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Soil-Gas Contamination and Entry of Volatile Organic Compounds into a House Near a Landfill

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Toxic volatile organic compounds (VOC) are commonly found in landfills, including those accepting only municipal waste. These VOC can migrate away from the site through the soil and result in contaminated off-site soil gas. This contaminated soil gas can enter houses built near landfills and is a potential source of human exposure to VOC.

This study investigated soil-gas contamination and the mechanisms of entry of VOC into a house with a basement sited adjacent to a municipal landfill. The VOC were identified and quantified in the soil gas and in indoor and outdoor air. Pressure coupling between the basement and the surrounding soil was measured. Using soil-gas tracers, the pressure–driven advective entry of soil gas was quantified as a function of basement depressurization. From the measurements, estimates were made for the diffusive and advective entry rates of VOC into the house.

A comparison of the chlorinated hydrocarbons found in soil gas at the site and in the landfill suggests that the landfill is the source of the halogenated compounds in the vicinity of the house. At the conditions of the study, the diffusive and advective entry rates of VOC from soil into the basement were estimated to be low and of similar magnitude. Advective entry of soil gas into the house was limited by the low soil air permeability and the low below-grade leakage area of the basement. For this reason, high indoor concentrations due to the intrusion of VOC from soil gas are unlikely at this house, even under conditions that would produce relatively large underpressures in the basement.

Landfills, including municipal facilities designated to accept only nonhazardous waste, have been found to contain elevated concentrations of toxic volatile organic compounds (VOC). In a recent study of predominantly municipal landfills mandated by the California Air Resources Board (CARB), one or more of the ten toxic VOC selected as indicators of hazardous waste were detected in landfill gas in approximately 70 percent of the 288 sites tested.[1] These VOC can migrate from the landfill site through the subsurface by advective transport in the gas and aqueous phases or by diffusion.

The CARB study provides direct evidence for the subsurface transport of gaseous contaminants away from landfill sites.[1] Perimeter gas wells at 288 landfills were sampled for total organic gases measured as methane. Sixty-four percent of the landfills had perimeter concentrations of total organic gases in excess of 5 ppmv, and 20 percent had concentrations in excess of five percent, the standard which officially defines offsite migration.

If houses are situated in the near vicinity of a site with subsurface gas migration, it is possible under some circumstances for soil-gas contaminants to enter the houses through their substructures. Such entry will result in elevated indoor concentrations of the contaminants.

Evidence for the entry of landfill contaminants into houses is provided by Wood and Porter who detected methane at concentrations approaching one percent in enclosed spaces of houses located near a landfill following an incident of gas migration.[2] In one house 180 m from the landfill, chlorinated hydrocarbons, presumably originating from the landfill, were detected at the entry point for soil gas.

The entry of soil-gas contaminants into houses has been studied in relation to the issue of indoor radon. These studies have demonstrated that radon enters houses by diffusion and by advective transport from the surrounding soil. In single-family residences with elevated indoor concentrations, the dominant entry mechanism is the advective flow of radon-bearing soil gas into the buildings.[3-7] The pressure differential which drives this flow is caused by indoor-outdoor thermal differences, wind loading on the building shell and soil, and unbalanced ventilation systems.[3,6-8] In extreme weather conditions, the depressurization of building substructures can approach −10 Pa.[9] The resulting advective entry of soil gas can constitute a significant portion of the total amount of air infiltrating into a house if the building substructure is sufficiently leaky and

Implications

Since gas in landfills is commonly contaminated with toxic VOC and off-site migration of landfill gas through the subsurface is also common, there may be locations in the vicinity of landfills in which populations are being exposed to elevated levels of VOC in their homes. For the house in this study, the entry rate of VOC was low due to the low soil-air permeability and the low below-grade leakage area of the basement. However, in some circumstances, a large percentage of the ventilation air for a house may derive from the advective entry of soil gas. It is possible that locations with significant potential for elevated indoor exposures via this pathway may be identified from data on off-site migration of contaminants, soil type and housing characteristics.

the soil is sufficiently permeable to soil-air flow.[7]

In this study, the mechanisms involved in the entry of VOC from soil into a single-family residence with a basement were investigated using techniques similar to those employed in the radon studies cited above. The house was located in an area of contaminated soil adjacent to a municipal landfill. Volatile organic compounds were identified and quantified in indoor and outdoor air and in the soil gas surrounding the house. Pressure coupling between the basement and the surrounding soil was measured to determine the region of influence of the house on the soil and to elucidate the entry pathway for soil gas. Using soil-gas tracers, the pressure-driven entry of soil gas was quantified by experimentally depressurizing the basement. From the field measurements, estimates were made for the diffusive and advective entry rates of VOC into the house at normal operating conditions. In a previous report, the results of a numerical model were compared with the measurements of pressure coupling and the pressure-driven entry of soil-gas under experimental conditions.[10]

Experimental

The study was conducted at a single-family residence sited adjacent to the Geer Road Landfill in Stanislaus County, California. This is an active landfill accepting only municipal waste. The landfill is contained by a perimeter berm constructed of soil. The berm lies approximately 70 m from the house at its closest point. The land between the berm and the house is flat. At the time of the study, the region of the landfill nearest the house was full and capped with soil. A plan view of the study site is shown in Figure 1.

The house is a single-story structure built over a basement and a garage. The basement floor is ~2.5 m below grade. The foundation and basement of the house were constructed by excavating the soil, pouring a cement slab with an integral footing, and building up a wall of cement blocks on top of the slab. The cavities in the blocks were back-filled with cement. The exterior of the wall was coated with an asphalt sealant, and the interior of the wall was painted, but otherwise bare. The floor areas of the first floor and the basement are 183 and 103 m^2, respectively. The respective volumes are 430 and 290 m^3. The effective leakage area of the entire house, as measured by the technique of Sherman and Grimsrud, is 0.125 m^2, indicating that the structure is relatively tight.[11] For several months prior to the study and throughout the study, the house was unfurnished and unoccupied.

Investigations were conducted from late July through early November 1987. Data on local wind speed and direction, precipitation, and indoor and outdoor temperatures were continuously collected throughout this period. Precipitation was only 1.5 cm.

The soil surrounding the house was analyzed for particle-size distribution, moisture content, and permeability. Samples for particle-size and moisture analyses were extracted by bucket auger at sampling depths of 0.3 to 2.8 m from three vertical profiles located 4 and 11 m from the west basement wall. Soil-air permeabilities were measured using 30 probes installed in the soil around the house at distances of 0.5 to 7 m from the basement wall and at depths of 1.5 and 3 m. The probes and the in-situ measurement of permeability have previously been described.[7] The probes were also used to measure pressure coupling between the soil and the house and to collect samples of soil gas for analysis of VOC and tracer gases. Probe locations are shown in Figure 1.

The analysis of particle-size distribution, by a standard sieving and sedimentation technique, revealed a range of U.S. Department of Agriculture soil types from loamy sand to silt loam.[12] Horizontal layering was evident in the two profiles farthest from the house. Above 2.4 m, the layers alternated between loamy sand and sandy loam, which has more fine particles. Between a depth of 2.4 to 2.8 m, the soil was silt loam, which is predominantly silt. The profile 0.8 m from the house was relatively uniform loamy sand, probably because this region was excavated and refilled during construction. Moisture content, determined by weighing before and after oven drying, was two to four percent by weight over a depth of 0.5 to 2 m and increased to approximately 12 percent in the silt-loam layer. The mean in-situ soil air permeability at a depth of 1.5 m was 2.5×10^{-12} m^2 with a range of 0.3–20 $\times 10^{-12}$ m^2. This range is consistent with the particle-size composition of the soil.[6] The permeability at a depth of 3 m was similar.

Pressure coupling between the house and the soil at the probe locations was measured in an attempt to define both the region of influence of the house on the surrounding soil and the pathway for entry of soil gas into the house. This measurement was carried out using a previously described technique.[8] With the door between the garage and outdoors open, the door between the basement and the upper floor closed, and the windows and doors on the upper floor open, the basement was held at 25 ± 2 Pa below atmospheric pressure using a large exhaust fan installed in the doorway between the basement and the garage (Figure 1). During depressurization, the pressure differences between the basement and the atmosphere, dP_b, and the soil probes and the atmosphere, dP_s, were measured. The pressure coupling in percent was calculated as $100 * (dP_b - dP_s)/dP_b$.

On a number of occasions during the measurement of pressure coupling, the exhaust fan was switched off or the exhaust flow rate was abruptly changed. Pressures at the soil probes
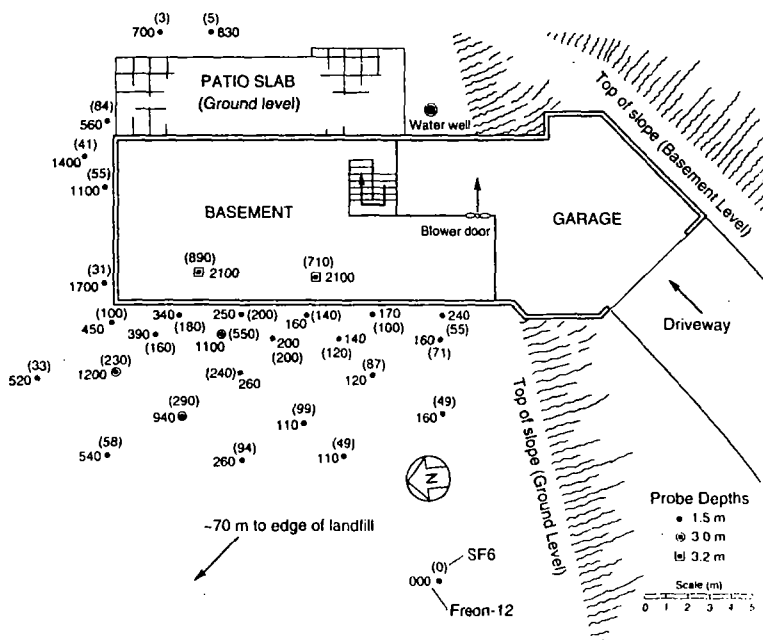

Figure 1. Plan view of the study site and the basement level of the house showing the locations of the soil probes and the concentrations of Freon-12 and SF6 tracer gas in soil gas sampled from each probe in early November.

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responded within a minute of the change in fan mode. This direct response demonstrated that the depressurization at the probes originated at the basement. In addition, pressures at the probes were found to be linear with basement pressure.

Soil-gas entry into the house was measured as a function of basement depressurization using sulfur hexafluoride (SF6) and dichlorodifluoromethane (Freon-12) as soil-gas tracers. In September, a total of 490 cm^3 (3 g) of pure SF6 was injected into five probes to the north and west of the house in approximately equal portions to provide a source of labeled soil gas. By early November, when the measurement was conducted, the SF6 had diffused over much of the probe field. Freon-12 was found to be present throughout the probe field as a soil-gas contaminant.

Immediately prior to the measurement of soil-gas entry, soil gas at each of the probe locations was analyzed for SF6 and Freon-12. First, a volume of soil gas equal to two probe volumes was vented from a probe; then, duplicate samples were collected using plastic syringes. Analyses were conducted on-site with a gas chromatograph (GC) equipped with an electron-capture detector (ECD) and a molecular sieve 5A column. Meanwhile, the basement was thoroughly ventilated to reduce indoor concentrations of the soil-gas tracers to outdoor levels by running the exhaust fan at high speed for an extended period with the interior door to the upper floor, and all windows and doors on the upper floor, open. The door to the upper floor and all of the heating ducts in the basement were then closed, and the GC-ECD was set up to automatically sample and analyze basement air for SF6 and Freon-12 at one-minute intervals. The exhaust fan was operated to depressurize the basement in stages by 20, 30, 40 and 50 Pa relative to atmospheric pressure. Each stage of depressurization was maintained long enough to achieve near steady-state concentrations of the analytes in the basement.

Samples for analysis of VOC were collected on three occasions during the study. A preliminary qualitative survey of soil gas, outdoor air, and basement air was conducted in July. In September, samples for both qualitative and quantitative analyses were obtained from several soil probes and from outdoor and basement air. In October, samples for quantitative analysis only were collected from four soil probes and from indoor air in both the basement and the upper floor. Samples of outdoor air were omitted in October since the number of samples that could be collected and analyzed was limited and outdoor VOC concentrations in September were generally very low.

Samples for qualitative and quantitative analysis of VOC were collected and analyzed using previously described methods.[13] In brief, samples were collected on multisorbent samplers containing Tenax-TA, Ambersorb XE-340 and activated charcoal in series. Sampling flow rates of ~100 cm^3 min^{-1} (20°C, 760 torr) were regulated with electronic mass-flow controllers. Sample volumes for soil gas, outdoor air and indoor air were typically 0.23, 5.6 and 2.5–5.6 L, respectively. Single samples were collected for qualitative analysis. Duplicate samples were simultaneously collected for quantitative analysis. A volume of air equal to two probe volumes was vented from each soil probe before samples of soil gas were collected.

For analysis, a sample was thermally desorbed with a sample concentrating and inletting system (UNACON Model 810A, Envirochem Inc.) and injected into a GC equipped with a capillary column (DB-1701, J & W Scientific, Inc.). The GC was connected via a direct capillary interface to a Mass Selective Detector (MSD, Series 5970B, Hewlett-Packard Co.). For qualitative analyses, the MSD was scanned over a mass range of 33–250 m/z. Compounds were identified using mass spectral data bases, and identifications were confirmed, in most cases, by analyses of authentic standards. For quantitative analyses, the MSD was operated in the selected-ion-monitoring mode. Multi-point calibration curves were constructed using authentic standards.

Results

Volatile Organic Compounds

Twenty-six individual VOC were identified in samples of soil gas collected in July and September. In general, halogenated hydrocarbons and oxidized compounds were the dominant classes, both in terms of the numbers of compounds and the relative chromatographic (total-ion-current) peak areas of the compounds. Based on the qualitative results for these samples, 14 individual VOC were selected for quantitative analysis in samples of soil gas and indoor and outdoor air collected in September and October. These compounds are representative of the major hydrocarbons, halogenated hydrocarbons and oxidized compounds found in soil gas at the site. The concentrations of the compounds are summarized in Table I. It is notable that the range of soil-gas concentrations for many of the dominant compounds was relatively broad in both sampling periods.

There is a difference in the composition of VOC in the soil probes between the September and October sampling periods. In September, three compounds, Freon-12, Freon-11, and tetrachloroethylene, had average soil-gas concentrations in excess of 20 ppbv. In October, dichloromethane, acetone, hexanal, 2-methylbutane, and toluene also had concentrations in excess of this level. Even though two of the probe locations were common to both sampling periods, the concentration ranges for September and October do not overlap for any of these five compounds. The reason for this apparent temporal change in soil-gas composition is unknown.

The soil-gas concentration of Freon-12, which was measured at all probe locations by GC-ECD (Figure 1), is perhaps representative of the spatial variability in the distribution of VOC in soil gas at the site. The average concentration of Freon-12 for the site was 450 ppbv with individual concentrations ranging from 100 to 2,100 ppbv. As shown in the figure, the 3-m deep probes had concentrations considerably higher than the average, and concentrations on the north and east sides of the house were higher than on the west side, which averaged 250 ppbv. It is probable that the spatial variations of Freon-12 and of the other VOC in Table I arose from a combination of interrelated factors, such as the degree of coupling with the source (presumed to be the landfill), the presence of relatively impermeable layers in the soil as discussed in Reference 10 and other boundaries limiting transport to the surface, spatial variations in the sorptive capacity of the soil for VOC, and the degree of protection from the wind.

Thirteen of the 14 compounds quantified in soil gas in September and October were also detected in indoor air (Table I). With the exception of acetone, the concentrations of VOC in the house were low (6 ppbv or less) and did not change appreciably between the sampling periods. The high concentration of acetone in October was attributed to a source of this compound brought into the house by the investigators. In October, concentrations of VOC in the basement were compared to concentrations in a bedroom on the upper floor. All of the compounds had nearly equivalent concentrations in the basement and the bedroom. This similarity in concentrations of VOC between floors suggests that the air in the house is well-mixed when the house is in a closed condition, at least during periods of low infiltration. Concentrations measured in outdoor air in September, with the exception of acetone, were all less than 1 ppbv.

	Concentration (ppbv)							
	September				October			
	Soil gas[a]				Soil gas[b]			
Compound	Range	Avg	Basement	Outdoor air	Range	Avg	Basement	Bedroom
Halogenated Hydrocarbons								
Freon-12	230–920	550	2.3	0.2	110–340	190	3.5	2.3
Freon-11	7.6–110	46	0.8	0.3	42–230	140	0.8	1.3
Dichloromethane	<0.1–2.1	0.7	1.2	0.1	50–200	120	3.9	5.4
1,1,1-Trichloroethane	1.4–11	4.9	0.7	0.3	2.8–9.4	6.1	0.6	0.7
Tetrachloroethylene	23–150	70	0.7	0.1	26–79	56	0.8	0.8
Oxidized Compounds								
Acetone	16–27	20	12	4.9	190–370	250	82	15
Hexanal	3.3–7.9	6.1	1.0	ND[c]	37–52	42	1.5	1.9
4-Methyl-3-penten-2-one	<0.1–10	3.4	ND	ND	ND	—	ND	ND
3-Heptanone	<0.1–6.8	4.2	0.6	ND	7.8–15	9.9	ND	ND
Hydrocarbons								
2-Methylbutane	ND	—	5.2	0.3	14–74	36	4.4	5.0
Toluene	2.1–3.6	14	4.4	1.1	40–92	70	4.8	4.4
Ethylbenzene	ND	—	0.6	ND	2.8–3.6	3.3	0.8	0.7
m-,p-Xylene	ND	—	1.9	ND	9.3–12	11	2.7	2.3
o-Xylene	0.2–1.7	0.7	1.0	0.2	3.4–7.2	5.8	1.6	1.2

[a]Soil probes AW2, CW2 and B2.
[b]Soil probes AW2, CW2, DE1 and DE2.
[c]Not present above detection limit of ~0.1 ppbv.

Entry of Volatile Organic Compounds into the Basement

The measurements of pressure coupling, described in detail in Reference 10, were used to estimate the distribution of the leakage area over the basement shell. An average pressure coupling of 30 percent was measured in the probes 0.5 m from the west and north basement walls, with a range of 4–44 percent. Pressure coupling was fairly evenly distributed along the two walls. This indicates that the entry of soil gas was probably not localized at only a few points as was observed in earlier studies.[5,8] Instead, entry was probably more evenly distributed over the basement shell, at least in the horizontal plane. This conclusion is supported by numerical modeling.[10] The results of this modeling demonstrated that entry probably occurred through the semi-permeable cement-block basement walls, distributed over their area, rather than through a gap at the wall-floor interface, as is assumed in other models.[14,15] The floor would not contribute significantly to entry because of the lack of penetrations and the very low air permeability of a poured concrete slab.

The soil tracer gases, SF6 and Freon-12, were used as surrogates for VOC to assess the magnitude of VOC entry into the basement. The concentrations of both tracers in the soil gas at all of the probes are shown in Figure 1. Since the pathway for the entry of soil gases into the house is apparently distributed over the basement walls, the concentrations of the tracer gases for use in estimating the entry of VOC by diffusion and advective transport were obtained by first averaging the concentrations of SF6 and Freon-12 in the probes nearest each of three walls that are adjoined by soil. For the west and north walls, the concentrations in the 1.5-m deep probes 0.5 m from the walls were averaged. For the east wall, the concentrations in the 1.5-m deep probes next to the patio were averaged since the presence of the patio prohibited measurements adjacent to the wall. These values were then weighted by the lengths of their respective walls and averaged. This yielded weighted-average tracer-gas concentrations contributing to entry by diffusion and advective transport of 74 ppbv for SF6 and 620 ppbv for Freon-12. The spatial heterogeneity of the tracer-gas concentrations in the soil and the possibility that the pathway for entry of gases is not entirely uniform over the basement walls introduce considerable uncertainty into these estimates.

During the study period, the average indoor-outdoor temperature differential was approximately 6° C, and the average wind speed was 2 m s^{-1}. At these moderate natural conditions, the maximum underpressurization of the basement would be expected to be on the order of only several Pa. Due to this lack of a strong driving force for advective transport and the apparently low effective leakage area between the basement and the soil, it is reasonable to assume that entry of VOC into the basement from the soil would be dominated by diffusion under the natural conditions at the time of the study.

The calculation of the diffusive entry rate for a compound requires that its diffusion coefficient in the cement-block wall be measured or estimated. Since no measurements were available, the diffusion coefficient for Freon-12 in the cement-block wall was approximated based on data for radon. The diffusion coefficients of radon in poured cement and in soil have been reported to be 7×10^{-6} and 7×10^{-3} m^2 h^{-1}, respectively.[6,16] It was presumed that cement blocks are considerably more permissive of air flow than poured cement but less permissive than typical soils. Adjusting for the difference in the molecular diffusivities of radon and Freon-12 in air, the diffusion coefficient for Freon-12 in the cement block was approximated to be in the range of 10^{-3}–10^{-4} m^2 h^{-1}. Using this range, the weighted average soil-gas concentration of Freon-12 of 620 ppbv, an indoor concentration of 3 ppbv, a cross-sectional area of 99 m^2 (the area of the three sides of the basement wall), and a diffusion path length of 15 cm (the thickness of the cement-block wall), the diffusive flux of Freon-12 into the basement was estimated to be approximately 200–2000 ug h^{-1}. This is equivalent to an advective entry rate of soil gas containing the same concentration of Freon 12 of about 0.1 to 1 m^3 h^{-1}.

The advective entry rate of soil gas into the house as a function of basement underpressure was determined from the depressurization experiment. Immediately prior to initiating this experiment, the measured background concentrations of the tracers SF6 and Freon-12 were below detection and 1 ppbv, respectively, in the basement, the open upper floor of the house, and

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outdoors near the basement sill plate. During depressurization, air flow into the basement was detected at the electrical outlet boxes, which were recessed into cavities cut into the cement blocks near the bottom of the wall. The average concentrations of SF6 and Freon-12 in air samples collected from the cavities on the west wall were about 90 and 200 ppbv, respectively. These concentrations were similar to the average concentrations measured in the soil adjacent to this wall (Figure 1), indicating that air entering the basement from the walls had its origin in the soil and that the induced flow probably did not significantly dilute the soil-gas concentrations.

A simple mass-balance model assuming steady-state conditions was applied to the concentrations of SF6 and Freon-12 measured at the end of each depressurization stage. Setting the mass flow of a tracer gas in the exhaust air equal to the mass flow of the gas in the air entering the basement gives:

$$Q_f C_f = Q_s C_s + Q_o C_o \qquad (1)$$

The C_f is the steady-state concentration of the tracer gas in the basement, and C_s and C_o are the concentrations in the soil gas and outdoor air, respectively. The corresponding flow rates of soil gas and outdoor air are Q_s and Q_o. The ventilation rate of the basement, Q_f, is simply the calibrated flow rate of the exhaust fan. Solving for Q_s, and letting $Q_f = Q_s + Q_o$ yields:

$$Q_s = Q_f \frac{C_f - C_o}{C_s - C_o} \qquad (2)$$

Soil-gas entry rates (Q_s) at each applied basement underpressure were calculated from Equation 2 for both SF6 and Freon-12 using the weighted-average soil-gas concentrations. The results are shown in Figure 2. Although the relationship between entry rate and pressure is approximately linear for both compounds, the underlying uncertainties discussed above significantly limit the precisions of the estimated entry rates. These uncertainties are represented in the figure by assuming that the effective concentrations of the tracer gases in the soil gas near the basement walls have precisions of plus or minus one half the calculated weighted-average concentrations. Within the resulting confidence intervals, there is a region of overlap between the two compounds that defines the best estimate of the soil-gas entry rate. The fact that the estimated entry rates based on Freon-12 are higher than those based on SF6 suggest that entry might be somewhat higher on the north side of the house where Freon-12 concentrations are higher than their average, and SF6 concentrations are lower.
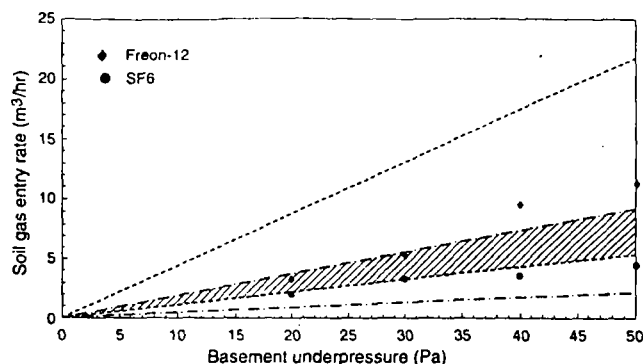
The relationship shown in Figure 2

Figure 2. Advective entry rates of soil gas into the basement as a function of basement depressurization relative to atmospheric pressure. The entry rates were estimated using a mass-balance model and concentrations of Freon-12 and SF6 tracer gas. The best estimate of the entry rate is given by the region of overlap for the two compounds (shaded area).

demonstrates that the minor underpressures of several Pa that would be expected to develop in the basement relative to the surrounding soil at the moderate conditions of the study would result in a probable entry rate of soil gas of less than 0.5 m³ h⁻¹. Therefore, the advective entry of soil gas contaminants would be approximately equivalent to diffusive entry at these conditions.

For comparison, an effective soil-gas entry rate (Q_s) at the natural conditions of the study was estimated from the concentrations of VOC measured in September and October. The total house infiltration rate at these conditions was predicted to be about 200 m³ h⁻¹ (0.2 air changes per hour).[11] This infiltration rate was substituted for Q_f in Equation 2. For each compound detected in the house, the equation was solved for Q_s assuming the whole-house concentration equaled the basement concentration in September and using a weighted whole-house concentration in October. The average value of Q_s for Freon-12, Freon-11 and tetrachloroethylene was 1.5 m³ h⁻¹ with a relative standard deviation of 50 percent (n = 6). This average is within the range of the combined diffusive

and advective entry rates that were estimated above. For the other compounds, this approach generally predicted entry rates that were one to two orders of magnitude higher. This result was interpreted as indicating the existence of indoor sources for these compounds.

Discussion

Data on the subsurface gas concentrations of selected toxic VOC in the Geer Road Landfill are available from the Landfill Gas Testing Program of the California Air Resources Board.[1] Samples collected in 1987, just prior to the present study, from five gas-sampling wells within the landfill were analyzed for ten VOC plus methane. The targeted compounds and their concentration ranges in the landfill gas are shown in Table II. The compounds with the highest concentrations in landfill gas are dichloromethane, 1,1,1-trichloroethane, tetrachloroethylene, and vinyl chloride. With the exception of vinyl chloride, which was not quantified by the present study, these chlorinated compounds also occurred as contaminants in soil gas near the house. The maximum soil-gas concen-

Table II. Concentrations of methane and ten toxic VOC in landfill gas compared with concentrations of methane in soil gas at the perimeter of the landfill and with concentrations of VOC in soil gas near the house.

Compound	Conc. range landfill gas[a] (ppbv)	Conc. range soil gas (ppbv)	Max. soil gas/max. landfill gas
Methane	180,000–500,000ppmv	2–1000 ppmv (Perimeter)	0.002
Dichloromethane	2,500–51,000	<0.1–2000	0.004
1,1,1-Trichloroethane	<10–13,000	1.4–11	0.001
Tetrachloroethylene	620–18,000	23–150	0.008
Vinyl chloride	<500–19,000	NM[b]	—
1,2-Dichloroethane	<20–850	NM	—
1,2-Dibromoethane	<1	NM	—
Trichloromethane	<2–980	NM	—
Tetrachloromethane	<5	NM	—
Trichloroethylene	1,600–8,300	NM	—
Benzene	890–4,500	NM	—

[a]Landfill gas and perimeter soil gas concentrations are from Reference 1.
[b]Either not measured or not present above limit of detection of ~0.1 ppbv at study site.

trations of the three compounds are two to three orders of magnitude lower than their respective maximum landfill-gas concentrations (Table II). Concentrations of methane at 12 gas wells around the perimeter of the landfill, which were also analyzed as part of the Landfill Gas Testing Program, are reduced by about the same magnitude relative to the landfill (Table II). These limited data suggest that the air-injection pumps, which are installed around the perimeter of the landfill may significantly reduce, but not completely eliminate, subsurface gas migration away from the landfill.

The two Freons, which were dominant contaminants in soil gas near the house, were not measured by the Landfill Gas Testing Program. However, Freons can be expected to occur in municipal landfills at relatively high concentrations because of their widespread use as refrigerants, as blowing agents for various polymer foams, and, in the past, as aerosol propellants. Therefore, it is reasonable to assume that the landfill was also the source of the Freons.

Our data are generally consistent with the observations of Wood and Porter.[2] They measured concentrations of VOC in soil gas near the periphery of a different landfill and indoors at the entry point of soil gas into a house about 180 m away. Concentrations of tetrachloroethylene and 1,1,1-trichloroethane, which were detected at both locations, were about two orders of magnitude lower at the entry point than at the landfill periphery. At another site, the qualitative change in the composition of soil gas with distance beyond a landfill perimeter was investigated. The first compounds to disappear with distance were the oxidized compounds followed by the aromatic compounds, the other hydrocarbons, and the chlorinated hydrocarbons. Tetrachloroethylene was among the most persistent compounds. Similarly, this compound had the highest soil-gas to landfill-gas concentration ratio in the present study.

Since the study house was unoccupied and unfurnished, the indoor sources of VOC should have been significantly reduced relative to typical occupied residences. Nevertheless, a number of commonly occurring compounds were detected in indoor air at concentrations that exceeded their respective concentrations in outdoor air. The indoor concentrations are in the low to sub part-per-billion range and are generally typical of median indoor concentrations measured in the U.S.[17] It is probable that the soil gas was a relatively significant source of at least the compounds that were elevated in soil gas. However, this cannot be determined with certainty because of the

low concentrations and the almost ubiquitous occurrence of the compounds in residential environments.

The highest advective entry of soil-gas contaminants into the basement would be expected to occur in the winter. Under winter heating conditions, basements of houses are typically underpressurized relative to the surrounding soil by about 3 to 5 Pa with 10 Pa being a high value.[9] In the study house, an underpressure of 5 Pa would result in a predicted soil-gas entry rate in the range of approximately 0.5 to 1 m^3 h^{-1} based on the relationship in Figure 2. The diffusive flux of VOC would not be affected as long as the soil-gas concentrations remained the same.

The potential impact on indoor air quality of the advective transport of VOC into the house in the winter can be assessed by comparing the predicted soil-gas entry rate with the total house infiltration rate to determine the fraction of soil gas in indoor air. A winter-time infiltration rate was estimated using the model of Sherman and Grimsrud.[11] Given the measured effective leakage area of the house, an average wind speed of 4 m s^{-1}, and an indoor-outdoor temperature differential of 22° C, the model predicts a total house infiltration rate of about 500 m^3 h^{-1} (0.7 air changes per hour). Therefore, soil gas entering the basement and completely mixing throughout the house would be diluted with outdoor air by about three orders of magnitude. Thus, a concentration of a contaminant in soil gas of 1 ppmv would be expected to result in an average increase in the concentration of the contaminant in the house of about 1 ppbv.

The advective entry of soil gas into the study house is limited by the relatively low permeability of the soil at the site and the relatively small leakage area between the basement and the soil. These factors are actually coupled since low soil permeability will result in a low below-grade effective leakage area. Low advective entry at this site is consistent with studies of radon entry into houses, which predict relatively low advective flux for soils with permeabilities lower than about 10^{-11} m^2.[6,18]

For houses sited in more permeable soils and with larger below-grade leakage areas, the fractional contribution of the advective entry of soil gas to the total infiltration rate can be significantly larger. This was demonstrated in a study of 15 houses in the Pacific Northwest with elevated indoor concentrations of radon.[7] These houses were sited in soils with a geometric mean permeability of 5×10^{-11} m^2. The high soil permeability was largely responsible for the high entry rates for

radon. From the radon data, the estimated ratio of soil-gas entry to the total infiltration rate for the 15 houses ranged from 1 to 21 percent with a median of four percent.

Conclusions

The Landfill Gas Testing Program of the State of California has demonstrated that landfills typically contain toxic VOC regardless of the type of waste they are designated to accept and that off-site migration of landfill gas is a fairly common occurrence.[1] Studies of radon entry into houses have demonstrated that the advective entry of soil gas into substructures can constitute a significant portion of total air infiltrating into a house under the right combination of soil air permeability, structural factors and weather conditions.[7] In some circumstances, the ratio of the soil-gas entry rate to the total infiltration rate of a house can be as high as 20 percent. Therefore, it is reasonable to assume that there are situations in which the indoor air quality of houses in the vicinity of landfills and hazardous waste sites is being significantly affected by soil-gas contamination. It is further possible that in some situations, this contamination is a dominant source of occupant exposures to VOC.

Fortunately, the existence of soil-gas contamination alone is not sufficient to result in significantly elevated indoor exposures. This was demonstrated by the present study. The house was sited in soil contaminated with VOC which presumably originated from the adjacent municipal landfill. However, the entry rate of these VOC from the soil into this house was demonstrated to be low. The limited entry that occurred at the conditions of the study was apparently the result of diffusive and advective flux of VOC though the cement blocks used to construct the basement walls, with both mechanisms being of similar magnitude. The pressure-driven advective entry of soil gas into the basement was restricted by the relatively low soil permeability and the relatively low below-grade leakage area of the house. Higher pressure-driven entry would be expected to occur in the winter; although only moderate increases in indoor concentrations of VOC in this house are predicted from the experimental data.

There is a general need to attempt to identify residential sites with the highest potentials for significantly elevated indoor exposures resulting from soil-gas contamination. This might best be accomplished by assessing available data on off-site gas migration, the soil type and the size and construction characteristics of the housing stock in

fills and waste sites on a site-by-site basis. If high-risk areas are identified, studies could be conducted in these areas to determine if the advective entry of soil gas into substructures is resulting in significantly elevated indoor exposures to VOC.

Acknowledgment

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