#4579

88-95B.1

TRANSPORT OF VOLATILE ORGANIC COMPOUNDS FROM SOIL INTO A RESIDENTIAL BASEMENT

ALFRED T. HODGSON
KARINA GARBESI
RICHARD G. SEXTRO
JOAN M. DAISEY

UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

APCA
FOUNDED IN 1907
The Association
Dedicated to
Air Pollution Control and
Hazardous Waste Management

**For Presentation at the
81st Annual Meeting of APCA
Dallas, Texas
June 19-24, 1988**

ABSTRACT: The objective of this study was to assess the importance of pressure-driven flow of soil gas into the basement of a house adjacent to a municipal landfill as an entry mechanism for volatile organic compounds (VOC). Twenty-six VOC were identified in soil gas. The concentrations of many of these compounds were much higher in soil gas than in outdoor and indoor air. Measurement of the pressure field developed in the soil around the house while the basement was depressurized with an exhaust fan showed that soil gas, up to a distance of 12 m from the house, was well coupled with basement air. However, monitoring of the movement of tracer gas from the soil into the basement with depressurization demonstrated that the convective flow of soil gas into the basement would be negligible at typical operating conditions. This flow was limited by the relatively low permeability of the soil ($\sim 2 \times 10^{-12}$ m^2). Although diffusion is probably the dominant entry mechanism for VOC in soil gas at this particular house, pressure-driven flow can be an important entry mechanism under conditions of high pressure coupling, more permeable soil, and high concentrations of VOC in soil gas.

INTRODUCTION

The entry of soil gas into houses built on or near landfills is just beginning to be recognized as a potentially important source of contaminants in the indoor environment. Even municipal landfills accepting only nonhazardous material have been found to contain toxic volatile organic compounds (VOC) at elevated concentrations. In a study by Wood and Porter,[1] vinyl chloride and benzene were detected in landfill gas in 85 percent of 20 municipal landfills investigated, often at concentrations exceeding 1 ppm. Several landfills closed for many years were among those with elevated concentrations of these compounds. They concluded that while only some landfills are currently impacting nearby residents, there is a potential for indoor exposure at a large percentage of sites due to subsurface gas migration.

The entry of soil gas into houses has been studied in relation to the issue of indoor radon. It has been demonstrated that convective flow of soil gas into substructures is the primary source of radon gas in single-family residences with elevated concentrations.[2,3] This flow is driven by depressurization of the substructure with respect to the surrounding soil. Depressurization of a few Pascals results from the stack effect caused by thermal differences between indoors and outdoors and from the Bernoulli effect from wind loading on the building superstructure.[4,5] If the soil is sufficiently permeable, a persistent pressure differential can draw soil-gas bearing contaminants into a house at a higher rate than would be predicted by diffusion alone. In one field study, pressure coupling between basements and surrounding soil was measured, and the entry of soil gas was demonstrated using a tracer-gas technique.[5] While significant differences from radon are expected due to differences in the physical and chemical properties of VOC, it is clear that VOC in soil gas around landfills can enter houses via the same convective-flow pathway.

The primary objective of this study was to assess the importance of pressure-driven flow of soil gas in the entry of VOC into a house with a basement adjacent to a municipal landfill. The study consisted of two interrelated components. In the first, the physical mechanisms of soil-gas entry were investigated using two techniques: 1) measurement of the pressure field developed in the soil around the house while the basement was depressurized with an exhaust fan, and 2) monitoring of the movement of tracer gas from the soil into the basement with depressurization. Contamination of soil gas and indoor-air quality were examined in the second component by means of measurements of VOC in soil gas, outdoor air and indoor air. No attempt was made to evaluate the potential health hazards to former occupants nor was any attempt made to investigate the effects of changes in in the operation of the landfill on concentrations of VOC at the site.

METHODS

Description of Study Site

The study site was an unoccupied, single-family residence in Central California located adjacent to a covered municipal landfill. There was previous evidence of migration of landfill gas and VOC from the landfill to the site. In 1983, the county, which operates the landfill, installed air-injection pumps at the perimeter of the landfill to contain methane which was detected at this house and other nearby residences. Samples of well water collected by several agencies at the site from 1985 through 1986 were found to contain Freon-12, Freon-11, tetrachloroethylene and other halogenated compounds.

The residence was constructed in 1977 after the landfill had begun operation. It is a three-bedroom, one-story structure built over a garage and a basement which is below grade. The foundation and basement of the house were constructed by excavating the soil, pouring a cement slab and building up a cement-block wall on top of the slab. The cavities in the wall were backfilled with cement, and the exterior of the wall was sealed with an asphalt-based product. The interior of the wall and the floor were painted. The areas of the first floor and the basement are 183 and 103 m^2, respectively. A plan view of the house and site is shown in Figure 1. The berm containing the landfill is approximately 70 m to the west of the house at its closest point. The land between the berm and the house is flat and covered with grass. The land immediately to the east of the house slopes steeply downward for a vertical drop of approximately 10 m. The prevailing wind during the study was from the direction of the landfill.

Investigations at the site were conducted over a period of about four months from late July through early November, 1987. Thus, the study was largely conducted during the hot, dry summer season. There was only 1.5 cm of rainfall which occurred in the last two weeks of October. Rainfall during the preceding winter was low.

Sampling and Characterization of Soil

In late October, eighteen soil samples were extracted by bucket auger from three vertical profiles located 0.8, 4.3 and 10.7 m from the west basement wall. Sampling depths ranged between 0.3 and 2.8 m. The samples were sealed in moisture proof containers at the time of collection and were refrigerated within six hours. The moisture content of the samples was determined by weighing subsamples before and after drying to constant weight at 110°C. Samples were analyzed for particle-size distribution using standard sieving and hygrometer-technique sedimentation analyses.[6]

Construction and Installation of Soil Probes

Soil probes were installed at the site and were used in experiments to determine in-situ permeability of the soil, pressure-coupling between the basement and the soil, soil-gas entry into the basement, and concentrations of VOC in soil gas. Thirty probes were installed around the house at distances ranging from 0.5 to 12 m from the basement wall and at depths ranging between 1 and 3 m (Figure 1). The majority of these probes terminated at a depth of 1.5 m and were located to the west of the house between the house and the landfill. No probes were installed to the south of the house which was distant from the basement. Two probes were installed through the basement floor.

The soil probes consisted of 2- or 3-m lengths of 13-mm OD, 9-mm ID galvanized steel pipe open at both ends with the outlet end threaded to accommodate pipe-to-tube connectors. A guide hole was drilled in the soil prior to installation of a probe in order to minimize disturbance of the soil. A stainless steel rod was inserted into the probe so that it extended 1 cm beyond the inlet end. The pair was then driven into the soil to the desired depth using a sledge hammer. After installation, the center rod was removed, and the inlet was augered to break up compacted soil. During both drilling and hammering, distinct soil layers offering greater or less resistance were detected. Probes were generally terminated in a relatively low resistance, presumably more permeable, layer. Soil probes were capped at the outlet when not in use.

Measurement of In-situ Permeability

The in-situ permeability of the soil was measured at the soil probes using the technique suggested by DMSA.[7] Because there is no discrimination in flow direction, this technique gives an effective permeability. In brief, a regulated flow of compressed air was directed into the soil through a probe while measuring the air flow rate and the pressure difference between the soil and the ambient air. A diaphragm differential-pressure gauge (0-125 Pa, Dwyer Instr., Inc.) and either a microflowmeter (0-15 $cm^3 min^{-1}$) or a rotameter (0-450 $cm^3 min^{-1}$) were used to measure pressure and flow rate. Permeability, which assumes Darcy flow, is calculated from:

$$k = \frac{Q\mu}{4\pi R}, \tag{1}$$

where:

k = permeability (m^2);
μ = viscosity of air (1.83×10^{-5} kg m^{-1} s^{-1});
P = probe pressure (Pa);
Q = flow rate (m^3 s^{-1}); and
r = radius of the probe (4.5×10^{-3} m).

Permeabilities down to as low as approximately 10^{-14} m^2 can be determined at which point the flow rates become too small to measure at reasonable applied pressures. The measurements are accurate to better than a factor of two, there being some observed variation in apparent permeability with applied pressure.

Measurement of Pressure Coupling

Pressure coupling between the basement and the soil was determined using the technique of Nazaroff *et al.*[6] (1987). A large exhaust fan (blower door), typically used to make leakage-area measurements in houses, was installed in the doorway between the basement and the garage (Figure 1). With the garage door open, the door between the basement and the upper floor closed, and the windows and doors on the upper floor open, the fan was operated to achieve a basement depressurization with respect to outdoor air of -25 Pa. This pressure was measured with a diaphragm differential-pressure gauge (0-60 Pa) and was maintained to within 2 Pa. With the basement at the desired pressure, differential pressures with respect to outdoor air were measured in the soil probes using a variable reluctance pressure transducer (Model DP103, Validyne Instr., Inc.). The pressure transducer was calibrated in the field and was periodically checked during use with a micromanometer.

Estimation of Soil-gas Entry into the Basement

An experiment was conducted to estimate the entry rate of soil gas into the basement as a function of basement depressurization. The purpose of this experiment was to obtain an order-of-magnitude estimate of pressure-driven inflow of soil gas under typical operating and environmental conditions. Pure sulfur hexafluoride (SF_6) was injected into the soil around the house to provide a source of labeled soil gas. In September, a total of 490 cm^3 of SF_6 was injected into five soil probes to the north and west of the house (probes AN2, AW2, BW3, BW4 and BW5) in approximately equal portions. The experiment was conducted one month later in October after the SF_6 had diffused over most of the soil-probe field.

Shortly before beginning the experiment, duplicate samples of soil gas were collected from each probe using plastic syringes. The concentrations of SF_6 and Freon-12, a soil-gas contaminant present at the site at relatively high concentrations, were measured with an on-site, transportable gas chromatograph (GC) (Model 1030A, Baseline Industries, Inc.) equipped with an electron capture detector (ECD), a gas sampling loop and valve, and a molecular sieve (5A) column. Before the samples were collected, a volume of air equal to two probe volumes was withdrawn from the probe and discarded.

Meanwhile, the basement was thoroughly ventilated 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. Then the door to the upper floor and all of the heating ducts in the basement were closed, and the GC-ECD was set up to automatically sample and analyze basement air for SF_6 and Freon-12 at one-minute intervals. The exhaust fan was operated to produce pressures in the basement of -20, -30, -40 and -50 Pa relative to ambient pressure. Each stage of depressurization was maintained long enough to achieve near steady-state conditions.

Sampling and Analysis of VOC

Samples of soil gas, outdoor air, and indoor air for qualitative and quantitative analysis of VOC were collected and analyzed using previously described methods.[8,9] Samples were collected on multisorbent samplers containing Tenax-TA, Ambersorb XE-340 and activated charcoal (Part No. ST-032, Envirochem, Inc.). Sampling flow rates were 113 cm^3 min^{-1} (20°C, 760 torr). Flow rates were regulated with electronic mass-flow controllers placed between the samplers and a diaphragm vacuum pump. 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 analyses at each sampling location. For quantitative analyses, duplicate samples were collected. Before samples of soil gas were collected from a soil probe, a volume of air equal to two probe volumes was withdrawn and vented. Soil gas was then drawn through either one or two parallel, in-line samplers.

Samples for VOC were collected on three occasions during the study. A preliminary survey was conducted in July in which samples for qualitative analysis only were obtained from two soil probes, outdoor air between the house and the landfill, and basement air. In September, samples for both qualitative and quantitative analyses were collected. Qualitative samples were obtained from one soil probe, outdoor air, and basement air at ambient pressure and at a depressurization of -20 Pa. Quantitative samples were collected from three soil probes, outdoor air and basement air at ambient pressure. In the final sampling period in October, samples for quantitative analysis only were collected from four soil probes and indoor air in both the basement and the upper floor of the house. Prior to this period, the house had been closed for four weeks with the door between the basement and the upper floor closed. Samples were collected immediately after entering the house and before significant ventilation due to opening and closing of doors had occurred.

For analysis, a sample is thermally desorbed from the sampler and introduced into a capillary GC with a UNACON Model 810A (Envirochem, Inc.) sample concentrating and inletting system. Sample components are resolved with a GC (5790A Series, Hewlett-Packard Co.) equipped with liquid nitrogen subambient cooling and a fused-silica capillary column (DB-1701, J & W Scientific, Inc.). The GC is connected via a direct capillary interface to a 5970B Series Mass Selective Detector (MSD) (Hewlett-Packard Co.). For qualitative analyses, the MSD is continuously scanned from *m/z* 33 to *m/z* 250. For quantitative analyses the MSD is operated to monitor multiple, individually selected mass ions.

RESULTS AND DISCUSSION

Soil Characteristics

The range of soil type at the site as characterized by the sieving and sedimentation analyses is loamy sand to silt loam. Samples taken from the vertical profile 0.8 m distant from the basement wall were of a single soil type, loamy sand. Uniformity of soil type in this profile was expected since the profile was within the region that was backfilled after construction of the basement wall. Some horizontal layering of the soil was evident in the vertical profiles 4.3 and 10.7 m distant from the house. Above the 2.4 m horizon, the layers variously alternated between loamy sand and sandy loam. Below 2.4 m, the soil was the less permeable silt loam. The water content of the soil increased from approximately two to four percent by weight over a depth range of 0.5 to 2 m. The water content of the deep silt-loam layer was approximately 12 percent.

The in-situ soil permeabilities calculated from the field data using equation (1) are presented in Table I. The mean permeability at a depth of approximately 1.5 m is 2.4×10^{-12} m^2 with a range of $0.3\text{-}20 \times 10^{-12}$ m^2. The permeability at the three, 3 m deep probes is not appreciably different. Since the soil probes were terminated in soil layers of apparent higher permeability, based upon resistance to insertion, the calculated mean permeability may somewhat exceed the actual average permeability of the soil. The range of permeabilities measured at the site is in agreement with the particle-size composition of the soil described above. Nazaroff *et al.*,[10] for example, report that permeabilities for uniform fine sands to uniform silts are typically in the range of 5×10^{-12} to 5×10^{-14} m^2.

Pressure Coupling between the Basement and Soil

With the basement depressurized, a pressure field was propagated through the soil around the house and was measured at the soil probes. Pressures in the probes are presented in Table I as percentages of basement depressurization. Pressure coupling 0.5 m from the basement wall was typically 30-40 percent, and, as expected, there was a general decrease in pressure coupling with increasing distance from the basement wall. Significant pressure coupling, in excess of ten percent, was observed 7 to 12 m away from the house. Similar results were reported for a house situated in soil with a uniform permeability of approximately 6×10^{-11} m^2 in which pressure coupling of about eight percent was observed 5 m away from the house.[3]

On a number of occasions during the experiment, the exhaust fan in the basement was abruptly switched on or off to verify that the underpressures measured at the probes resulted from the depressurization of the basement. In each case, the soil pressure reached equilibrium within seconds of turning the fan on or off. Soil depressurization was measured as a function of basement depressurization at probes AN3, BW4 and DE1. Figure 2 shows that the soil pressures at these locations were quite linear with the pressure in the basement. Pressures at probe AN3, only 0.5 m from the basement wall, were most strongly coupled. Within the uncertainty in the measurements, the intercepts of the slopes incorporate the origin.

VOC in Soil Gas

The composition of VOC in soil gas that was sampled from several soil probes in July and September is shown in Table II. A total of 26 individual compounds were identified in these samples. Identifications were determined using mass spectral data bases and were confirmed, in many cases, by analyses of standards. No attempt was made to analyze compounds with very low boiling points (most Freons and C_4-C_5 hydrocarbons) in July. There was no major qualitative difference in the composition of the other compounds between July and September. In general, halogenated and oxygenated compounds were the dominant classes, both in terms of the numbers of compounds detected and relative peak heights. Compounds with distinctly high peak heights were dichlorodifluoromethane (Freon-12), trichlorofluoromethane (Freon-11), 1,1,1-trichloroethane, tetrachloroethylene, 2-propanone (acetone), 4-methyl-3-penten-2-one (mesityl oxide), and 2-ethyl-1-hexanol.

The concentrations of 14 compounds which were measured by GC-MSD in soil gas collected at several probes in September and October are presented in Table III. Both the ranges of concentrations and the mean concentrations are shown since there were large quantitative differences among the probes in each sampling period. The generally larger variations in September may have been due to the inclusion of data from a 3-m deep probe with data from two 1.5-m deep probes, while the four probes sampled in October were all 1.5-m deep. Nevertheless, even in October, concentrations of individual compounds generally ranged over a factor of three to five among the probes. There were also major differences in the concentrations of the compounds between the two sampling periods. In September, the dominant compounds were Freon-12, Freon-11 and tetrachloroethylene. These compounds still had relatively high concentrations in October, while the concentrations of five other compounds increased considerably from September to October. These compounds were dichloromethane, 2-propanone, hexanal, 2-methylbutane and toluene. These changes occurred over a period in which there was a general decrease in average ambient temperature and some precipitation (1.5 cm). However, these factors would not be expected to alter soil parameters at the sampling depth.

In October, Freon-12 was quantified at all probe locations by GC-FID. Considerable spatial variability was observed. The average concentration of Freon-12 for the site is 630 ppb with concentrations in the individual probes ranging from 100 to 2100 ppb. Concentrations in the 1.5-m deep probes on the west side of the house average 250 ppb and are distinctly lower than concentrations in the other probes. The average concentration for the 3-m deep probes, including the basement probes, is 1500 ppb, and the average concentration for all probes (1.5 m deep) to the north and east of the house is 1000 ppb. Higher concentrations of Freon-12 on the north side of the house suggest that this area may be closest to the path of migration of landfill gas. The considerably higher concentrations at depth suggest the possible presence of a layer of soil of lower permeability lying between 1.5 and 3 m and limiting diffusion to the atmosphere.

Gas in the landfill adjacent to the study site was not analyzed, and, in general, there are few data on the composition of the minor constituents of landfill gas. Nevertheless, it is probable that many, if not all, of the dominant compounds in the soil gas around the house originated from the landfill.

Brookes and Young[11] present a list with some quantitative data of compounds that were detected in soil gas at six landfills in Great Britain. More than 100 compounds encompassing all of the major classes of organic compounds were detected and either identified or partially classified. Thirteen of the compounds found in soil gas in the present study (Tables I and II) appear in this list. In most cases their concentrations in the landfill gas were greater than several ppm. At one of the six landfills, the dominant classes both in terms of numbers of compounds and concentrations were oxygenated compounds, halogenated compounds and alkanes. Similarly, oxygenated and halogenated compounds are dominant in the present study.

If conditions are favorable, VOC contained in landfills can be transported away from the site by subsurface water and by subsurface gas-phase migration. Gas-phase migration of VOC into surrounding areas was detected at two sites included in a survey of 20 nontoxic, municipal landfills in Southern California.[1] At one location where methane was detected in nearby houses at concentrations approaching one percent, a sample of migrating gas was taken from a gas well outside the periphery of the landfill and another sample was taken from under the kitchen sink of a house approximately 180 m away. Tetrachloroethylene and 1,1,1-trichloroethane were detected at both locations. Concentrations at the entry point into the house were about two orders of magnitude lower than in the well. At another location, qualitative changes in the composition of soil gas with distance beyond the landfill perimeter were investigated. The first compounds to disappear with distance were the oxygenated compounds followed by the aromatic compounds, the other hydrocarbons and the polar halogenated compounds. Tetrachloroethylene, a dominant compound in the present study, was one of the most persistent compounds.

Entry of Soil Gas into the Basement

The concentrations of SF_6 and Freon-12 measured by GC-ECD in samples of soil gas collected from the soil probes closest to the house are summarized in Table IV. As indicated by the averages and ranges for soil probes on the two sides of the house, the spatial variability in the concentrations of both of these compounds was large. This variation occurred in an area of relatively uniform soil. An examination of all of the data for SF_6 revealed that concentrations predictably decreased with increasing distance from the points of injection. As shown in the table, concentrations of SF_6, 0.5 m from the basement wall, were somewhat higher on the west side of the house than on the north side. In contrast to SF_6, the concentrations of Freon-12 were higher on the north side of the house than on the west side by about a factor of four. For both compounds, the highest concentrations occurred in the two probes penetrating the basement floor.

After thorough ventilation, the concentrations of SF_6 and Freon-12 in the basement at the beginning of this experiment were 0 and 1 ppb, respectively. Volumes of air equivalent to 4.8, 3.0, 5.9, and 5.6 basement volumes were respectively exhausted from the basement at depressurizations of -20, -30, -40, and -50 Pa. Figure 3, which shows concentrations of SF_6 in the basement at -20 Pa as a function of time, demonstrates that near steady-state conditions were achieved within about one hour at this pressure. Concentrations of SF_6 and Freon-12 in air sampled in the open upper floor of the house and outdoors near the basement sill plate were 0 and 1 ppb, respectively.

Direct evidence of the entry of soil gas into the basement was obtained during the experiment. Air flow into the basement was detected during depressurization at the electrical outlet boxes which were recessed into cavities cut into the cement block wall approximately 45 cm above the floor. The average concentrations of SF_6 and Freon-12 in air samples collected from the cavities on the west wall were about 90 and 200 ppb, respectively. These concentrations are similar to the average concentrations measured in the adjacent soil outside the wall. Air flow into the basement was also detected at the sill plate running around three sides of the basement at a height of about 30 cm above the surface of the soil. This location may serve as a major entry pathway for outdoor air.

A simple mass-balance model assuming steady-state conditions was applied to the concentration data obtained 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:

$$aC_{\infty} = C_sQ_s + C_oQ_o. \tag{2}$$

The C_{∞} is the final concentration of the tracer gas in the basement at equilibrium, and C_s and C_o are the concentrations in the soil gas and the outside air, respectively. The Q's are the corresponding flow rates of soil gas and outside air. The ventilation rate of the basement, a, is simply the calibrated flow rate of the exhaust fan. Solving for Q_s, and letting $a = Q_s + Q_o$ yields:

$$Q_s = a\frac{C_{\infty} - C_o}{C_s - C_o}. \tag{3}$$

It was assumed that any soil gas entering the basement would be drawn from near the basement wall. Therefore, the averages of concentrations of SF_6 and Freon-12 in probes 0.5 m from the west and north walls and in the two basement probes were selected as the best estimates of concentrations for use in the mass-balance model. This results in values of C_s of 230 and 780 ppb for SF_6 and Freon-12, respectively. There is, however, considerable uncertainty in the estimates due to the large spatial variations which were observed (Table IV) and the lack of data for soil gas close to the east wall of the basement. As a result, the effective concentrations in soil gas entering the basement could vary from these values by a factor of two or more. The uncertainty due to spatial variations in concentrations is compounded by the fact that the distribution of the pathways for entry of soil gas into the basement is unknown. Together, these factors introduce considerable uncertainty into the estimation of entry rates.

The entry rates of soil gas into the basement as a function of basement depressurization which were estimated from the SF_6 and Freon-12 concentration data are shown in Figure 4. The relationship is linear for both compounds. The divergence between the two slopes, which is undoubtedly due to the large uncertainties discussed above, emphasizes the limitations of the experiment. Clearly, only order-of-magnitude estimates of entry rates of soil gas can be obtained by this method. However, despite the limitations, the regressions suggest that the entry rate of soil gas due to pressure-driven flow would be less than 1 m^3 h^{-1} at a basement depressurization of a few Pascals which would result from wind and an indoor-outdoor temperature differential.[12] For comparison, the infiltration rate of outdoor air for the whole house was calculated for relatively extreme winter conditions by the method of Sherman and Grimsrud.[15] Using the measured leakage area of the house and assuming a wind speed of 4 m sec^{-1} and an indoor-outdoor temperature differential of 22°C, this infiltration rate would be approximately 500 m^3 h^{-1}, or almost three orders of magnitude higher than the estimated soil-gas entry rate.

VOC in Indoor Air

The compositions of VOC in the basement of the house in July and September are compared to the compositions of VOC in outdoor air and soil gas in Table II. For September, the compositions in the basement with the basement both at ambient pressure and at a depressurization of -20 Pa are presented. In July, only a few compounds were detected in the basement, and the composition is similar to that of outdoor air. Most of the oxygenated compounds present in soil gas did not appear indoors. In September, many more compounds were detected in the basement. Most of the halogenated compounds in soil gas appeared indoors, and more oxygenated compounds were detected indoors in this month. A number of alkane and aromatic compounds, e.g. n-hexane, methylcyclopentane, n-decane, n-undecane, and trimethylbenzenes, were detected only in the basement suggesting indoor sources for these compounds. No significant increase in the number of compounds was observed when the basement was depressurized. However, seven of the compounds decreased to concentrations that were near their detection limits. This decrease was due to the dilution of basement air with infiltrating outdoor air.

The concentrations of VOC in the house in September and October are compared to the concentrations in outdoor air and soil gas in Table III. Thirteen of the 14 compounds quantified in soil gas appeared indoors, and eight of these were also present in outdoor air. In general, the concentrations of VOC in the house were very low, particularly in September when they typically ranged from less than one to a few parts per billion. In this month, acetone had the highest indoor and outdoor concentrations; Freon-12, which had very high concentrations in the soil gas, was not elevated in indoor air. Concentrations in outdoor air, with the exception of acetone, were all less than 1 ppb. Concentrations of VOC in the house in October were, with the exception of one compound, higher than they were in September by a factor of two or more. This increase may have been due to the additional care which was taken in October not to disturb the ventilation of the house prior to collecting samples. In this sampling period, concentrations of VOC in the basement were compared to concentrations in a bedroom on the upper floor. The concentration of acetone in the basement approached the mean soil gas concentration which had increased considerably from September to October. The concentration of acetone in the bedroom was much lower suggesting that the source was in the basement. All of the other compounds had nearly equivalent concentrations in the basement and bedroom, with the possible exception of Freon-12 which was somewhat higher in the basement.

CONCLUSIONS

The measurement of significant pressure coupling at a distance of 12 m from the west side of the house demonstrates that soil gas can potentially be drawn by depressurization of the basement from a large area that extends out from the house toward the landfill. The significant pressure coupling that was measured on three sides of the house suggests that the pathway for the entry of soil gas into the basement is distributed around the house rather than concentrated in a few penetrations. The similarity of concentrations of tracer gas and Freon-12 in air coming from cavities on the inside of the cement-block wall when the exhaust fan was operating and in the adjacent soil outside the wall provided direct evidence of the entry of soil gas. However, the actual entry pathway for this soil gas is unknown. Existing models for air flow rate through soil are being applied to the pressure-field data in an attempt to further understand the entry mechanisms.[14]

The convective flow of soil gas into the basement of this particular house due to the pressure differential caused by wind and indoor-outdoor temperature differences is estimated to be only a small fraction, ~0.1 percent, of the inflow of air into the house due to infiltration, even at conditions of moderate wind and a relatively large temperature difference. Consequently, the infiltrating air would significantly dilute the concentrations of any contaminants entering from the soil. Although the basement is well coupled with the soil gas, the pressure-driven entry of soil gas, is limited by the relatively low permeability of the soil, about 2×10^{-12} m^2, on average. In houses situated in more permeable soils and in which there is significant pressure coupling, the relative contribution of pressure-driven inflow to total inflow can be much higher. Studies of radon entry into houses have shown that, in some cases, the fraction of soil-gas entry to the total infiltration rate can approach 10-20 percent, or two orders of magnitude larger than observed for this house.[15]

The concentrations of Freon-12 and other VOC in soil gas were found to be highly variable in the vicinity of the house in an area of relatively uniform soil. It is probable that these variations arose from a combination of interrelated factors, such as the degree of coupling with the source, the presence of boundaries limiting transport to the surface, and differences in the sorptive capacity of the soil for VOC.

Some VOC, which were significantly elevated in soil gas relative to outdoor air, also occurred in indoor air at higher concentrations than in outdoor air, suggesting that the source of these compounds in indoor air was the soil gas. Diffusion from the surrounding soil probably accounts for the entry of these compounds since pressure-driven entry is estimated to be negligible, particularly at the meteorological conditions during this study. When the basement was depressurized with the exhaust fan, compounds which appeared to originate from the soil decreased rather than increased in concentration, which further suggests that diffusion, a considerably slower process, is more important than pressure-driven flow for this house. Nevertheless, in other houses under conditions of high pressure coupling, more permeable soil, and high concentrations of VOC in soil gas, convective flow of soil gas into substructures is certain to be an important mechanism for entry of VOC.

ACKNOWLEDGMENTS

This work was supported by the Occidental Chemical Corporation under Agreement No. BG 8602A and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U. S. Department of Energy under Contract No. DE-Ac03-76F00098.

REFERENCES

1. J.A. Wood and M.L. Porter, "Hazardous pollutants in class II landfills," *J. Air Pollution Control Assoc.* 37(5): 609-615 (1987).

2. T. W. D'Ottavio, R.N. Dietz, C. Kunz and B. Kothari, "Radon source managements using multiple perfluorocarbon tracers," In: *Proceedings of the 4th International Conference on Indoor Air Quality*, Berlin (West), August 17-21, 1987, B. Seifert, *et al.*, Eds., Institute for Water, Soil and Air Hygiene, Berlin, Vol. 2, pp. 338-392 (1987).

3. R. G. Sextro, B.A. Moed, W.W. Nazaroff, K.L. Revzan and A.V. Nero, "Investigations of soil as a source of indoor radon," In: *Radon and Its Decay Products: Occurrences, Properties, and Health Effects*, P. Hopke, Ed., American Chemical Society, Washington D.C, 1987, pp. 10-29.

4. W.W. Nazaroff, H. Feustal, A.V. Nero, K.L. Revzan, D.T. Grimsrud, M.A. Essling and R.E. Toohey, "Radon transport into a detached one-story house with a basement," *Atmos. Enviro.*" 19(1): 31-46 (1985).

5. W.W. Nazaroff, S.R. Lewis, S.M. Doyle, B.A. Moed and A.V. Nero, "Experiments on pollutant transport from soil into residential basements by pressure-driven airflow," *Environ. Sci. Technol.* 21(5): 459-466 (1987).

6. D. Hillel, *Fundamentals of Soil Physics*, Academic Press, New York, 1980, pp. 55-64.

REFERENCES (Continued)

7. DMSA Atcon Ltd., "Review of existing information and evaluation for possibilities of research and development of instrumentation to determine future levels of radon at a proposed building site," Report INFO-0096, Atomic Energy Control Board, Ottawa, Canada (1983).

8. A.T. Hodgson, J. Binenboym and J.R. Girman, "A multisorbent sampler for volatile organic compounds in indoor air," Paper No. 86-37.1, *Proceedings of the 79th Annual Meeting of the Air Pollution Control Association*, Minneapolis, MN, June 22-27, 1986, Air Pollution Control Association, Pittsburgh, PA (1986).

9. A.T. Hodgson and J.R. Girman, "Application of a multisorbent sampling technique for investigations of volatile organic compounds in buildings," In: *Proceedings, ASTM Symposium on Design and Protocol for Monitoring Indoor Air Quality*, April 26-29, 1987, Cincinnati, OH, (In Press).

10. W.W. Nazaroff, B.A. Moed, R.G. Sextro, K.L. Revzan and A.V. Nero, "Factors influencing soil as a source of indoor radon: A framework for geographically, assessing radon source potentials," Report No. LBL-20645, Lawrence Berkeley Laboratory, Berkeley, CA (1986).

11. B.I. Brooks and P.J. Young, "The development of sampling and gas chromatography-mass spectrometry analytical procedures to identify and determine the minor organic components of landfill gas," *Talanta* 30(9): 665-676 (1983).

12. W.W. Nazaroff, B.A. Moed and R.G. Sextro, "Soil as a source of indoor radon: Generation, Migration and Entry," In: *Radon and Its Decay Products Indoors*, W.W. Nazaroff and A.V. Nero, Eds., John Wiley & Sons, New York, 1988, pp. 57-112.

13. M.H. Sherman and D.T. Grimsrud, "Measurement of infiltration using fan depressurization and weather data," In: *Proceedings of the 1^{st} Symposium of the Air Infiltration Center on Instrumentation and Measurement Techniques*, Windsor, England, October 6-8, 1980.

14. K. Garbesi, MS Thesis, Energy and Resources Group, Univ. Calif., Berkeley, CA. In preparation.

15. B.H. Turk, R.J. Prill, W.J. Fisk, D.T. Grimsrud, B.A. Moed and R.G. Sextro, "Radon and remedial action in Spokane River Valley homes, Volume 1: Experimental design and data analysis," Report No. LBL-23430, Lawrence Berkeley Laboratory, Berkeley, CA (1987).

TABLE I. Soil permeability and pressure coupling of soil gas with basement air at soil-probe locations.

Probe ID	Distance from House[a] (m)	Depth[a] (m)	Soil Permeability[b] (m^2)	Pressure Coupling[c] (%)
AW1	0.5	1.5	2.2×10^{-13}	30±6
AW2	0.5	1.5	2.1×10^{-12}	33±4
AW3	0.5	1.5	1.0×10^{-12}	37±6
AW4	0.5	1.5	4.9×10^{-13}	33±13
AW5	0.5	1.5	1.1×10^{-12}	27±6
AW6	0.5	1.5	2.6×10^{-12}	4±3
AN1	0.5	1.5	5.8×10^{-13}	44±6
AN2	0.5	1.5	5.3×10^{-13}	37±6
AN3	0.5	1.5	3.9×10^{-13}	23±4
BW1	1.5	1.5	1.1×10^{-12}	17±5
BW2	1.5	1.5	3.4×10^{-12}	17±3
BW3	1.5	1.5	4.2×10^{-12}	20±3
BW4	1.5	3	1.6×10^{-11}	6±1
BW5	1.5	1.5	2.0×10^{-13}	28±6
BN1	1.5	1.5	2.7×10^{-13}	25±6
CW1	3	1.5	9.3×10^{-13}	12±3
CW2	3	1.5	3.0×10^{-11}	14±3
CW3	3	3	3.8×10^{-12}	18±3
CW4	3	1.5	6.6×10^{-13}	14±4
DW1	5	1.5	1.5×10^{-12}	10±2
DW2	5	1.5	2.4×10^{-12}	9±2
DW3	5	3	2.7×10^{-13}	21±5
DE1	5	1.5	2.3×10^{-13}	10±7
DE2	5	1.5	3.9×10^{-13}	7±7
EW1	7	1.5	1.1×10^{-12}	7±2
EW2	7	1.5	2.6×10^{-13}	17±5
EW3	7	1.5	1.3×10^{-12}	10±3
FW1	12	3	1.9×10^{-13}	16±3
FW2	12	2	5.6×10^{-14}	-[d]
FW3	12	1	2.1×10^{-13}	-
B1	0	3.2	2.1×10^{-11}	-
B2	0	3.2	1.6×10^{-13}	-

a. Distances and depths are approximate

b. Uncertainty is x/÷2

c. As percent of basement depressurization of -25 Pa; uncertainty is based upon instrumental noise

d. No data

TABLE II. Composition of VOC in soil gas, indoor air and outdoor air in July and September. "X" = present; "XX" = very high concentration; "t" = trace concentration and "-" = not detected.

		July			September		
	Soil-Gas[a]	Basement	Outdoor Air	Soil-Gas[b]	Basement		Outdoor Air
Compound					0 Pa	-20 Pa	
HALOGENATED							
Dichlorodifluoromethane				XX	X	X	t
Chlorodifluoromethane				X	-	X	-
Dichlorotetrafluoroethane				X	-	-	-
Trichlorofluoromethane				XX	X	X	t
Trichlorotrifluoroethane	X	-	-	-	-	-	-
Dichloromethane	-	X	t	-	X	t	t
1,1,1-Trichloroethane	XX	X	X	X	X	X	t
Tetrachloroethylene	XX	-	t	XX	X	X	t
OXYGENATED							
2-Propanone	XX	X	X	X	X	X	X
2-Propanol	X	-	-	-	-	-	-
2.4-Dimethyl-2-pentanol	-	-	-	X	-	-	-
Acetic acid	-	X	t	X	X	X	X
Hexanal	X	t	-	X	X	X	-
4-Methyl-3-penten-2-one	XX	-	-	X	-	-	-
3-Methyl-3-penten-2-one	-	-	-	X	-	-	-
3-Heptanone	X	-	-	X	X	X	-
2-Heptanone	X	-	-	X	-	-	-
Heptanal	X	-	-	X	t	t	-
2-Butoxyethanol	X	-	-	-	-	-	-
6-Methyl-2-heptanone	X	-	-	X	-	-	-
2-Ethyl-1-hexanol	-	-	-	XX	-	-	-
Nonanal	X	-	-	-	-	X	-
Decanal	X	-	-	-	X	t	X

TABLE II. (Continued)

Compound	July			September			
	Soil-Gas[a]	Base-ment	Outdoor Air	Soil-Gas[b]	Basement 0 Pa	Basement -20 Pa	Outdoor Air
ALKANE AND CYCLOALKANE							
2-Methylpropane				X	t	X	-
2-Methylbutane				-	X	X	t
n-Hexane	-	-	t	-	X	t	-
Methylcyclopentane	-	-	t	-	X	t	-
n-Heptane	-	t	t	-	X	t	X
n-Decane	-	-	-	-	X	t	-
n-Undecane	-	-	-	-	X	-	-
AROMATIC							
Toluene	X	X	X	X	X	X	X
Ethylbenzene	-	-	t	-	X	X	-
1,3- 1,4-Dimethylbenzene	-	t	X	t	X	X	t
1,2-Dimethylbenzene	-	-	t	X	X	X	t
Trimethylbenzene	-	-	t	-	X	X	-
Trimethylbenzene	-	-	-	-	X	t	-
Trimethylbenzene	-	-	-	-	X	X	-

a. Soil probes CW3 and DW3

b. Soil probe CW2

TABLE III. Concentrations of VOC in soil gas, indoor air and outdoor air in September and October.

Compound	Concentration, ppb							
	September				October			
	Soil Gas		Basement	Outdoor Air	Soil Gas		Basement	Bedroom
	Range	Mean[a]			Range	Mean[b]		
HALOGENATED								
Dichlorodifluoromethane	230-920	490	2.3	0.2	110-340	190	15	10
Trichlorofluoromethane	7.6-110	46	0.8	0.3	42-230	140	2.0	3.3
Dichloromethane			1.2	0.1	50-200	120	9.6	13
1,1,1-Trichloroethane	1.4-11	4.9	0.7	0.3	2.8-9.4	6.1	1.5	1.6
Tetrachloroethylene	23-150	70	0.7	0.1	26-79	56	2.0	1.9
OXYGENATED								
2-Propanone	16-27	20	12	4.9	90-370	250	200	38
Hexanal	3.3-7.9	6.1	1.0		37-52	42	3.7	4.8
4-Methyl-3-penten-2-one	0-10	3.4						
3-Heptanone	0-6.8	4.2	0.6		7.8-15	9.9		
ALKANE AND AROMATIC								
2-Methylbutane			5.2	0.3	14-74	36	11	12
Toluene	1.4-35	13	4.3	0.9	41-92	66	12	11
Ethylbenzene			0.6		2.8-3.7	3.3	2.0	1.8
1,3- 1,4-Dimethylbenzene	0-0.9	0.1	1.9		9.3-12	11	6.8	5.9
1,2-Dimethylbenzene	0.2-1.7	0.7	1.0		3.4-7.2	5.8	3.9	3.0

a. Soil probes AW2, CW2 and B2

b. Soil probes AW2, CW2, CE1 and CE2

TABLE IV. Concentrations of SF_6 and Freon-12 in soil probes adjacent to the basement. Probes to the North and West were ~0.5 m from the basement wall and ~1.5 m deep.

Probe Location	Concentration, ppb Mean	Range	No. of Probes
SF_6			
North	56	30-84	3
West	130	55-200	6
Basement	800	710-890	2
Freon-12			
North	1100	560-1700	3
West	270	160-450	6
Basement	2100		2

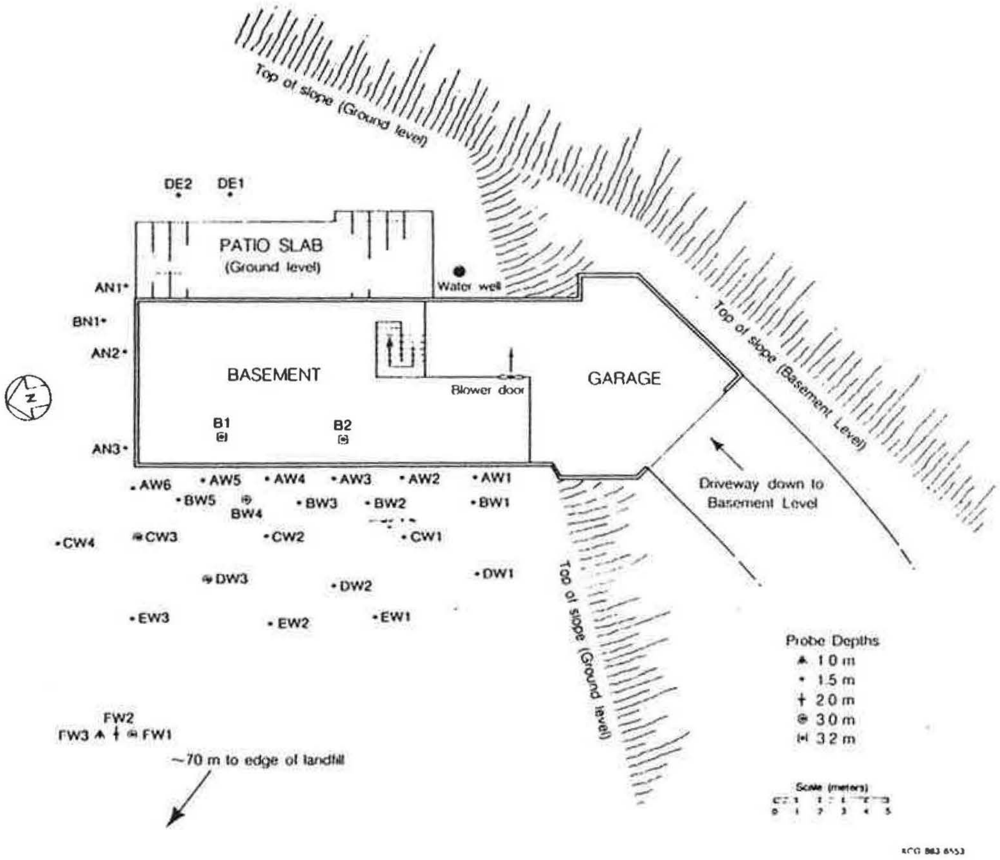
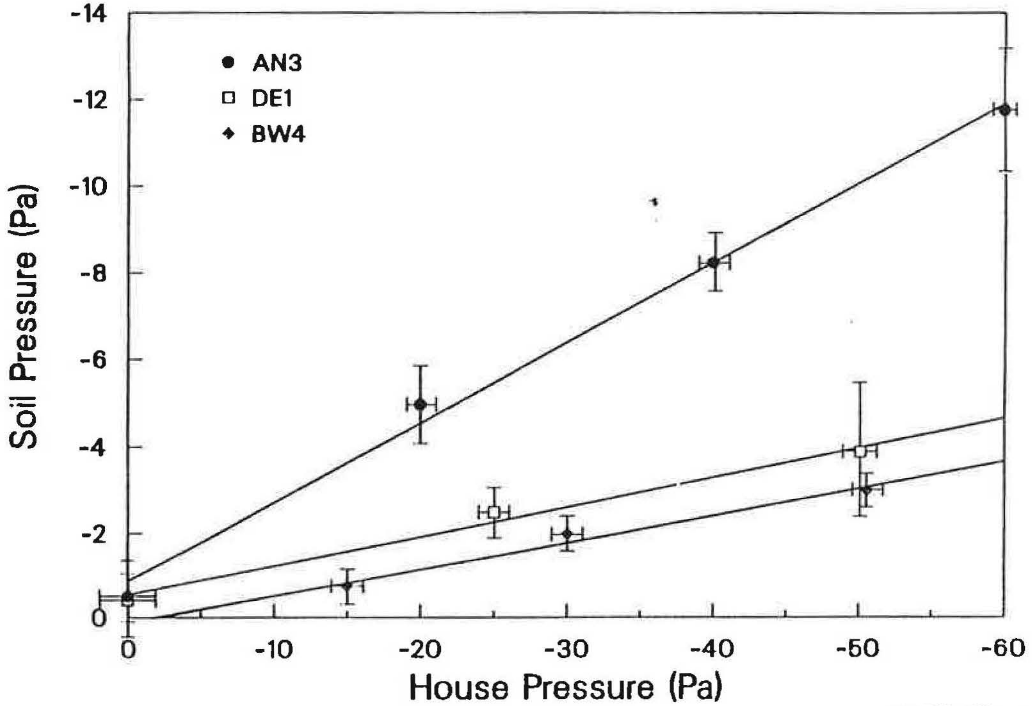
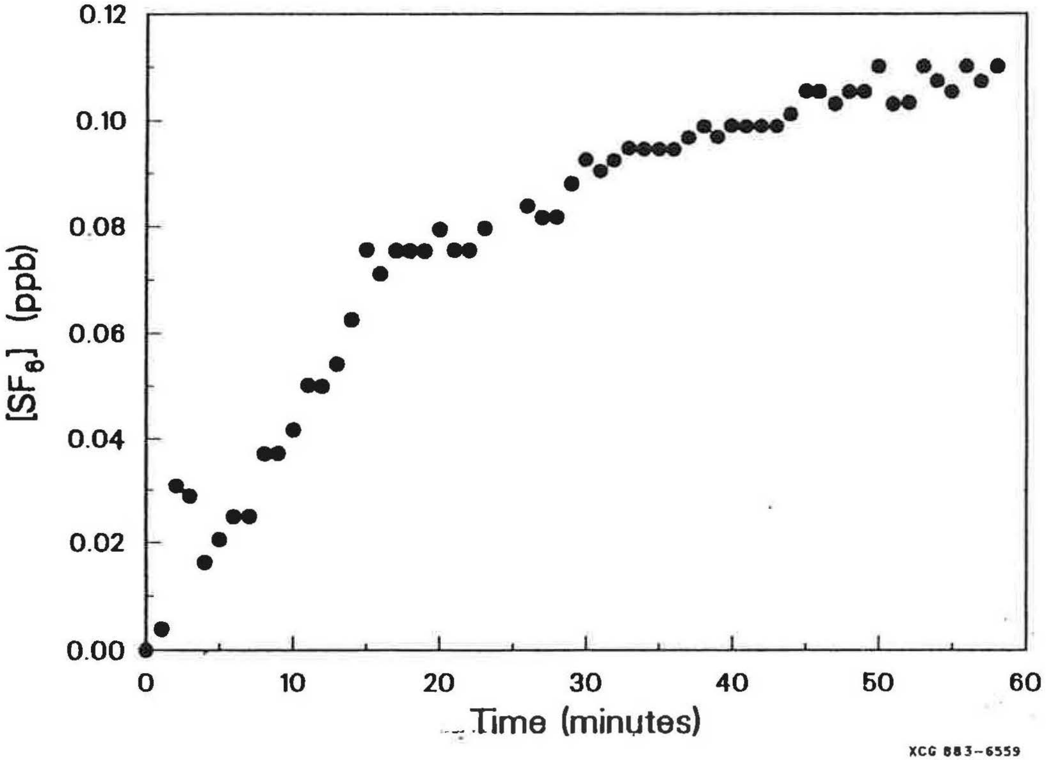


Figure 1. Plan view of the study site and the basement level of the house showing the locations and depths of the soil probes.



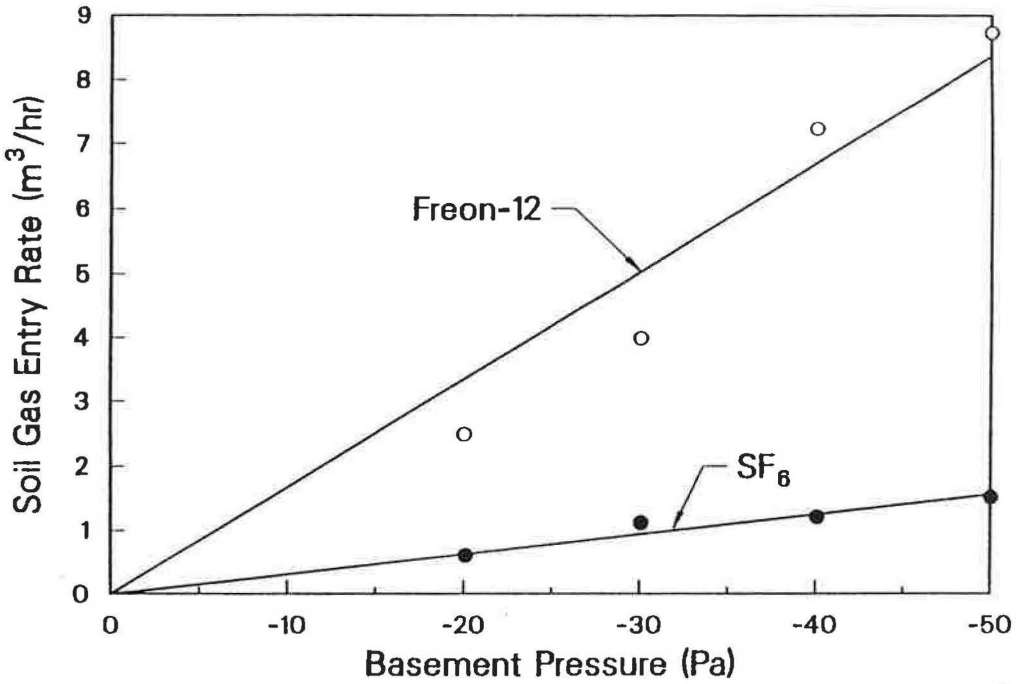
XCG 883-6558
3/10/88

Figure 2. Depressurization of the soil as a function of basement depressurization at three soil probes. The error bars represent the uncertainties in the measurements due to instrumental noise. Linear regressions fitted to the data are shown as solid lines.



XCG 883-6559
3/10/88

Figure 3. Concentrations of SF_6 tracer gas in the basement as a function of time with the basement at a depressurization of -20 Pa.



XCG 883-6564
3/15/88

Figure 4. Entry rates of soil gas into the basement as a function of basement depressurization estimated using a mass-balance model and concentrations of Freon-12 and SF_6 tracer gas in basement air, outdoor air, and soil gas adjacent to the house. Linear regressions fitted to the data are shown as solid lines.