1995).

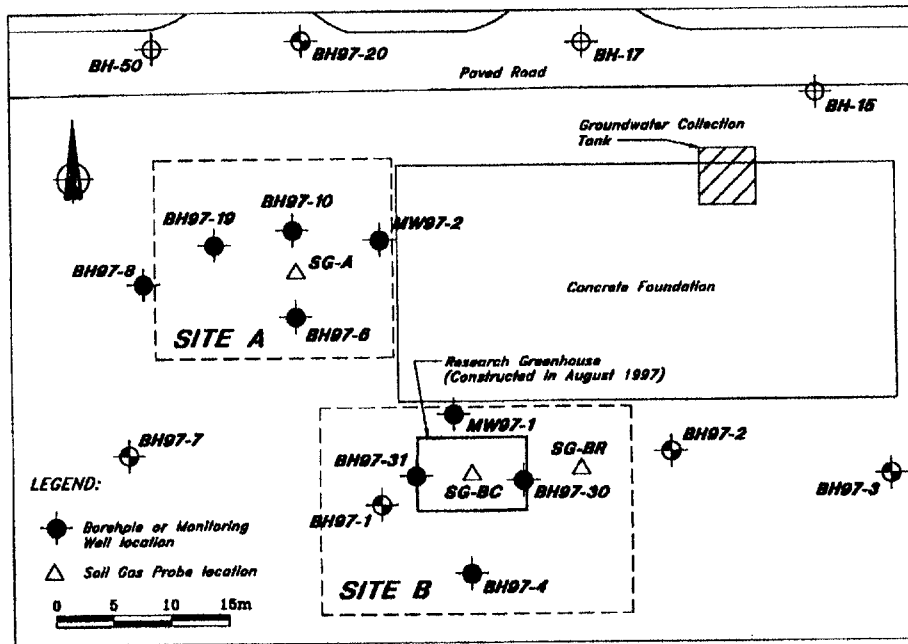


Figure 1  
Site Plan

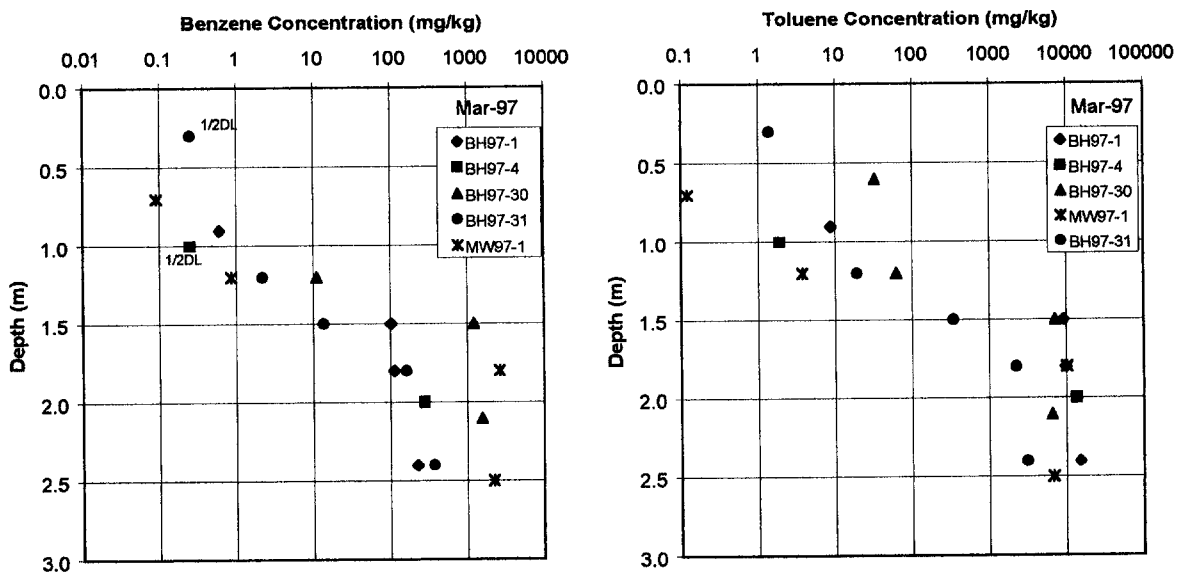


Figure 2  
BTX Concentrations in Soil at Site B.

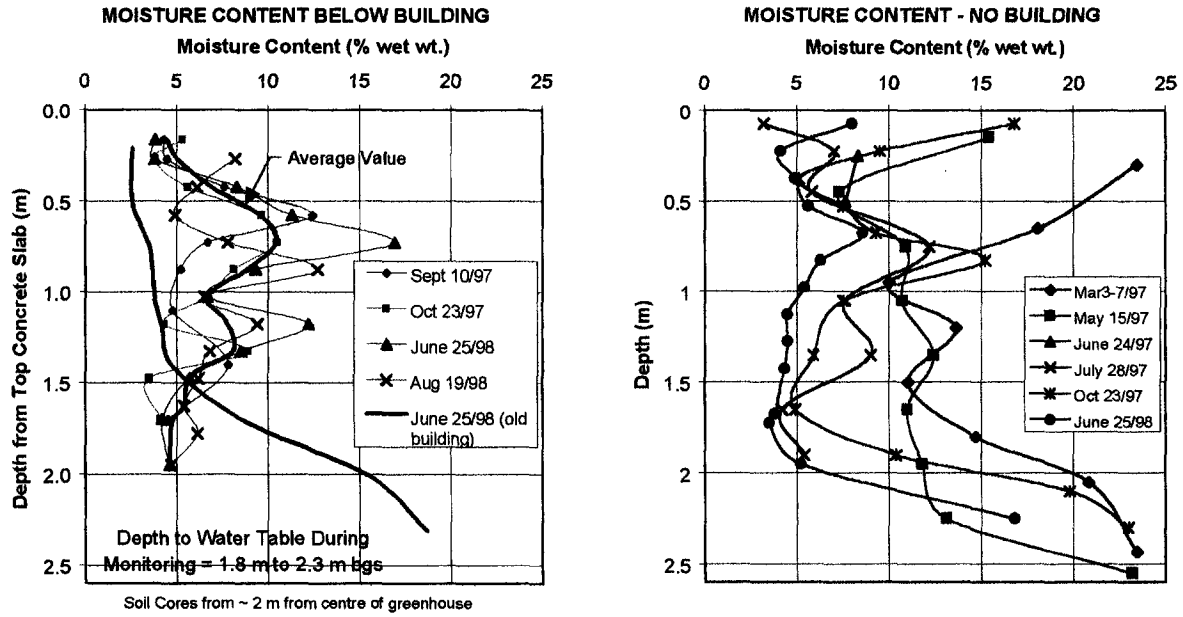
### Soil Gas

Soil gas samples were analyzed for BTX and light gases (oxygen (O<sub>2</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrogen (N<sub>2</sub>) and ethane). Soil gas samples were collected using 5 ml glass and Teflon syringes from either 6 mm or 12.5 mm I.D. steel probes driven to the desired depth, and analyzed for BTX on-site using a SRI 8610 gas chromatograph with photoionization detector (GC/PID). Samples for light gas analyses were collected using a 500 ml SKC Tedlar™ bag and analyzed using a GC with thermal conductivity or flame ionization detector (FID or TCD), or using a Landtec Control Technologies GA-90 field portable gas detector. Samples for BTX analysis were analyzed within four hours of collection, while samples for laboratory light gas analysis were analyzed between four and 48 hours of collection. The Landtec gas detector utilizes a galvanic cell for O<sub>2</sub> and infrared detector for CO<sub>2</sub> and CH<sub>4</sub>. To investigate the accuracy of the field portable unit, two samples taken consecutively from selected probes were submitted for both field and laboratory analysis. The results indicate a significant bias for O<sub>2</sub> and CH<sub>4</sub>. For example, Landtec O<sub>2</sub> concentrations were between 0.5 and 3 % lower than GC/TCD concentrations with the difference increasing at lower levels. Analysis by GC/TCD is considered more accurate than a galvanic cell.

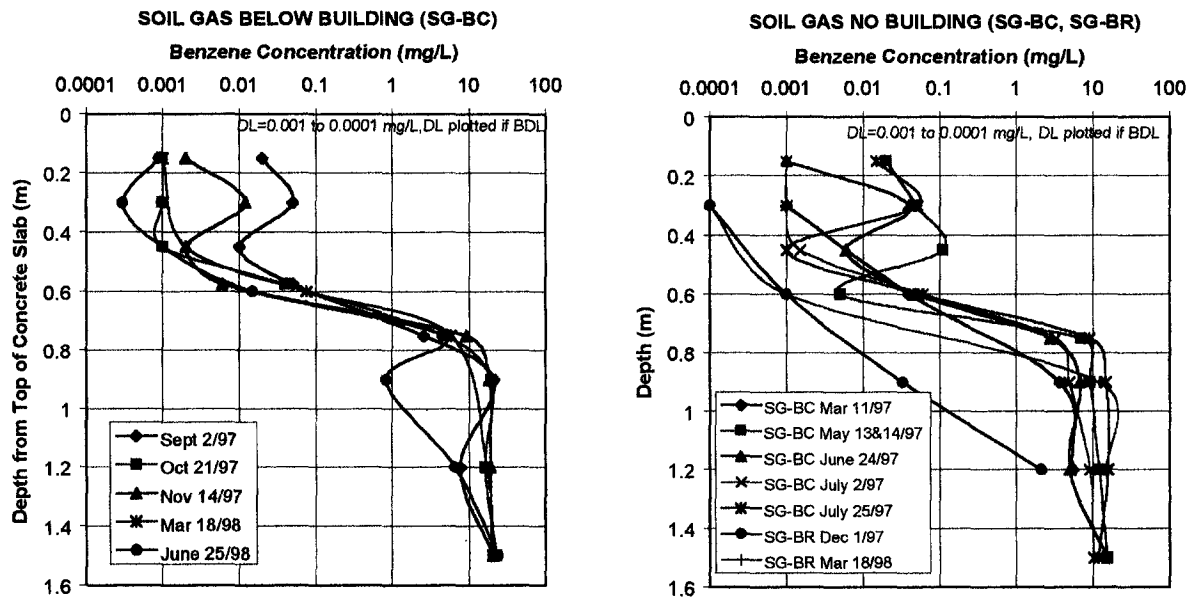
Soil gas benzene concentrations below the building, and at probes not covered by a building (*i.e.*, below the present greenhouse before it was constructed, or adjacent to the greenhouse) are presented in Figure 4. The benzene concentration profiles below the centre of the greenhouse were relatively consistent over time and are characterized by high concentrations at depth, significant attenuation (about 3 orders-of magnitude) between about 0.4 to 0.8 m depth, and lower but variable concentrations within 0.4 m depth below slab surface. The measured soil gas concentrations below 1 m depth are close to those predicted assuming equilibrium partitioning between the NAPL and soil gas phases, and vapour pressure adjusting using the mole fraction and Raoult's Law. For example, the predicted benzene soil gas concentrations range from 13 to 26 mg/L based on a temperature range of 10 to 20°C, and benzene mole fraction of 0.08. Measured benzene concentrations ranged from 5 to 23 mg/L. The benzene concentration profiles for the no building case were somewhat more variable than those below the building. Postulated causes include variation in surface water infiltration and moisture content, and advective soil gas pumping caused by barometric pressure and/or temperature fluctuations. The low benzene concentrations for the December 1, 1997 monitoring round may have been caused by high soil moisture contents since precipitation over the previous week was about 40 mm (Richmond Nature Park station). Similar results were obtained for toluene and xylene both below and adjacent to the greenhouse with results for one typical monitoring round presented in Figure 5.

The O<sub>2</sub> concentrations below the building, and at probes not covered by the building are presented in Figure 6. The O<sub>2</sub> concentrations below the building were relatively consistent over time and indicate significant O<sub>2</sub> consumption is likely occurring between about 0.6 to 0.9 m depth. Oxygen levels in near surface soil below the centre of the building slab were depleted and ranged between approximately 8 and 13 %. Carbon dioxide concentrations within 0.9 m depth generally ranged from 6 to 9 %, while below 0.9 m generally ranged between 10 and 13 %. The O<sub>2</sub> concentration profiles for the no building case exhibit greater variability, likely for the same reasons as described above. Oxygen concentrations at a non-contaminated reference site with similar soils were close to ambient levels (*i.e.*, 20.7 %) while CO<sub>2</sub> concentrations were equal to or below 0.1 %.

On three occasions (October 1997, November 1997 and June 1998), BTX and light gas concentrations in soil gas were measured at other probes below the concrete slab (*i.e.*, in addition to centre probes) (Figure 7). When compared to the centre probe cluster, the results indicate BTX and light gas concentrations were similar at probes located near the north, east and south edges of the slab (SG-BNC, SG-BEC, and SG-BSC). In contrast, BTX concentrations directly below the west edge of the slab were slightly higher, and BTX concentrations at probe SG-BMW (directly below slab) were significantly higher (typically, over two orders-of-magnitude). In addition, O<sub>2</sub> concentrations were typically several percent lower at this location. The combined BTX and light gas results indicates significant biodegradation may be occurring below the slab. However, the lateral variability in soil gas concentrations suggest that O<sub>2</sub> transport in subslab soils varies spatially, and that the variation in O<sub>2</sub> transport may be causing lower BTX biodegradation rates below the west portion of the slab. Variable BTX concentrations at 0.3 m depth (see Figure 4) also suggest that lateral transport of soil gas below the concrete slab may be occurring. It is noted that a 1 to 1.5 m strip of plastic was placed along the north,



**Figure 3**  
Moisture Content for Below Building and No Building Cases at Site B.



**Figure 4**  
Soil Gas Benzene Concentrations for Below Building and No Building Cases at Site B.

west and east edges of the greenhouse to shed rain water away from the edges of the greenhouse. This may influence O<sub>2</sub> replenishment toward the west end of the slab.

#### *In Situ Diffusion Coefficients*

*In situ* diffusion coefficients, while rarely measured, were considered important for this project due to the possible uncertainty associated with empirical relationships for effective diffusivity, and desire to accurately separate diffusive transport from other attenuation processes. *In situ* diffusion coefficients were measured at selected soil gas probe locations using a push-pull test involving injection and extraction of a non-reactive tracer gas (helium). The test is described by Johnson *et al.* (1998). The test procedure involved injection of 0.1 litre of helium followed by extraction of 1 litre of soil gas from the same probe using a Tedlar™ bag. The test was repeated several times at each probe by varying the time between injection and extraction. Helium was measured using a Mark Instruments, Inc. 9822 field portable detector. Prior to conducting each test, soil gas near the probe was purged by injecting a minimum of 15 litres of air, and a soil gas blank was collected to ensure that helium concentrations were below the detector detection limit (0.01 %).

The measured effective diffusion coefficients and tortuosities are presented in Table 4. The effective diffusion coefficients were calculated using actual air-filled porosities measured below the greenhouse. The repeatability of tests conducted at different times was relatively good with a relative standard deviation (RSD) on the order of 20 %. As expected, the effective diffusion coefficients decreased with increasing moisture. In addition, a good comparison was obtained between the measured tortuosity and that predicted using the Millington and Quirk (1961) relationship with measured values consistently about twice the predicted values. The results indicate the Millington and Quirk (1961) relationship, which is commonly used to estimate tortuosity, is appropriate over the range of moisture contents evaluated.

**TABLE 4**  
**Measured *In situ* Effective Diffusion Coefficients Based on Push-Pull Tests<sup>1</sup>**

Location	Depth (m)	Moisture Content <sup>3</sup> (% wt.)	Air- filled Porosity	Measured Eff. Diffusivity - Varying Extraction Times					Mean <sup>2</sup> Effective Diffusivity (cm <sup>2</sup> /sec)	Mean Measured Tortuosity	Predicted Tortuosity <sup>4</sup> (M&Q '61)
				Time= 1.24 min (cm <sup>2</sup> /sec)	Time= 3.24 min (cm <sup>2</sup> /sec)	Time= 6.24 min (cm <sup>2</sup> /sec)	Time= 11.2 min (cm <sup>2</sup> /sec)	Time= 16.2 min (cm <sup>2</sup> /sec)			
SG-A	0.60	6.9	0.24	0.075	0.053	0.063	0.056	0.049	0.055	0.17	0.069
SG-BC	0.3	5	0.27	0.12	0.081	0.064	0.078	0.063	0.071	0.22	0.10
SG-BC	0.45	8	0.22	0.067	0.040	0.027	0.020	0.026	0.028	0.085	0.053
SG-BC	0.58	10	0.19	0.054	0.027	0.026	0.021	0.022	0.024	0.072	0.031
SG-BC	0.75	12	0.16	0.017	0.018	0.013	0.011	0.010	0.013	0.039	0.016
SG-BC	0.9	7	0.24	0.072	0.043	0.038	0.028	-	0.037	0.11	0.067

<sup>1</sup> Physical/chemical properties for Helium: D<sub>air</sub> = 0.33 cm<sup>2</sup>/sec, H (dimensionless) = 121; K<sub>d</sub> = 0.002

<sup>2</sup> Arithmetic mean based on results for time equal to 3.24, 6.24, 11.2 and 16.2 minutes

<sup>3</sup> Moisture contents approximate values based on data in Figure 3, total porosity = 0.356.

<sup>4</sup> Predicted tortuosity based on Millington and Quirk (1961) relationship,  $\tau = \phi_g^{10/3} / \phi^2$

#### *Advective Soil Gas Transport*

Potential advective soil gas transport in subslab soil was investigated by continuous monitoring of O<sub>2</sub> concentrations directly below the slab, differential pressure between the soil and building, soil temperature, and environmental conditions (*e.g.*, temperature, barometric pressure). Continuous O<sub>2</sub> concentrations were measured using an electrochemical cell (DRC XT-252) adjacent to probe SG-BMW. Significant fluctuation in O<sub>2</sub> levels below the slab was observed during the fall of 1997 (from less than 2 to 15 %). The following trends with respect to O<sub>2</sub> are noted: (i) diurnal changes in concentrations (up to 2 %) with O<sub>2</sub> concentrations decreasing as the greenhouse temperature increased, (ii) day-long to week-long O<sub>2</sub> trends that appear to be correlated to barometric pressure with O<sub>2</sub> concentrations inversely proportional to pressure, and (iii) seasonal O<sub>2</sub> trends indicating an overall decline in O<sub>2</sub> concentrations between September and December 1997. Diurnal effects were significant in September 1997 but dissipated to non-detectable levels as the daily temperature

gradients decreased during the fall. The O<sub>2</sub> concentrations increased slowly as the barometric pressure increased, but appeared to decrease quickly in relation to a decrease in barometric pressure, which may be due to a flushing effect. It is postulated that the longer-term decrease in O<sub>2</sub> below the slab is due to increased precipitation during the fall, higher soil moisture content and corresponding decrease in soil air permeability. The decrease in permeability would likely be greatest for the silt and fine sand crust which would tend to retain water to a greater extent than the underlying sand, and thus hinder O<sub>2</sub> replenishment below the slab.

Differential pressure between the greenhouse and soil was measured below the centre of the greenhouse on a continuous basis using differential pressure transducers (Setra Systems 264) connected to soil gas probes located 0.15 and 0.58 m below the top of slab. Variation in differential pressure for the 0.15 m probe was negligible indicating that there was significant pressure coupling between the greenhouse and soil immediately below the slab, likely due to a relatively high slab permeability. Variation in differential pressure for the deeper 0.58 m probe was significant with diurnal variations in differential pressure of up to 3 Pascals. The diurnal fluctuations reflect heating (expansion) and cooling (contraction) of soil gas below the building, and result in soil gas movement into and out of soil directly below the slab. No barometric-induced variation in differential pressures were apparent.

#### *Conceptual Model for Vadoze Zone Below Greenhouse*

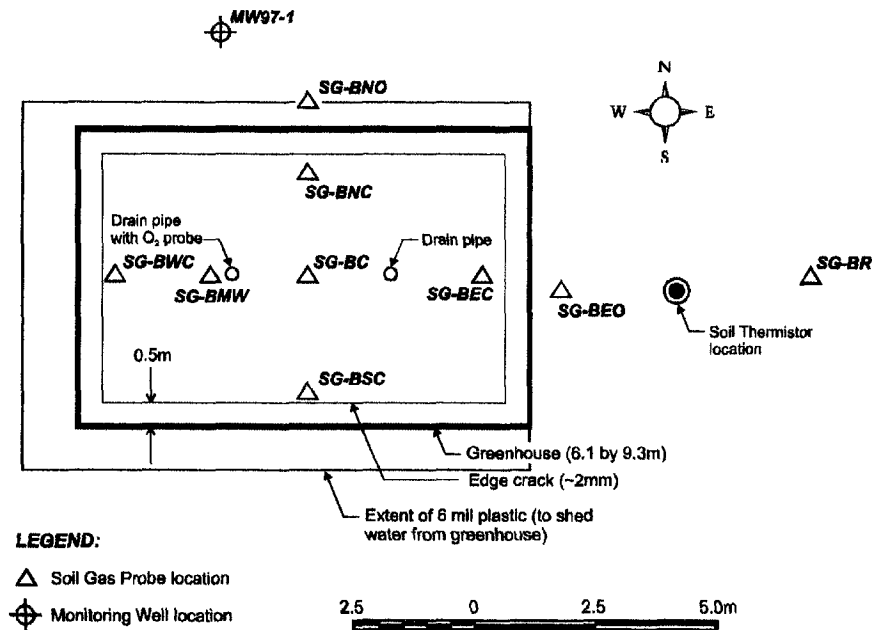
The conceptual model for the vadose zone processes below the greenhouse is presented in Figure 8. Based on monitoring conducted to date, processes affecting fate and transport can be divided into three zones based on depth below ground surface. In the deep zone, diffusive transport is the dominant process with likely very little bioattenuation as a result of oxygen depletion and potential toxic conditions due to high BTX concentrations. In the mid-depth zone, significant attenuation of BTX occurs below the approximate centre of the slab, but as described above, attenuation may not be spatially uniform. The BTX attenuation is attributed to be primarily due to biodecay since testing of soil properties (Table 2) and pressure gradients indicated physically-based mechanisms are unlikely to be significant. Elevated soil moisture within the mid-depth zone may be due to the generation of water as a by-product of hydrocarbon mineralization, and/or enhanced water retention within microbial biomass. In the shallow zone, advective transport is likely the dominant transport process. The driving forces for advection under static conditions (*i.e.*, no induced building depressurization) are temperature and barometric pressure fluctuations, and possibly wind-loading.

The consistent soil gas BTX profiles and relatively uniform soil physical properties suggest that fate and transport processes over the mid-depth zone are dominated by steady-state diffusion and biodecay, when sufficient O<sub>2</sub> is present for aerobic degradation. Based on this model and assuming homogeneous soil conditions, first order degradation coefficients were estimated by fitting model-predicted BTX concentrations based on an analytical solution for one-dimensional diffusion and reaction to measured values over the portion of the BTX profile that is approximately log-linear (*i.e.*, 0.5 to 0.8 m, see Figure 4). The first order degradation model assumes that both oxygen and hydrocarbon-degrading microbes are available in excess. Using approximate mean values for measured tortuosity and moisture content, the estimated first order degradation rate constants based on soil pore water concentrations ( $k_w$ ) were on the order of 1.2 hr<sup>-1</sup> for benzene and 0.9 hr<sup>-1</sup> for toluene. These values compare closely to first order degradation coefficients based on laboratory and field studies, presented by DeVaul *et al.* (1997). On-going testing is being conducted to further corroborate biodegradation processes including an *in situ* respiration test and microbial enumeration of BTX-degraders.

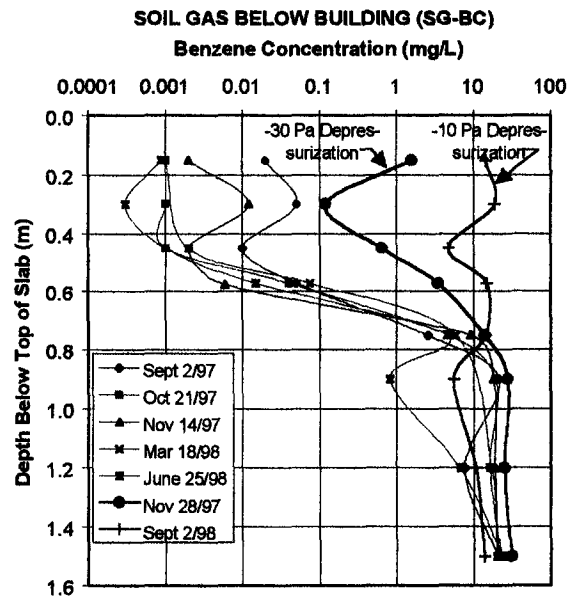
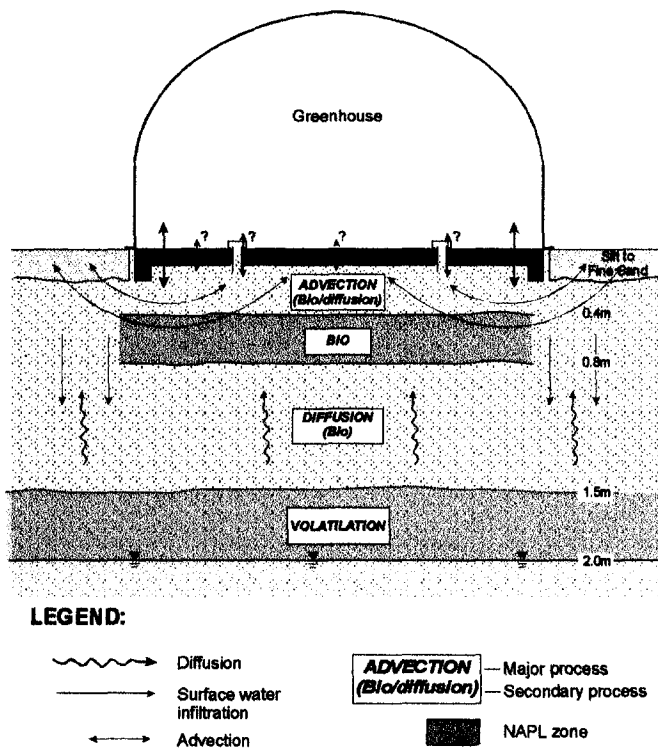
## **SOIL GAS INTRUSION INTO BUILDING**

Monitoring of soil gas intrusion into the greenhouse was conducted under static conditions (*i.e.*, no induced depressurization) and dynamic conditions (*i.e.*, fan-induced building depressurization) at -10 and -30 Pa relative to ambient air. For the static case, VOC intrusion into the building occurs through diffusion and potentially advective pumping caused by barometric pressure and temperature fluctuations, and/or wind

loading. Possible routes of soil gas entry through the building envelope are the 2-mm wide edge crack (total length of 27 m), and



**Figure 7**  
Greenhouse Location Plan.



**Figure 8**  
Conceptual Model for Vadose Zone  
Processes Below Greenhouse

hairline cracks potentially surrounding soil gas probes and two capped PVC drain pipes penetrating the concrete slab. In addition, a small north-south trending shrinkage crack bisects the middle of the slab. A preliminary depressurization test conducted in October 1997 indicated that soil gas flow rates through the slab were very high with very little pressure drop across the slab. For this reason, portions of the edge crack were either sealed with concrete grout, or were covered with plastic weighted with sandbags (to enable future opening of the crack if desired) in October 1997. Four 0.9-m lengths of the crack (*i.e.*, along north, east, south and west edges) were left uncovered corresponding to a crack to slab area ratio of 0.013 %.

**Figure 9**  
Effect of Depressurization on  
Soil Gas Benzene Profile

For the static case, the VOC flux into the building was estimated by (i) comparing indoor and outdoor BTX concentrations, and (ii) measuring potential VOC emissions through open portions of the edge crack using a stainless steel flux chamber (90 cm x 9 cm x 9 cm). Extensive chamber blanks were tested to ensure materials used were clean. The flux chamber was bolted to the concrete and sealed using a rubber gasket. After purging five chamber volumes, sampling with replacement (flow in = flow out) using a flow rate between 150 to 300 ml/min was used to obtain a sample with VOCs collected on two sorbant tubes (Supelco Inc. Carbotrap 300) in series. Inlet air to the chamber was scrubbed using a activated carbon trap. During the tests, the differential pressure between the chamber and greenhouse was periodically measured using a micromanometer (Dwyer Microtector). No pressure gradient was detected between the flux chamber and greenhouse. Indoor and outdoor air samples were also collected using sorbant tubes over a 4 to 20 hour period. During the tests, ventilation louvers in the greenhouse wall were partially open providing some natural ventilation.

For the dynamic case, flux chamber sampling without air replacement was employed to measure both soil gas advective flow through the edge crack and BTX flux. Soil gas flow rates were adjusted until there was no measurable pressure difference between the chamber and greenhouse. Soil gas samples were collected from the chamber outlet using Tedlar™ bags. In addition, soil gas flow and VOC flux were indirectly estimated using the mean indoor, outdoor and subslab BTX concentrations, and building ventilation rate (*i.e.*, mass balance approach). For the subslab BTX concentrations, the average of the four shallow probes adjacent to the edge crack was used.

The soil gas intrusion monitoring results are presented in Table 5. Statistical hypothesis testing indicated that, in all but one case, the mean indoor and outdoor concentrations were significantly different for the dynamic case (using two-tailed test and significance level of 0.10). Differences were not statistically significant for the static case, although it is recognized that only a limited number of samples were analyzed. For the dynamic case, the low flux chamber concentrations and non-significant difference in indoor and outdoor concentrations suggest that BTX flux through the building envelope is very low and potentially not significant. In contrast, highly elevated flux chamber concentrations were measured for the dynamic case. The BTX flux rates through the edge crack were further evaluated for toluene. The estimated toluene flux based on direct measurements of concentration and flow was on the order of 0.5 mg/min (-10 Pa test). In comparison, order-of-magnitude BTX flux rates and soil gas flows backcalculated using the measured toluene concentrations and building ventilation rate, were 6.6 mg/min and 6.4 L/min (-10 Pa), and 4.3 mg/min and 3.0 L/min (-30 Pa). The higher backcalculated toluene fluxes likely reflect other potential entry routes for soil gas intrusion, in addition to the four open edge cracks, although it is noted results are relatively uncertain due to experimental inaccuracy.

The effect of induced building depressurization was further evaluated by monitoring soil gas BTX concentrations below the centre of the greenhouse nine days (-30 Pa test) to twelve days (-10 Pa test) days after building ventilation had started (Figure 9). These profiles diverge significantly from the "static" profiles obtained during previous monitoring rounds and indicate that building depressurization caused significant upward migration of soil gas. For the -30 Pa test, steady state conditions may not have been reached resulting in lower BTX concentrations. For the -10 Pa test, lower soil moisture outside the greenhouse in August 1998 may also have contributed to deeper advective soil gas transport, and therefore higher concentrations. The

results demonstrate the significant effect building depressurization can have on soil gas fate and transport. However, it is cautioned that numerous factors contribute to likely "worst case" conditions with respect to induced advective transport. These include shallow contamination, relatively permeable soil, a highly permeable or "leaky" concrete slab (relative to typical building construction) and relatively high building depressurizations. On-going testing is being conducted to evaluate the effect of a less permeable slab.

**TABLE 5**  
**Results of Soil Gas BTX Intrusion Monitoring<sup>1</sup>**

Test	Location	Date	Building Ventilation Rate (m <sup>3</sup> /min)	Soil Gas Flow Rate (L/min)	Mean Concentrations		
					Benzene (ug/m <sup>3</sup> )	Toluene (ug/m <sup>3</sup> )	m&p-Xylene (ug/m <sup>3</sup> )
<b>No Building Depressurization (Static) Case</b>							
Test 1	Flux Chamber Tests (4 Edge Cracks)	Nov 7-13/97	NA	NA	1.0	4.5	2.2
	Air Inside Greenhouse	Nov 7-13/97	NA	NA	18	61	8.0
	Ambient Air Outside Greenhouse	Nov 7-13/97	NA	NA	10	22	4.4
Test 2	Flux Chamber Tests (4 Edge Cracks)	NA	NA	NA	NT	NT	NT
	Air Inside Greenhouse	June 30-July 24/98	NA	NA	2.3	16	4.6
	Ambient Air Outside Greenhouse	Aug 25-Sept 3/98	NA	NA	4.5	19	3.2
<b>Building Depressurization (Dynamic) Case</b>							
-30 Pa	Flux Chamber Tests (4 Edge Cracks)	Nov 19-26/97	30	NT	<sup>3</sup>	<sup>3</sup>	<sup>3</sup>
	Air Inside Greenhouse	Nov 19-26/97	30	NA	44	209	34
	Ambient Air Outside Greenhouse	Nov 19-26/97	30	NA	15	60	13
-10 Pa	Flux Chamber Tests (4 Edge Cracks)	Aug 28-Sept 1/98	10	1.84 <sup>2</sup>	334000	294000	24000
	Air Inside Greenhouse	Aug 25 - Sept 3/98	10	NA	112	690	243
	Ambient Air Outside Greenhouse	Aug 25-Sept 3/98	10	NA	4.5	19	3.2

<sup>1</sup> All concentrations are arithmetic mean values for 3 to 4 measurements, NA = not applicable, NT = not tested

<sup>2</sup> Total gas flow rate through four 0.9 m-long open portions of edge crack (*i.e.*, not covered with plastic) measured using flux chamber.

<sup>3</sup> Sorbant tube breakthrough occurred.

<sup>4</sup> Approximate rates, volume of greenhouse = 125 m<sup>3</sup>

Preliminary comparison of model-predicted to measured intrusion of BTX was conducted using a one-dimensional "screening-level" model based on the Johnson and Ettinger (1991) framework. The model includes steady-state diffusion in soil with no bioattenuation, and diffusion and advection through the building envelope, and is described in Hers *et al.* (1997). For the no induced building underpressurization case, BTX flux rates were very low and, in effect, could not be measured. However, comparison of predicted to measured indoor BTX concentrations provide some insight as to model accuracy. For example, the model-predicted indoor toluene concentrations (static diffusion case) are on the order of several thousand ug/m<sup>3</sup>, depending on the input parameters chosen (*e.g.*, soil properties, natural building ventilation rate). Toluene concentrations of this magnitude are at least two orders-of-magnitude higher than actual measured values. For the dynamic case, the model-predicted values are within one order-of-magnitude of the measured values based on the input parameters used. It is noted that the overall model-predicted BTX flux into the building is controlled by the diffusive flux rate in soil.

## CONCLUSIONS

Monitoring of vadose zone fate and transport of BTX and intrusion into a research greenhouse indicates that processes and factors affecting this pathway are complex with temporal and spatial variability observed. In the vadose zone, significant bioattenuation of BTX in soil gas was observed over a small depth interval below and adjacent to the greenhouse. Biodegradation below the greenhouse is dependent on oxygen transport, which for soil directly below the slab is thought to occur primarily through advective processes, as induced by temperature (*i.e.*, diurnal) and barometric pressure fluctuations. Oxygen transport rates are affected by soil permeability, and hence soil moisture, which is consistently at relatively low levels below the greenhouse but

varies seasonally in surface soil adjacent to the greenhouse. Soil moisture is a critical parameter that influences all the major processes affecting vadose zone fate and transport (*i.e.*, diffusion, advection and biodegradation). Monitoring of BTX intrusion into the greenhouse indicates that under static conditions (*i.e.*, no fan-induced building depressurization) BTX flux rates are very low and likely insignificant. Model predictions based on the Johnson and Ettinger (1991) framework were highly conservative for the static case. The BTX flux into the greenhouse was significantly higher for the dynamic case and indicates that advective processes extended to a sufficient depth to draw BTX to below and into the greenhouse. The relatively high slab and subslab soil permeability and shallow contamination contribute to the higher BTX intrusion rates for the dynamic case.

Further work that we consider important at this site include investigation of potential long-term drying of soil below a building and effects on biodegradation, O<sub>2</sub> transport through pumping below a building including consideration of spatial variation in O<sub>2</sub> and building effects, and transport processes through a building envelope including assessment of a less permeable or "leaky" slab.

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