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Characterizing exposure to chemicals from soil vapor intrusion using a two-compartment model

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Abstract

Though several different models have been developed for sub-surface migration, little attention has been given to the effect of subsurface transport on the indoor environment. Existing methods generally assume that a house is one well-mixed compartment. A two-compartment model was developed to better characterize this exposure pathway; the model treats the house as two well-mixed compartments, one for the basement and one for the remainder of the house. A field study was completed to quantify parameters associated with the two-compartment model, such as soil gas intrusion rates and basement to ground floor air exchange rates. Two residential test houses in Paulsboro, New Jersey were selected for this study. All experiments were completed using sulfur hexafluoride (SF_6) as a tracer gas. Soil gas intrusion rates were found to be highly dependent on the soil gas to basement pressure difference, varying from $0.001\,m^3\,m^{-2}\,h^{-1}$ for a pressure drop of –0.2 Pa to $0.011\,m^3\,m^{-2}\,h^{-1}$ for a pressure drop of –6.0 Pa. Basement ventilation rates ranged from 0.17 to 0.75 air changes per hour (ACH) for basement to ambient pressure differences ranging from –1.1 to –7.6 Pa (relative to ambient). Application of experimental results in conjunction with the two-compartment model indicate that exposures are highly dependent on gas intrusion rates, basement ventilation rate, and fraction of time spent in the basement. These results can also be significantly different when compared with the simple well-mixed house assumption.

Keywords: Indoor air; Soil vapor intrusion; Soil gas; Basement ventilation; Exposure assessment

1. Introduction

Chemical migration from sub-surface to indoor air can be an important exposure pathway for numerous contaminants, e.g., radon, gasoline vapors associated with leaking underground storage tanks, and chlorinated organics associated with landfills or contaminated groundwater. The driving force for soil gas intrusion into buildings is the negative pressure difference that typically exists between indoor and outdoor environments. Building underpressurizations have been measured from 0–50 Pa (Nazaroff et al., 1985), with typical values ranging from 0–5 Pa (Robinson et al., 1997). Transport through the building foundation can occur from one or more of the following pathways: advection and/or diffusion through cracks in the foundation, diffusion through the foundation itself, or advection through "intentional" openings, e.g., drains or sumps. Though advection is believed to be the dominant transport mechanism for radon (Nazaroff, 1992), field studies have also indicated the importance of molecular diffusion (Robinson et al., 1997). Upon entering a

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building, contaminants are transported throughout the indoor environment via air exchange between rooms.

Significant uncertainties still remain in attempting to characterize this exposure pathway, both in terms of quantifying exposure and validating results with experimental data. The overall objective of this research was to present a two-compartment model for estimating residential exposure from the soil to indoor air pathway. The parameters measured using two test houses were used to demonstrate differences between two-compartment and traditional one-compartment models.

2. Background

2.1. Case studies

Although there has been no wide-scale assessment on the importance of the soil vapor intrusion pathway to human exposure to VOCs, several case studies point to its possible importance. Wood and Porter (1987) reported methane concentrations of nearly 1% in enclosed spaces of homes located near a landfill. Several chlorinated hydrocarbons were also detected in a home located approximately 180 m from the landfill. Moseley and Meyer (1992) sampled soil gas, air, and groundwater in a school that was located near several underground petroleum storage tanks suspected of contributing to sub-surface contamination. Measured hydrocarbon concentrations in the occupied space of the school were as high as 40% of the lower explosion limit (LEL). Later studies indicated total hydrocarbon concentrations as high as $8.4\,\mathrm{mg\,m^{-3}}$ in classrooms and $390\,\mathrm{mg\,m^{-3}}$ in the crawl space below the floor. Though this school represents an extreme case, it points to the potential for build up of organic chemicals in indoor air, particularly when an identifiable source is nearby. Fischer et al. (1996) conducted experiments at a building located near a site characterized by gasoline contamination. Maximum total VOC concentrations of $60\,\mathrm{g\,m^{-3}}$ were measured 0.7 m below the building. Indoor air concentrations of several gasoline-range VOCs were between 1.9 and $37\,\mu\mathrm{g\,m^{-3}}$.

Existence of an identifiable source of contamination does not necessarily lead to high indoor air concentrations. Hodgson et al. (1992) detected 26 VOCs in the basement of a house located approximately 70 m from a landfill. However, all samples ranged from low to sub-parts per billion levels, which were noted to be comparable to median values of indoor air concentrations of VOCs measured in the US. The authors noted that although intrusion from soil gas likely contributed to VOC concentrations in indoor air, significant uncertainty existed since measured indoor concentrations were consistent with levels typically found in indoor air.

2.2. Existing models

Existing methods for estimating soil vapor intrusion into buildings generally assume that a constant source of known depth and concentration exists near a building. It is also typically assumed that either advection or diffusion dominates the transport process. Little et al. (1992) presented three different transport models: (1) diffusion-dominated transport where the chemical is introduced at a fixed distance below the building; (2) diffusion-dominated transport where the chemical is assumed to be at a constant concentration surrounding the building and (3) advection-dominated transport where the chemical is introduced at a fixed longitudinal distance from the building. In all cases, the source concentration is assumed to be constant and the entire VOC flux entering the zone of influence also enters the building. The resistance to air flow from the basement slab was not considered, i.e., the basement slab was considered to be a negligible impedance to soil gas transport relative to soil permeability. This assumption will tend to overestimate the amount of soil gas entering the basement. Sanders and Stern (1994) combined the first model presented in Little et al. (1992) with a source of decreasing strength as formulated by Jury et al. (1990). For a given chemical, exposure estimates varied by up to seven orders of magnitude, depending on whether a finite or infinite source thickness was assumed and whether biodegradation was assumed. Johnson and Ettinger (1991) developed a model considering both advection and diffusion from a planar source. Assumed crack lengths and crack areas were used to predict soil gas transport through the basement foundation. In a model first developed by Ferguson et al. (1995) and later elaborated on by Krylov and Ferguson (1998), both diffusive and advective transport were considered. For diffusive transport, resistance through the soil and through several building materials were considered. For advective transport, resistance across the basement foundation was neglected (meaning that the effect of the basement slab was considered negligible relative to soil permeability).

One criticism common to many of the above methods is that they contain numerous adjustable "fitting" parameters and that typical values for such variables are either not available or subject to significant uncertainty. In addition, field data to calibrate or evaluate existing models are generally lacking. Garbesi et al. (1993) found that measured soil gas intrusion rates at a small-scale test basement were higher than predictions using a three-dimensional finite difference model. Differences were attributed to bias in soil permeability measurements and the existence of high-permeability flow paths.

The effects of soil vapor intrusion on indoor air concentrations can be approximated through the use of attenuation factors. Little et al. (1992) used values of soil gas and indoor air radon activities from the literature and reported a representative attenuation factor for radon of 0.0016. Assuming VOC and radon transport are analogous processes, this means that the indoor air concentration is 0.0016 times the soil gas concentration. This should only be regarded as a first-order approximation, as the attenuation factor is highly system-dependent (Little et al., 1992).

3. Two-compartment model

Exposure to chemicals from soil vapor intrusion can be estimated using the two-compartment model shown in Fig. 1. Assuming each floor behaves as a well-mixed compartment, a mass balance on both the basement and ground floor results in the following:

$$V_b \frac{dC_b}{dt} = Q_{b,\,in} C_{in} + Q_L C_L - Q_b C_b + E, \tag{1}$$

$$V_L \frac{dC_L}{dt} = Q_{in} C_{in} - Q_{out} C_L + Q_b C_b - Q_L C_L, \tag{2}$$

where V_b is the basement volume (m^3), C_b is the pollutant concentration in the basement (mg m^{-3}), $Q_{b,in}$ is the air flow rate from ambient to basement (m^3 h^{-1}), C_{in} is the pollutant concentration in outdoor (ambient) air (mg m^{-3}), Q_L is the air flow rate from first floor to basement (m^3 h^{-1}), C_L is the pollutant concentration on the first floor (mg m^{-3}), Q_b is the air flow rate from basement to first floor (m^3 h^{-1}), E is the pollutant emission rate from soil to basement (mg h^{-1}), V_L is the first floor volume (m^3), Q_{in} is the air flow rate from ambient to first floor (m^3 h^{-1}), and Q_{out} is the air flow rate from first floor to ambient (m^3 h^{-1}).

Eqs. (1) and (2) can be simplified by assuming there is no airflow from ground floor to basement ($Q_L = 0$) and the inlet chemical concentration is negligible ($C_{in} = 0$):

$$V_b \frac{dC_b}{dt} = E - Q_b C_b, \tag{3}$$

$$V_L \frac{dC_L}{dt} = Q_b C_b - Q_{out} C_L. \tag{4}$$

Integrating from $C_b = C_L = 0$ at $t = 0$ to $C_b = C_b$ and $C_L = C_L$ at $t = t$ results in the following:

$$C_b = \frac{E}{Q_b}\left[1 - \exp\left(-\frac{Q_b}{V_b}t\right)\right], \tag{5}$$

$$C_L = \frac{E}{Q_{out}\left(\dfrac{V_b Q_{out}}{Q_b V_L} - 1\right)} \exp\left(-\frac{Q_b}{V_b}t\right) - \frac{E}{Q_{out}} \times \left[1 + \frac{1}{(V_b Q_{out}/Q_b V_L) - 1}\right] \exp\left(-\frac{Q_b}{V_b}t\right) + \frac{E}{Q_{out}}. \tag{6}$$

At steady state conditions ($t \to \infty$), Eqs. (5) and (6) reduce to the following:

$$C_b = \frac{E}{Q_b}, \tag{7}$$

$$C_L = \frac{E}{Q_{out}}. \tag{8}$$

4. Site description

A series of field experiments were completed to better characterize parameters described in the previous section. The field site was Terminal No. 4555 located in Paulsboro, Gloucester County, New Jersey. The Paulsboro Terminal is currently owned and operated by BP Amoco. The facility covers an area of approximately 125 acres, and consists of 63 above-ground bulk storage tanks with a capacity of approximately 2.77 million barrels, a marine loading area, and rail and truck loading. The facility operated until May 1996 when BP decided to cease operations.

The two houses used for this study were both unoccupied and located near the facility. Test house A consisted of two stories and a basement, two bedrooms and one full bathroom, with an area of approximately 1300 ft^2. Test house B consisted of one story and a basement, three bedrooms and one full bathroom, with an area of approximately 1500 ft^2. The basement flooring of both test houses consisted of a concrete slab of 6″ depth. Several noticeable cracks (<0.05″ wide) existed on the basement flooring of both houses.

5. Experimental methods

Two major components of the soil gas to indoor air exposure pathway were studied: (1) chemical migration

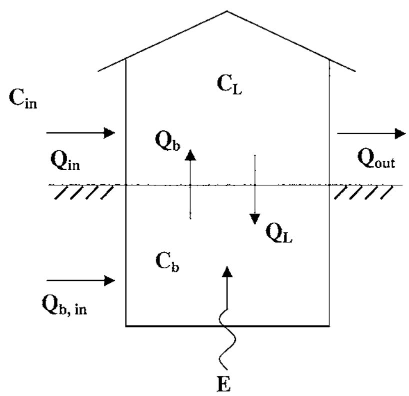

Fig. 1. Schematic of two-compartment model.

through the basement foundation and (2) air exchange rate between the basement and the remainder of the house. Sulfur hexafluoride (SF_6) was used as a tracer gas for both sub-surface and basement ventilation experiments. Tracer gas measurements were analyzed using a Lagus Applied Technology, Inc. Model 101 AUTOTRAC Automatic Tracer Gas Monitor. The device consists of a gas chromatograph equipped with an electron capture detector (GC/ECD), an eight-port sampling manifold and a manual injection port. In addition to SF_6 samples, temperature and pressure were measured continuously during all experiments using an automated performance testing (APT-8) system with data logger (The Energy Conservatory).

5.1. Sub-surface experiments

All sub-surface experiments were completed at test house A. Experiments were completed with all windows closed, except in the basement where a fan and plastic covering were placed on one window to create a negative pressure difference (relative to outdoors). A 19-mm diameter hole was drilled through the basement slab in the center of the basement. The void space between the soil and basement slab was filled with coarse gravel. Two 6-mm i.d. Teflon™ lines were placed in the hole for sub-surface measurements; one line was used for gas sampling and the other for pressure measurements. Both lines extended just below the bottom of the basement slab. The remaining space in the hole was then filled with cement.

Sub-surface experiments began with an initial injection of SF_6 below the basement surface using two existing monitoring wells (indicated by "I" in Fig. 2). A Tedlar™ bag was filled with 2 l of air mixed with 0.25 l of pure SF_6. Injection of this mixture occurred using a single personal sample pump (SKC PCXR8) and 6-mm i.d. Nylon tubing. The bag and sample pump were placed outside of the house to minimize cross-contamination. The Nylon tubing was connected to a Swagelok™ tee which split the Nylon tubing equally into two lines that were then connected to the wells using a Swagelok™ quick-connect fitting. Prior to all experiments, windows throughout the house were opened and several fans were activated in an effort to minimize the initial SF_6 concentration inside the house. After sufficiently low SF_6 concentrations were measured, i.e., generally less than 50 ppt, all windows were closed and all fans were de-activated. The basement fan was then set to the appropriate indoor–outdoor pressure difference.

Air temperature was measured continuously at three locations: basement, first floor, and ambient. The pressure difference was measured continuously at three locations: first floor to ambient (reference), basement to ambient (reference), and basement to soil gas (reference). Sulfur hexafluoride samples were taken every 2 min using the Lagus SF_6 analyzer. All sub-surface experiments used eight sampling locations, one on the first floor (near the stairs leading to the basement and referred to as P1) and seven in the basement (labeled as P2–P8 in Fig. 2). Sampling location P1 was located 4 ft above the first floor and sampling locations P2–P8 were each located 1 ft above the basement floor.

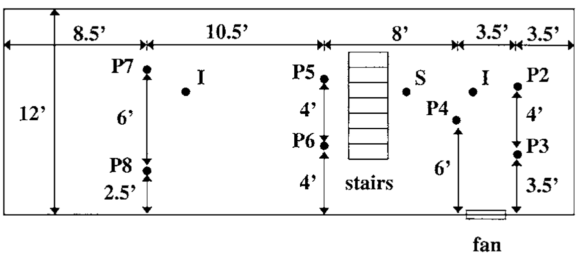

Fig. 2. Sampling locations for sub-surface experiments (I = injection line; S = sub-surface sampling line).

5.2. Basement ventilation experiments

All basement ventilation experiments were completed in test house B. Experiments were completed with all windows closed, except in the living room where a fan and plastic covering were placed on the window to induce a negative pressure difference (relative to outdoors). For each experiment, 1.0 ml of pure SF_6 was injected into a 2-L Tedlar™ bag filled with air. The SF_6 was then injected into the basement using a personal sample pump (SKC PCXR8) and 6-mm i.d. Tygon™ tubing. Two basement fans were used to mix the SF_6 for 10–20 min after injection.

After the initial mixing, the basement fans were de-activated and the basement door was closed. Sampling started after the window-mounted fan on the first floor was activated. The basement door remained closed for approximately 2 h; the door was then opened and sampling continued for approximately one additional hour.

Air temperature was measured continuously at three locations: basement, first floor, and ambient. Pressure difference was measured continuously at two locations: first floor to ambient (reference) and basement to ambient (reference). Four sampling locations were used for all basement ventilation experiments (labeled as P1–P4 in Fig. 3). Sampling locations P1, P2, and P3–P4 were located 5, 2.5, and 4 ft above the basement floor, respectively. Sulfur hexafluoride concentrations were measured every 2 min using the Lagus SF_6 analyzer.

6. Data analysis

6.1. Sub-surface experiments

The rate of SF_6 intrusion into the basement was characterized using Darcy's law for describing flow through porous media, modified to include pressure gradient and specific permeability to replace the more typical "hydraulic" conductivity and "hydraulic" gradient:

$$Q = -\frac{k\gamma}{\mu} A \frac{\mathrm{d}}{\mathrm{d}z}\left(z + \frac{p}{\gamma}\right), \tag{9}$$

where Q is the flow rate through area A ($\mathrm{m^3\,s^{-1}}$), k is the specific permeability (darcys) and a darcy is $0.987 \times 10^{-8}\,\mathrm{cm^2}$, γ is the specific volume of air ($\mathrm{N\,m^{-3}}$), A is the cross-sectional area ($\mathrm{m^{-2}}$), and $\mathrm{d}/\mathrm{d}z$ is the gradient with depth z ($\mathrm{m^{-1}}$), and p is the pressure (Pa). Since air flows vertically through the basement, the gradient term is written $\mathrm{d}h/\mathrm{d}z$ as opposed to the more typical notation of $\mathrm{d}h/\mathrm{d}x$. The flow rate of soil vapor into the basement was determined from the SF_6 emission rate divided by subsurface concentration. Since the forced airflow through the basement was relatively large, i.e., greater than 10 ACH, it was assumed that the concentration exiting the basement was equal to the average SF_6 concentration in the basement. A steady-state mass balance on the basement gives the following expression to determine the SF_6 mass intrusion rate (E):

$$E = C_\mathrm{B} Q_\mathrm{fan} - C_\mathrm{L} Q_\mathrm{fan}, \tag{10}$$

where Q_fan is the air flow rate induced by the window fan ($\mathrm{m^3\,h^{-1}}$).

6.2. Basement ventilation experiments

The air exchange rate in the basement was determined using a standard analysis for tracer decay from a pulse input, which is described briefly here. Assuming the basement is a well-mixed compartment results in the following mass balance:

$$\frac{\mathrm{d}}{\mathrm{d}t}(CV) = -CQ, \tag{11}$$

where C is the SF_6 concentration in basement air ($\mathrm{mg\,m^{-3}}$), V is the volume of the basement ($\mathrm{m^3}$), and Q is the air flow rate ($\mathrm{m^3\,h^{-1}}$) from the basement to the first floor of the house. Assuming a constant volume and integrating from $C = C_0$ at $t = 0$ to $C = C$ at $t = t$ results in the following expression:

$$\frac{C}{C_0} = \exp\left(-\frac{Q}{V}t\right) = \exp\left(-\frac{t}{\theta}\right), \tag{12}$$

where θ is the aerodynamic residence time (h). The inverse of θ is the air exchange rate in air changes per hour (ACH), which can be determined as the slope of a plot of natural logarithm of normalized concentration (C/C_0) versus time.

7. Results

7.1. Sub-surface experiments

A plot of SF_6 concentration in basement air for one experiment is presented in Fig. 4. The soil gas to basement pressure difference for this experiment was −0.2 Pa (relative to basement). Data points prior to $t = 0.8$ h indicate conditions where house windows were opened and fans activated in an effort to minimize background SF_6 concentrations; the house was sealed at $t = 0.8$ h. Clearly, there was a substantial increase in SF_6 concentrations when the house was sealed and the pressure difference changed from 0.0 to −0.2 Pa. Also noteworthy is the strong correlation of SF_6 concentration between sampling locations. This result indicates a high degree of mixing in the basement, likely the result of the relatively high forced ventilation rate.

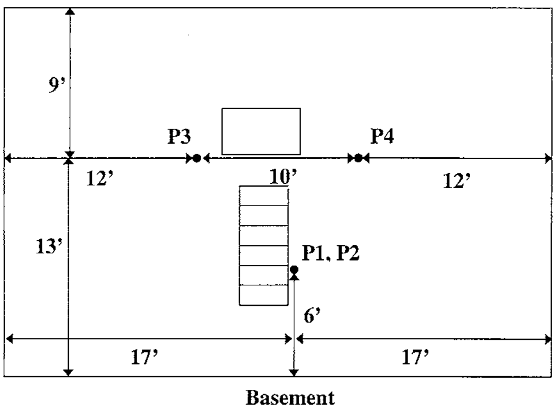

Fig. 3. Sampling locations for basement ventilation experiments.

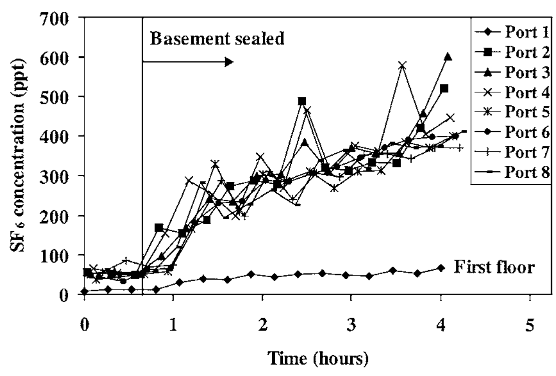

Fig. 4. SF_6 concentration in basement air as a function of time (soil to basement pressure difference of −0.2 Pa).

Table 1
Summary of sub-surface experimental results

Experiment	Soil to basement pressure difference (Pa)	SF_6 intrusion rate ($m^3 h^{-1}$)	Specific permeability, k (darcys)
1	−0.20	0.022	2.49
2	−1.63	0.15	2.09
3	−3.65	0.39	2.41
4	−6.02	0.40	1.50
5	−6.22	0.35	1.27

A summary of all sub-surface experiments is given in Table 1. Soil to basement pressure differences ranged from −0.20 to −6.22 Pa, which is consistent with typical values reported in the literature (Nazaroff et al., 1987). The calculated specific permeabilities for the five experiments are relatively constant, with all values within a factor of two of one another. This result is expected since the permeability is a function of medium only, i.e., the concrete floor of the basement. The permeabilities listed in Table 1 are consistent with the typical range of 1–10 darcys for fine sand (Johnson and Ettinger, 1991).

Though the true driving force for transport through the basement foundation is the soil to basement pressure difference (as opposed to the basement to ambient pressure difference), existing models assume that these two pressure differences are identical. In other words, existing models typically use the basement to ambient pressure difference to describe transport through the concrete, which will often overestimate the amount of soil gas transport. For this study, basement to ambient pressure differences ranged from −0.45 to −9.70 Pa, which was greater than the soil to basement pressure difference. There appears to be strong correlation between these two pressure differences (Fig. 5), albeit the data set is somewhat limited for this study.

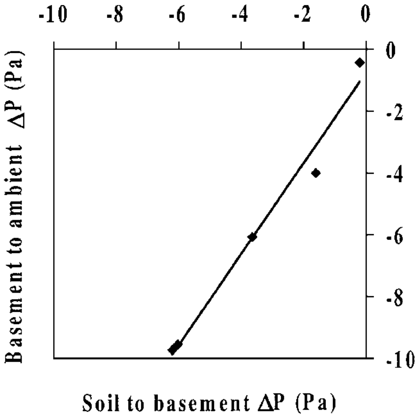

Fig. 5. Relationship between soil to ambient pressure difference and basement to ambient pressure difference.

Garbesi and Sextro (1989) estimated soil gas intrusion rates based on SF_6 dilution at a test basement. Soil gas intrusion rates ranged from 0.015to 0.12 $m^3 m^{-2} h^{-1}$ for a forced underpressurization of 30 Pa. Garbesi et al. (1993) estimated soil gas intrusion rates of 0.17–0.63 $m^3 m^{-2} h^{-1}$ based on radon measurements at a small-scale test basement constructed with intentional openings in the basement floor; forced underpressurizations for these experiments ranged from 20–70 Pa. For this study, soil gas intrusion rates varied from 0.001 $m^3 m^{-2} h^{-1}$ for a pressure drop of −0.2 Pa–0.011 $m^3 m^{-2} h^{-1}$ for a pressure drop of –6.0 Pa. Assuming similar transport path lengths and conductivities, differences in soil gas intrusion rates between two or more studies should be directly related to differences in soil-to-indoor air pressure drop between those studies. The underpressurization range of 20–70 Pa from previous studies is approximately 10 times the range of 0.2–6 Pa reported for this study. The soil gas intrusion rates for this study would then be expected to range from approximately 0.01 $m^3 m^{-2} h^{-1}$ to 0.1 $m^3 m^{-2} h^{-1}$ at these higher underpressurizations, which is consistent with the soil gas intrusion rates reported previously.

Attenuation factors determined for this study were also compared with those from previous studies. As discussed earlier, Little et al. (1992) estimated an attenuation factor of 1.6×10^{-3} based on radon data. Radon intrusion rates into basements are expected to be higher than those for either VOCs or SF_6, since the concrete itself may be an additional source for radon. Fischer et al. (1996) reported ratios of soil gas to indoor air concentrations ranging from 4.0×10^{-4} to 1.9×10^{-3} for several gasoline-range VOCs. Ratios of soil gas to indoor air concentrations for SF_6 were reported to range from 2.5×10^{-4} (no forced pressurization) to 4.5×10^{-4} (forced pressurization of 10 and 75 Pa). For this study, ratios of soil gas to indoor air concentrations for SF_6 ranged from 5.52×10^{-5} to 1.7×10^{-4}, which is reasonably consistent with existing field data given the differences in experimental conditions.

7.2. Basement ventilation experiments

Results associated with a typical basement ventilation experiment are shown in Fig. 6 for a basement to

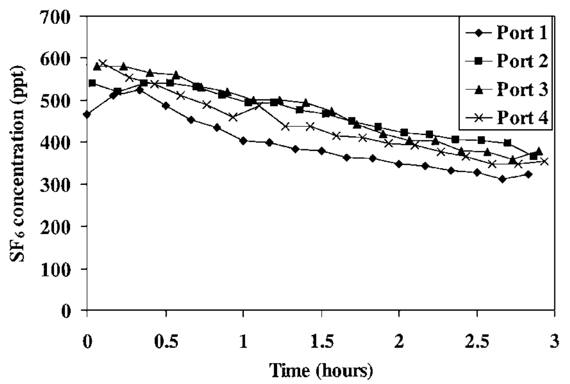

Fig. 6. SF_6 concentration in basement air as a function of time (ambient to basement pressure difference of -1.1 Pa).

Table 2
Summary of basement ventilation experimental results

Experiment	Basement to ambient pressure difference (Pa)	Air exchange rate (ACH)
1	−1.10	0.17
2	−3.61	0.22
3	−5.36	0.68
4	−7.60	1.08
5	−7.61	0.75

ambient pressure difference of –1.10 Pa (relative to ambient). The calculated air exchange rate for this experiment was $0.17\,h^{-1}$. As expected, SF_6 concentrations decreased with time for all four basement sampling locations (Ports 1–4). These four locations were relatively similar in magnitude, indicating that the basement was reasonably well mixed. There was no apparent difference in the ventilation rate when the basement door was opened at $t = 2$ h, indicating that there was little resistance to airflow from the door itself. This result is likely due to an observed opening of approximately 0.25″–0.5″ between the floor and bottom of the door.

A summary of all basement ventilation experiments is presented in Table 2. In general, the air exchange rate increased with increasing pressure difference. Little experimental data are available on air exchange rates from basements to the living space of a house. McGrath and McManus (1996) measured air exchange rates from basement to living space ranging from 2.7 to 4.9 ACH for two houses. However, these data likely represent an extreme case for US houses as both basements had large (approximately $1\,m \times 0.5\,m$) openings for fresh air to enter. Numerous studies have been completed on overall air exchange between indoor and outdoor air, the largest being a data set compiled by Brookhaven National Laboratory. Murray and Burmaster (1995) used these data to develop univariate lognormal distributions of air exchange rates. Over all regions and seasons, the arithmetic mean and standard deviation were 0.76 and 0.88 ACH, respectively. Though the data set in Table 2 is relatively limited, the basement air exchange rates for this study are comparable in magnitude to these larger distributions.

8. Model application

An example model application was completed to determine potentially important parameters and to compare results between the two-compartment model and a simpler well-mixed house model. The following values were selected based on the field experiments completed for this research: $V_L = 170\,m^3$; $V_B = 170\,m^3$; $E = 5\,mg\,h^{-1}$; $Q_{out} = 1$ ACH; $Q_B = 0.5$ ACH. Using these values in Eqs. (5) and (6), steady-state conditions were reached for both C_L and C_B within 8 h. Based on these results, only steady-state concentrations (Eqs. (7) and (8)) were used for the remainder of this example.

Comparisons of inhalation exposure were based on average exposure, which can be defined as the integration of instantaneous exposure over time (Georgopoulous and Lioy, 1994). For this example, average exposure is simply the chemical concentration multiplied by exposure duration.

A plot of relative exposure as a function of basement air exchange rate is given in Fig. 7. The term "relative exposure" refers to average exposure using the two-compartment solution divided by the one-compartment solution:

$$\text{Relative exposure} = \frac{C_B f t_{exp} + C_L(1-f)t_{exp}}{C t_{exp}} = \frac{(E/Q_b) f t_{exp} + (E/Q_{out})(1-f)t_{exp}}{(E/Q_{out})t_{exp}} = 1 + f\left(\frac{Q_{out}}{Q_b} - 1\right), \quad (13)$$

where f is the fraction of time spent in the basement, t_{exp} is the exposure time, and C is the concentration in the house using a one-compartment model. Values of f are based on activity pattern data from Tsang and Klepeis (1996), where 1.5 h was the 50th percentile value of cumulative minutes spent in the basement. This would correspond to $f = 0.125$ if 12.0 h were spent inside a house per day. For this example, the total air flow through the system was assumed to be 1 ACH for both one-compartment and two-compartment cases. As the air flow from basement to first floor increased, the one- and two-compartment solutions converged. This is

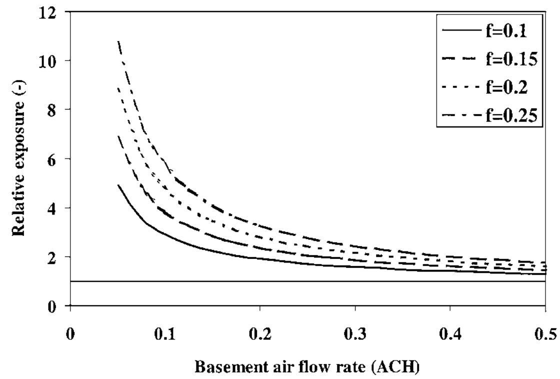

Fig. 7. Relative exposure as a function of basement air exchange rate.

shown by the line in Fig. 7 where relative exposure equals unity. In all cases in Fig. 7, the two-compartment model is characterized by a higher estimated exposure than the one-compartment model. For the one-compartment model, the concentration in the house simplifies to C_L under steady-state conditions (Eq. (8)). Since C_B is greater than C_L when soil vapor intrusion occurs, the estimated exposure will be higher using the two-compartment model. This also implies that the one-compartment model underestimates the total amount of mass in the house at any given time (for the same total air flow through the system). Average exposure using the two-compartment model is approximately a factor of five greater than the one-compartment model in many cases, particularly at lower basement exchange rates where the chemical residence time in the basement is longer.

9. Conclusions

An understanding of the soil gas to indoor air pathway is important for any exposure assessment involving sub-surface contaminants. The overall objective of this research was to present a two-compartment model for estimating residential exposure from the soil to indoor air pathway. To better characterize parameters associated with the two-compartment model, soil gas intrusion rates through building foundations and basement ventilation rates were measured under actual field conditions. Major conclusions and observations stemming from this work include the following:

- The rate of soil vapor intrusion is highly dependent on the pressure difference between soil gas and basement.
- The soil gas to basement pressure difference can be significantly lower than the basement to ambient pressure difference; this finding is particularly relevant as existing models generally assume that the two pressure differences are equivalent.
- The calculated "effective" specific permeability through the foundation was relatively constant for all experiments and approximately equal to 2 darcys.
- Basement ventilation rates ranged from 0.17 to 1.08 ACH for basement to ambient pressure differences ranging from –1.1 to –7.61 Pa (relative to ambient).
- Average chemical exposure from soil vapor intrusion using the two-compartment model is approximately a factor of five greater than the one-compartment model in many cases.

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