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AIR INFILTRATION MEASUREMENTS IN A FOUR-BEDROOM TOWNHOUSE USING SULFUR HEXAFLUORIDE AS A TRACER GAS

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Air infiltration represents an important part of the heating and cooling load of homes and is an important parameter in indoor-outdoor air pollution relationships. However, air infiltration rate is difficult to quantify, because it is not only a function of building tightness and configuration but also of inside-outside temperature differences, wind velocity, direction, and possibly other factors. There are formulas to estimate air exchange rates (1), but they are at best rough approximations.

The tracer dilution method has been used for a number of years to measure air infiltration rates. Helium was one of the first tracer gases used (2, 3, 4, 5), but others have also been used, such as ethane (6) and nitrogen dioxide (7). Since Gregory's (8) observation that sulfur hexafluoride (SF_6) could be detected in nanogram quantities by means of an electron capture detector, it has also been used as a meteorological tracer (9, 10, 11). More recently it has been applied to the prediction of smoke movement in fires (12) and to the measurement of air infiltration in buildings (13, 14). In addition to the fact that it can be measured in trace concentrations, it is not a normal background constituent of air and is odorless and nontoxic in the concentration used. For determination of its toxicity and as part of the quality control process, mice are subjected to 80% SF_6 - 20% oxygen mixtures for 24 hours. For the batch of gas to be certified as nontoxic, the mice must not show signs of irritation or distress (15).

Heating energy measurements were recently performed on an instrumented townhouse located in an environmental chamber for the purpose of validating a computer program (16). The temperature in the chamber, as well as the air temperature within the house was controlled and measured. This study also provided an opportunity to measure air infiltration rates under various inside-outside temperature differences and under conditions where wind velocity was negligible, thus eliminating one of the major variables. This paper describes the results of such measurements using SF_6 as a tracer. It attempts to determine the effect on air exchange rates of such factors as inside-outside temperature difference and the sealing of doors and ducts. It also considers the repeatability and accuracy of the SF_6 method, using different sampling techniques and reviews some of the possible sources of error.

DESCRIPTION OF TEST HOUSE AND ENVIRONMENTAL CHAMBER

The test house, a factory-produced four-bedroom townhouse, was assembled on its foundation in a high-bay environmental chamber of approximately 70,000 ft^3 (1980 m^3) volume. The volume of the test house was about 9500 ft^3 (269 m^3), and the floor area was 1200 ft^2 (111 m^2). The total window area was 137 ft^2 (12.7 m^2) or about 11.4 percent of the floor area, and closets represented slightly less than 5 percent of the volume of the house. A sketch of the house and a cut-away diagram of the environmental chamber are shown in Fig. 1. The floor plans of the first and second floors are shown in Fig. 2 and 3 respectively.

The air distribution system consisted of a duct system leading to the rooms and a common return located in the hallway between the dining area and the utility room. A circulating fan forced air through the furnace and into the distribution ducts leading to the various rooms.

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MEASUREMENT TECHNIQUES

SF_6 was introduced into the circulating fan and distributed throughout the house. Concentrations of tracer were measured with a small gas chromatograph equipped with an aluminum oxide column and a "pulsed mode" electron capture detector. Oxygen, which is also an electron capturing gas, elutes first and is followed by SF_6, which is measured separately. The response of the electron capture detector to SF_6 was treated as logarithmic (18). That is:

$$\log I/I_o = -kc, \tag{1}$$

where: c is the concentration of tracer
k is an empirical constant,
I_o is the standing current of the detector,
$I^o$is the low point of a chromatographic deflection.

Eq. 1 has the form of Beer's law. The instrument was calibrated three or four times during the course of each air exchange measurement with an SF_6/air mixture of fixed concentration, usually 13.8 ppb SF_6, as a check on possible instrumental drift.

Air samples were taken at recorded times and analyzed for SF_6. Three different sampling methods were used. In the first method, composite samples were collected manually with a hand pump and a balloon, going from room to room in a timed sequence. Upstairs and downstairs spaces were analyzed separately. In the second method, samples were collected through a sampling network consisting of 16 polyethylene tubes of identical length having a 6 mm ID. At least one tube extended to each of the rooms and hallways and converged at a common point, passing into a 12 liter/minute diaphragm pump. The approximate locations of the sampling probes are shown by circled crosses in Fig. 2 and 3. In the third method, samples were taken from the return air at the entrance to the main ventilating fan in the central air system.

When infiltration measurements are made in occupied houses, it is usually not practical to use the first two methods, so the third method is used. These different measurement techniques were used to compare one-point sampling of the return air with methods which sample directly from different parts of the house.

SF_6 concentration was also measured in the circulating air of the environmental chamber at a point about two ft above the ground and about six ft from the kitchen door (Point A in Fig. 2) to check possible tracer buildup in the environmental chamber. This could lead to tracer reentry error.

In separate measurements, helium and SF_6 were used simultaneously as tracers to compare air exchange rates indicated by the two gases. The helium technique (4) is based upon the change in the thermal conductivity of air containing small amounts of helium.

CALCULATION OF AIR INFILTRATION RATE

The principle of the tracer dilution method of measuring air exchange rates may be developed briefly by considering the average rate (v_o) air leaks into a house. This must equal the average rate at which air leaks out unless there is some steady increase or decrease in pressure. The rate of change in the total amount of tracer in the house is:

$$\frac{dQ}{dt} = (c_o - c_i)\, v_o \tag{2}$$

where: Q is the total amount of tracer,
c_o and c_i are the concentrations of tracer outside and inside.
If V is the total internal volume of the house, Eq. (1) may be expressed:

$$\frac{1}{V}\frac{dQ}{dt} = \frac{dc_i}{dt} = (c_o - c_i)\frac{v_o}{V} \tag{3}$$

where: v_o/V is the infiltration rate in air changes per unit time. If the outside concentration of tracer is small enough to be neglected, Eq. (3) reduces to:

$$\frac{dc_i}{dt} = -c_i \frac{V_o}{V} \tag{4}$$

Or in logarithmic form:

$$\log_e \frac{C_i}{C_{i_o}} = -\frac{v_o}{V} t \qquad (5)$$

where: c_{i_o} is the inside concentration of tracer at time t = 0. Thus if $\log_e (c_i/c_{i_o})$ is plotted against time, the idealized relationship calls for a straight line with negative slope equal to the air exchange rate, designated as ϑ for infiltration.

INFILTRATION RATE AND INSIDE-OUTSIDE TEMPERATURE DIFFERENCE

Air infiltration in the townhouse was determined through a series of measurements in which the house was heated electrically, the outside air temperature was maintained at different selected temperatures, and the inside air temperature was maintained at about 24 C (75 F). The results showing infiltration as a function of the difference between inside and outside temperature are given for the three sampling methods in Table 1. The outside concentrations of tracer were neglected in these calculations since they were small and showed no evidence of buildup. The estimated uncertainty due to tracer reentry was less than 0.03 air changes per hour in most cases. The results in the table show that when wind velocity is eliminated as a variable, a correlation between infiltration rate and inside-outside temperature difference is obtained. This correlation has been previously observed (1, 3, 5, 7). Best fit straight lines were calculated for each of the sampling methods. The equations and corresponding root mean square deviations are given as follows:

Hand Sampling: $\vartheta = 0.113 + 0.0104\Delta T, \quad \delta = 0.070$ (6)

Network Sampling: $\vartheta = 0.117 + .0108\Delta T, \quad \delta = 0.072$ (7)

Return Sampling: $\vartheta = 0.124 + 0.0114\Delta T, \quad \delta = 0.071$ (8)

where: ϑ is the infiltration rate in air changes per hour at temperature difference (ΔT)

δ is the root mean square deviation.

From the regression lines, the agreement between the three methods of sampling was within 0.06 air changes per hour over a 50 deg F range of ΔT, but scatter of some individual points was greater than this. These results were obtained under conditions in which the tracer was mixed as well as possible throughout the house by means of the furnace fan and the house duct system. Whether the furnace fan was operated continuously or intermittently (8 minute intervals) seemed to make little difference, as long as it was operated.

The total data for all three methods of sampling fit the equation:

$$\vartheta = 0.117 + 0.0108\Delta T, \quad \delta = 0.074 \qquad (9)$$

The total data and corresponding least squares line are presented in Fig. 4.

The ASHRAE HANDBOOK OF FUNDAMENTALS (1) gives an empirical relationship for estimating the flow through buildings due to the stack effect:

$$Q = 9.4A \sqrt{h(t_o - t_i)} \qquad (10)$$

or for a 9500 ft^3 house:

$$\vartheta = \frac{60Q}{9500} \qquad (10a)$$

where: Q is the air flow rate in cubic feet per minute,
A is the free area of inlets or outlets (assumed equal) in square feet,
h is the height from inlets to outlets in feet,
t_i is the average temperature of indoor air in height (h),
t_o is the temperature of outdoor air (F).

According to this relationship the infiltration rate is proportional to the square root of the difference between inside and outside temperature. From regression analysis of all the data it was found that:

$$\vartheta = 0.0869 \sqrt{t_o - t_i}, \quad \delta = 0.085 \qquad (10b)$$

This is plotted in Fig. 4 as the dotted line and gives a fair representation of the averaged data. The ASHRAE relationship predicts a vanishing air infiltration rate when the thermal head is reduced to zero. The experimental data extends to a temperature difference of 9.6 F, which is not a low enough value to conclusively prove or disprove zero infiltration rate at zero thermal head. However it seems reasonable that there might be some convective air movement and small thermal gradients when the average inside and outside temperatures are equal.

It should be noted in Table 1 that when hand sampling was used and the upstairs and downstairs data were analyzed separately, the calculated upstairs infiltration rates were usually lower than those obtained downstairs. Such a result might be expected if the upstairs infiltration rate were actually slower or if tracer escaping through the upper part of the house was partially replenished by tracer conveyed upward by the convective pattern within the house. A weighted average of the upstairs and downstairs infiltration rates are also given in Table 1, giving twice the weight to the downstairs values, since 2/3 of the volume of the house was downstairs.

EFFECT OF SEALING DOORS AND DUCTS

The effect of sealing doors and ducts with tape is shown in Table 2. First, the ducts to the kitchen, bathroom, and clothes dryer fans were sealed, and the infiltration rates measured. In the table these values are compared with those calculated from the appropriate equation, Eq (6, 7, 8), the calculated values being used as estimated of infiltration rates before sealing the openings. The overall results indicate a slight decrease in infiltration rate, but the effect is small compared with the normal statistical variations in the data. Likewise, when the doors were also sealed, no systematic further decrease in infiltration rate was observed. However, when a 150 cm^2 make-up air opening in the floor of the furnace compartment was sealed, the air exchange rates were consistently less than those estimated from the regression lines. It is possible that under conditions of very low wind velocity, door cracks and duct openings, which represent a small fraction of the area of the house, played a comparatively small role in air exchange. This is consistent with the observation of Elkins and Wensman (7) that unless wind velocity was comparatively high, the opening of doors had little effect. On the other hand, the fact that significant air leakage occurred with many of the obvious leakage paths sealed indicates the presence of alternate paths through other cracks and porous areas in the structure.

COMPARISON OF SF_6 AND He TRACER GAS TECHNIQUES

Because there was still significant air exchange with many of the obvious leakage paths sealed, the question of whether molecular diffusion plays a significant role in air exchange is raised. According to Graham's law, the rate of molecular diffusion is inversely proportional to the square root of the molecular weight of the diffusing molecule. Thus, He with a molecular weight of 4 would be expected to have a diffusion rate of approximately six times that of SF_6 with a molecular weight of 146. Simultaneous measurements of infiltration rates were made with He and SF_6 under different indoor-outdoor temperature conditions. The results are summarized in Table 3. While agreement in air exchange rates by the two methods was not perfect there was no evidence that He escaped from the house more rapidly than SF_6. From this it is concluded that molecular diffusion played no more than a secondary role in determining air infiltration rates.

It should also be noted that the data in Table 3 were obtained under different conditions than the data in the preceding tables. Gas heat was used in three of the comparisons, air conditioning in two, and electric heat in one. Also, less time was allowed for steady state thermal conditions to be reached in the walls and roof of the house itself. While the data are insufficient to allow generalizations to be made regarding the comparative effects the three conditions of heating and cooling, in the examples chosen, air exchange rates were higher with gas heat and air conditioning than when electric heating was used.

In the case of gas heat one of the obvious differences is that the chimney is left open while it is closed when electric heat is used. However in these measurements with electric heat there was little increase in infiltration rate when the chimney was opened, suggesting that other factors may also be involved.

FORCED AIR EXCHANGE RATES

As an independent check on air exchange rates, a centrifugal blower was attached to the front door as shown in Fig. 2, and air was blown into the house. The air delivery rate was measured by means of a calibrated orifice plate located in a duct at the blower intake. Air exchange rates were estimated from the air delivery rates and the volume of the house. Simultaneous air exchange measurements by SF_6 dilution were made for comparison with sampling probes in the house (Fig. 2 and 3) and with one probe at the inlet of the blower. The comparison was made without heating or air conditioning so that the inside-outside temperature difference was minimal. However the furnace fan was operated continuously during the measurements. Also, the chamber was open to the outside. The results are shown in Table 4. In this case the tracer reentry error was larger than in the preceding measurements, and a correction was applied. When the tracer was introduced into the main ventilation system, the agreement between the two methods of estimating air exchange rate was within 0.1 of an air change per hour in four of six comparisons. While the actual closeness of the agreement may be somewhat fortuitous because of uncertainties in the volume of the house, as well as the role of closet space and stud space and the volume of furniture, the results suggest that the SF_6 tracer technique is capable of giving an essentially correct estimate of air infiltration rate. On the other hand, when the tracer was introduced into the house through the blower at the front door, the infiltration rates were 15 to 25 percent higher by the tracer dilution method than those calculated from the fan delivery rate.

In one set of measurements the furnace fan was off during the initial introduction of SF_6 and during the subsequent concentration measurements. Under these conditions, the semi-log plots of concentration vs time showed strong curvature and were uninterpretable as a first order rate process.

It is to be noted in Table 4 that the agreement between values based on sampling the return air and multipoint sampling were good provided the ventilating system was operating.

The results in Table 4 also suggest that the concentration of SF_6 was not dominated by artifacts such as adsorption on walls and surfaces. This is not an unexpected result, since low concentrations of the order of a few parts per billion have been stored in steel containers for a month or longer without significant change in concentration.

SOURCES OF ERROR IN AIR INFILTRATION MEASUREMENTS

Effect of Non-Uniform Mixing. Air exchange rates based on tracer dilution rates and calculated, as outlined in the derivation of Eq (5), tacitly assume perfect mixing of tracer and air or at least that the air leaving the structure has the same average tracer concentration as the air within the structure at any given time in the dilution process. In analyzing the effect of departures from this condition, it may be useful to consider two alternate mechanisms of tracer dilution as limiting cases. The first of these is the "perfect non-mixing" model. This is illustrated in Fig. 5B, while the perfect mixing case is represented in Fig. 5A. In the non-mixing model, fresh air enters as a front and pushed the tracer containing air pushes ahead of it. For a fixed air exchange rate, the average tracer concentration over the entire volume is an inverse linear function of time. If this is represented on a semi-log plot, a downward curvature is obtained as shown in Fig. 6, curve B. This plot corresponds to one change per hour. Fig. 6, curve A represents the change in relative tracer concentration with time at the same air exchange rate with perfect mixing.

The second non-uniform mixing model is the "dead-spot" model which is illustrated in Fig. 5C. In this model the upper volume contains completely stagnant air while in the lower volume perfect mixing occurs. In volume a, the relative concentration remains unchanged. That is $c_i/c_{i_o} = 1$. In the b volume $c_i/c_{i_o} = e - \frac{V_o}{V_b} t$, while for the entire enclosure:

$$c_i/c_{i_o} = f_a + f_b\, e^{-\frac{V_o}{V_b} t} \qquad (11)$$

where: f_a and f_b are fractions of the total volume which are stagnant and mixed respectively,
V_b is the volume of the b space in which perfect mixing occurs
V_o is the average rate at which air enters and leaves the enclosure,
c_i is the inside concentration of tracer at time t,
c_{i_o} is the inside concentration at $t = 0$.

Curve C of Fig. 6 is a semi-log plot for the ease where f_a and f_b = 0.5, and the air exchange rate averaged for the total volume is one air change per hour. According to this analysis, even if sampling is completely representative, there is an inherent error in the tracer dilution method if the rate of mixing is slow in comparison with the rate of air exchange.

While perfect mixing may not be achieved in actual infiltration measurements, experience suggests that the perfect mixing model is usually a better approximation of actual conditions than either of the two alternate models. However, curved plots of c_i/c_{i_o} vs time serve as a warning if large errors due to poor mixing are present. The analysis presented in Fig. 6 also suggest that poor mixing could lead to air exchange rates by the tracer dilution method which are higher or lower than the true rate depending on whether elements of the "perfect non-mixing" or the "dead-spot" model predominate. In addition to the effect that imperfect mixing may have on the mechanism of tracer dilution, it also contributes a sampling error which leads to random scatter of the individual concentration measurements. Thus, small errors due to imperfect mixing can be masked by normal variation in the data.

ERRORS IN CONCENTRATION MEASUREMENT

In addition to imperfect mixing, errors in the measurement of tracer concentration also contribute to uncertainties in estimated infiltration rates. According to Lovelock (17) the response of an electron capture detector is not logarithmic. However, Lovelock and Zlatkis (18) have made empirical use of Beer's law in analyzing Tetraethyl lead. With the instrument used in the present measurements, response to concentrations of SF_6 in the range of 5 to 20 ppb were essentially logarithmic, although a more generally applicable approximation is:

$$\log_e \frac{I}{I_o} = -k\ (c - \lambda) \qquad (1a)$$

where: λ represents a small intercept at $I/I_o = 1$. The effect of λ is small at very low infiltration rates because the difference between initial and final concentrations is small but becomes larger at higher infiltration rates. In the results presented in Tables 1-4, which were obtained with Argon as the carrier gas, it is estimated that biases up to 5 percent of the reported value are possible from this source and failure to consider this point could in some cases lead to much larger errors.

Another source of error in the measurement of tracer concentration is drift in instrumental response with time, particularly when the instrument is first put into operation. The effect of this error is minimized by measuring instrumental response against a reference standard with sufficient frequency to establish that drift is not significant, or if it is, to make suitable corrections.

Judging from the results in Table 4, the combined effect of non-uniform mixing and tracer measurement errors ranged from small in the case where tracer was introduced into the house ventilation system to 15 - 25 percent of the reported value for the experiment when tracer was introduced directly into the blower.

CONCLUSIONS

Air infiltration measurements using SF_6 as a tracer gas were made on a four-bedroom townhouse located in an environmental chamber. Wind velocity was eliminated as a variable, and the rate of air infiltration was shown to be linearly related to the inside-to-outside temperature difference. Reasonable correlation was also obtained between infiltration rate and the square root of the inside-outside temperature difference, as called for by the ASHRAE equation which relates air flow to the stack effect.

It was demonstrated that the operation of a residential furnace ventilation system could be successfully used to inject and mix tracer gas. Also, air infiltration rates, determined from single-point return air sampling, agreed favorably with multi-point sampling techniques when the furnace ventilation system was operated.

These measurements showed that when wind velocity was negligible, sealing obvious leaks such as doors and ducts had little effect in reducing the rate of air infiltration.

Measurements using SF_6 and He simultaneously as tracer gases yielded comparable results indicating that molecular diffusion did not play a major role in the air leakage process.

Forced ventilation rates produced by blowing air into the house at a measured rate were in essential agreement with air exchange rates simultaneously measured by SF_6 dilution, particularly when tracer was introduced into the house ventilating system rather than blown into the living room area.

Analysis of the effects of imperfect mixing on infiltration as measured by the tracer dilution method suggests that large errors would be accompanied by noticeable departure of tracer dilution rates from the first order decay law. Small errors, on the other hand, could be masked by the normal variations in tracer concentration.

The empirical response of the instrument to SF_6 was logarithmic in the 5 to 20 ppb range, but biases up to 5 percent of the values reported were possible due to departures from Beer's law. The effects of this source of error would have to be analyzed separately for any SF_6 measurement system used. Another potential source of error was drift in instrumental response with time. This required standardization against a reference mixture of SF_6.

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METRIC CONVERSIONS

Certain English units have been used in this paper. To obtain metric equivalents the following conversions are offered:

$$ft^2 \times 0.9290 = m^2$$
$$ft^3 \quad 0.02832 = m^3$$
$$F - 32 \times \frac{5}{9} = C$$

Table 1

Infiltration Rate as a Function of Temperature
Using SF_6 as Tracer Gas

Temperature Difference Between Inside and Outside F	Infiltration Rate Air Changes Per Hour				
	Method 1 (Hand Sampling)			Method 2 (Network Sampling	Method 3 (Return Air Sampling)
	Up-stairs	Down-stairs	Weighted Average		
52.3	-	-	0.61[1]	0.59	0.61
52.1	0.60	0.81	.74	.74	.82
51.1	.69	.68	.68	.70	.70
49.3	.49	.72	.64	.72	.66
49.1	.44	.60	.55	.57	-
39.5	.33	.53	.46	.51	.60
36.8	.42	.44	.43	.55	.52
23.6	.41	.47	.45	.50	.50
23.6	.46	.49	.48	.28	.42
14.5	.14	.19	.17	-	.16
14.3	.21	.33	.29	.24	.33
9.6	.11	.20	.17	-	.22

[1] Air samples from upstairs and downstairs were blended to obtain this value.

Table 2

Effect of Sealing Doors and Vents on Air Infiltration Rates

	Infiltration Rate in Air Changes Per Hour											
	Temperature Difference Between Inside and Outside F	Hand Sampling					Network Sampling			Return Sampling		
		Up-stairs	Down-stairs	Average Observed	Average Calc. (Eq 6)	Difference Observed Minus Calculated	Observed	Calc. (Eq 7)	Difference Observed Minus Calculated	Observed	Calc. (Eq 8)	Difference Observed Minus Calculated
Kitchen, bathroom, and clothes dryer ducts sealed	52.4	0.56	0.74	0.68	0.66	+0.02	0.48	0.68	-0.20	0.55	0.72	-0.17
"	50.9	.63	.47	.58	.64	- .06	.60	.67	- .07	.58	.70	- .12
Kitchen, bathroom, and clothes dryer ducts sealed plus doors sealed	49.5	.62	.70	.67	.63	+ .04	.48	.65	- .17	.75	.68	+ .07
Kitchen, bathroom, and clothes dryer ducts sealed plus doors and air port under furnace sealed	44.6	.28	.41	.37	.58	- .21	.41	.60	- .19	.51	.63	- .12

Table 3

Comparison of Infiltration Rates Using He and SF_6 as Tracer Gases

Infiltration Rate		Inside-Outside Temperature Difference F
He	SF_6	
Air Changes Per Hour		
0.68	0.82	67[1]
.84	.81	-23[2]
.45	.59	-22[2]
.47	.48	60[3]
.68	.83	41[1]
.66	.84	30-47[1]

[1] House heated by gas furnace with chimney leading into exhaust system to keep combustion products out of environmental chamber.

[2] House air conditioned.

[3] House heated by electricity.

Table 4

Comparison of Infiltration Rates by SF_6 Dilution With Those Estimated From Fan Rate and Volume of House

	Infiltration Rate		
	Based on $\frac{\text{Measured Fan Rate}}{\text{House Volume}}$	Based on SF_6 Dilution	
		Network Sampling	Return Sampling
	Air Changes Per Hour		
SF_6 introduced into house circulating fan	1.79	1.66	1.51
	1.20	1.16	1.17
	1.76	1.77	1.78
SF_6 introduced into front door through blower (no internal premixing)	1.77	2.07	-
	1.03	1.37	1.32

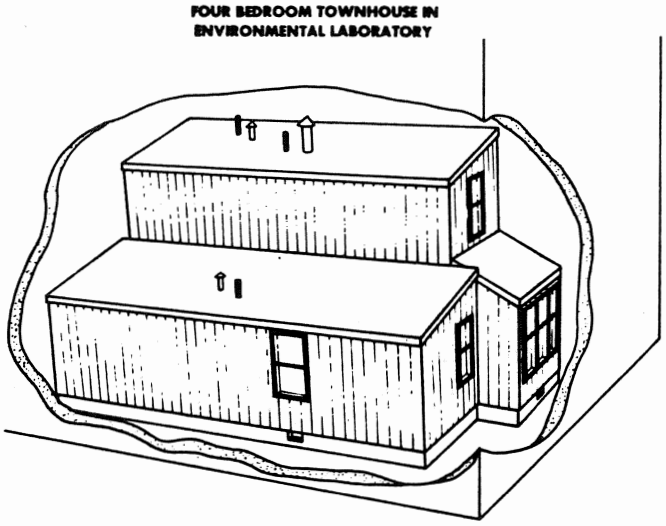


Fig. 1 Four-bedroom townhouse in environmental chamber

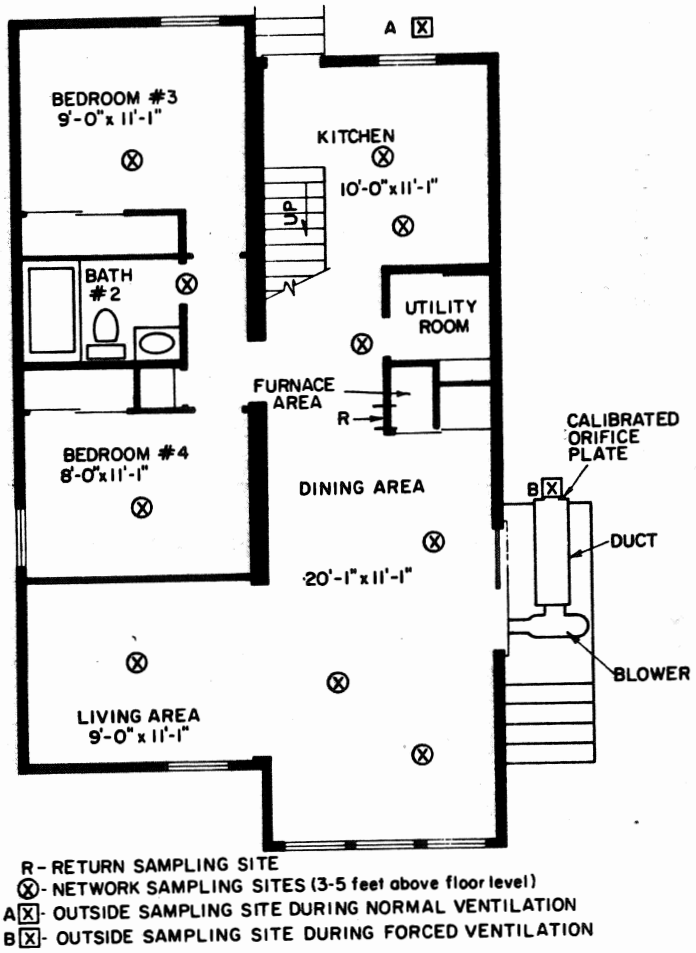


Fig. 2 First floor plan of townhouse

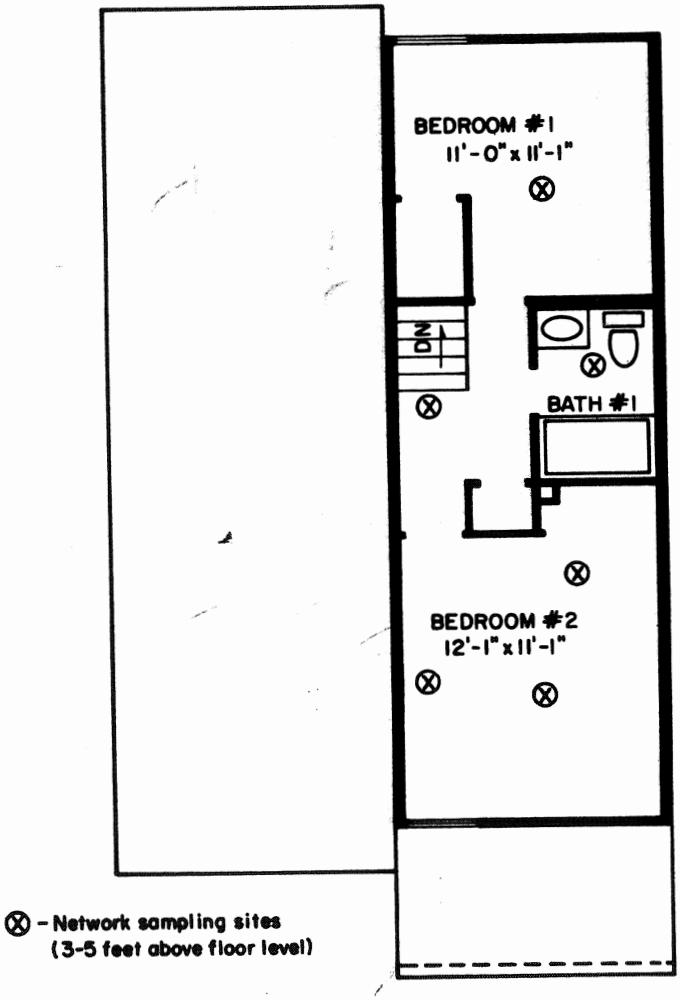


Fig. 3 Second floor plan of townhouse

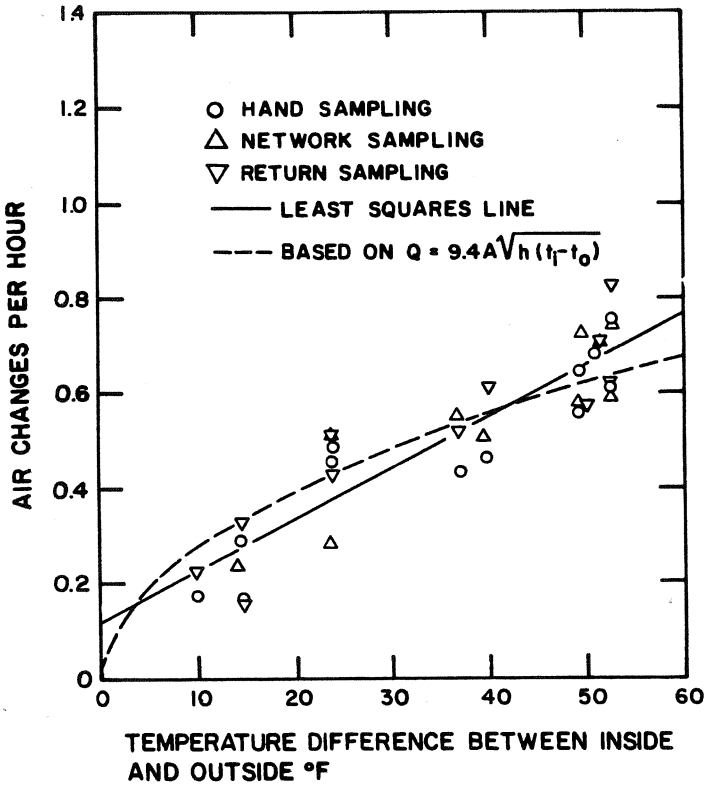
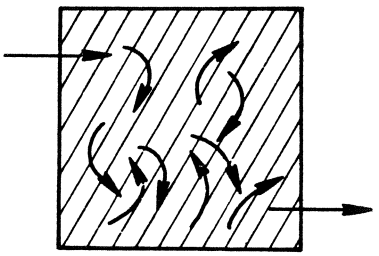
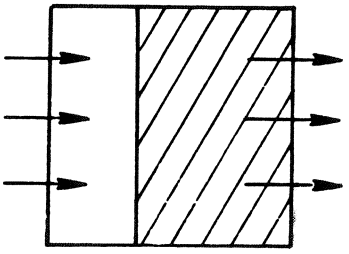


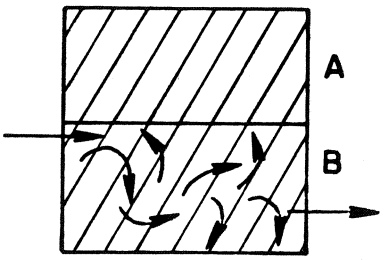
Fig. 4 Infiltration as a function of temperature difference between inside and outside



A. PERFECT MIXING MODEL



B. PERFECT NON-MIXING MODEL



C. DEAD-SPOT MODEL

Fig. 5 Diagrammatic representation of three possible models of tracer dilution

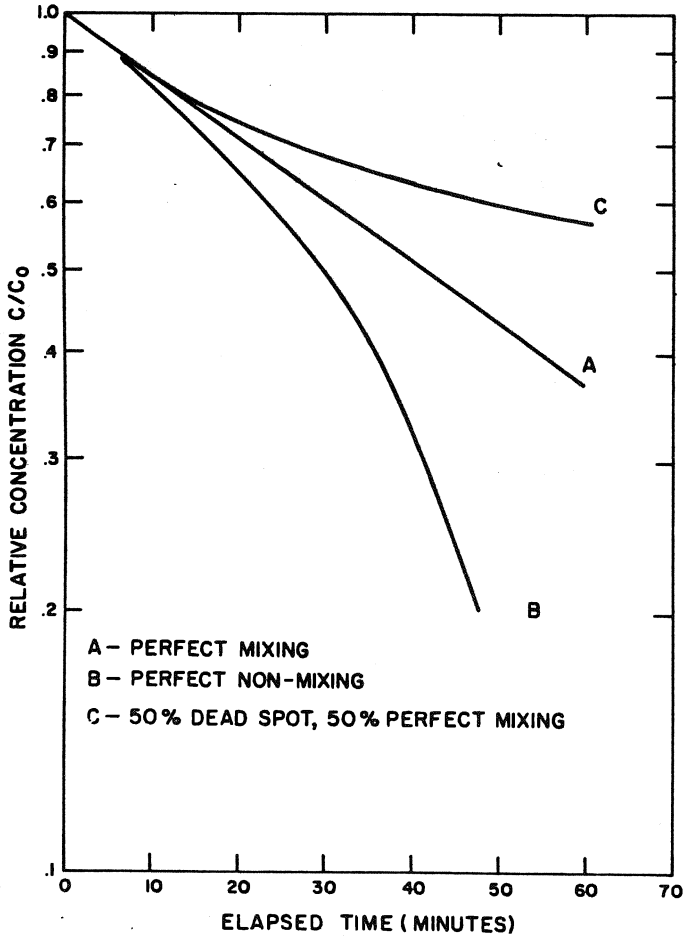


Fig. 6

DISCUSSION

ROBERT A. MACRISS (Institute of Gas Tech, Chicago IL): You indicated that use of SF_6 tracer gas in the parts per billion range to measure the level of air infiltration in houses can be interferred with by Freon or other halogented hydro-carbons in the air of the house. Do you then agree that since the presence of such substances in the house may be at high levels of several PPM at a time (from air conditioner leakage and refrigerator leakage of aerosol propellant use in the home), the SF_6 method might not be a feasible, practical tracer technique to use in occupied homes and buildings?

HUNT and BURCH: Nearly every building in which we have made measurements has contained a refrigerator and an air conditioner. Normal leakage from these devices is not detectable as evidenced by background measurements before release of SF_6. We have, however, encountered high concentrations in our own laboratory when refrigerants have been added to or released from experimental equipment.

Aerosol propellants are another matter. There would have to be some control over their use when making measurements in an occupied home. If an aerosol were used before or during a run, however, it would usually be detectable.

Also, in a chromatographic procedure there is the possibility of separating interfering substances from SF_6 before detection, but it would be better if possible to avoid them.

HAROLD ORR (National Research Council of Canada, Saskatoon, Sask. Canada): Have you considered controlling the concentration of tracer gas in the space and then measuring the rate of addition to determine the infiltration rate? The slope of the concentration time curve is fine for steady-state conditions, but it is not suitable for real conditions?

HUNT and BURCH: Controlling the concentration of tracer gas is difficult because there is a time lapse between addition of tracer and achievement of reasonably uniform mixing. An alternate approach, although we have never used it, might be to add tracer at a measured rate and monitor the concentration as a function of time. This method might have some advantage in automated measurement of infiltration. However, mixing of the tracer may present a problem. When using the time-decay method it is possible to wait until mixing is fairly uniform before making measurements.

The view that the concentration decay rate is not suitable for real conditions implies that infiltration rate is continually changing and that a meaningful average rate over a selected time interval cannot be obtained. Experience suggests that this is too pessimistic a view.

LORNE NELSON (Honeywell, Minneapolis MN): From some of our tracer gas measurements on air infiltration rates, the effect of relative humidity was noted on the value of the air change rate. Were measurements of relative humidity made during the tests and if so, was a relationship determined between relative humidity, as affected by a humidifier, and the air change rate?

HUNT and BURCH: We have not examined the effect of relative humidity on infiltration rate. If leakage occurs through larger openings, it would be difficult to postulate a mechanism by which relative humidity affects infiltration rate. However, if significant leakage occurs through the wall material to a greater extent than is generally supposed, skrinking and swelling might be expected to exert an effect. We are currently studying another house in an outdoor environment where relative humidity data is available, and we will certainly examine it from this point of view.

SAUL STRICKER(Ontario Hydro, Toronto, Ont., Canada): Does SF_6 dissociate as it goes through the hot furnace, and in this manner does it cause an increase in electronegative gas with a resulting lower infiltration rate?

HUNT and BURCH: According to data supplied by the manufacturer, SF_6 is stable in quartz at 500 C (932 F) but may decompose at lower temperatures, possibly 150 C (300 F) in the presence of certain metals. We have measured detector response to samples taken upstream and downstream from the heat exchanger of an oil furnace. If any decomposition of SF_6 occurred, it was not evident in the response of the electron capture detector.

DR. ULRICH BONNE (Honeywell, Inc., Bloomington, MN): A quick look at Table 3 of your paper seems to indicate that the air exchange rates obtained for He are generally smaller than those obtained for SF_6. Could it be that the small concentrations used in the tracer studies with SF_6 are reduced more rapidly than those of He due to a contribution of adsorption to interior furnishings?

HUNT and BURCH: Regarding the differences between infiltration rates by He and SF_6 as reported in Table 3, He is an ideal tracer if adsorption on walls and furnishings is an important source of error. Helium is not significantly adsorbed even by colloidal solids at the temperature of liquid nitrogen. No other tracer gas can meet this condition. However, we believe the adsorption of SF_6 on walls and surfaces is not a significant source of error in normal infiltration measurements. For example, many surfaces in homes are cellulosic in nature (ie, wall paper, woods, celotex, press board, cotton fabrics, etc.). When SF_6 was introduced into a balloon containing 3 grams of absorbent cotton, where the surface to volume ratio was much greater than in a house, a concentration of 7.4 ppb was measured within the first minute of exposure and 7.6 ppb after an elapse of an hour. The standard deviation of samples measured from the same container is usually about 0.2 ppb. Perhaps this type of experiment might be extended to other materials such as synthetic fibers, plastics, wool, gypsum, concrete, etc.

Indirect evidence that SF_6 is not significantly adsorbed on surfaces derives from the fact that it may also be used to estimate the volume of an enclosed space. When a measured amount of tracer is uniformly distributed throughout the space, the concentration should be inversely proportional to the volume of the space. If significant adsorption on surfaces occurred, volumes estimated by this method might exceed the gross volume of the enclosure. This has never been observed. For the foregoing reasons, we believe that the differences between infiltration rates by SF_6 and He in Table 3 are due to some other cause than adsorption on walls and furnishings.

DR. BONNE: The increase in infiltration mass flow as the outdoor temperature decreases would indicate that its contribution to the total house energy load increases faster than directly proportional to the room-outdoor temperature difference. Does this mean that the total house load also increases faster than that temperature difference (if the effect of wind and solar radiation are disregarded)? What functional relationship would you recommend to use with your building load program NBSLD?

Referring to your Table 3, I wonder if the stack was closed when you measured infiltration losses while the house was being heated electrically. If so, a comparison between data on the first and fourth row could be used to determine the fraction of combustion furnace air requirements that would add to total house infiltration (assuming that wind conditions were similar). Preliminary data of our field study put that figure between 50 to 80%.

HUNT AND BURCH: Regarding the calculation of energy load due to infiltration as it is affected by outside temperature, the following relationship is used:

$$q_i = \rho V C_p \mathcal{J}(\Delta t) \cdot \Delta t$$

where:

q_i = hourly energy requirement due to infiltration

ρ = density of air at inside temperature

V = volume of house

Cp = heat capacity per unit mass at constant pressure

$\mathcal{I}_{(\Delta t)}$ = infiltration rate corresponding to the observed inside-outside temperature difference. Air change/hr

Δt = temperature difference between in - and outside air

It might be useful to consider what would happen if the density of air at outside temperature instead of indoor temperature were substituted in the equation. For a 50 F temperature difference, such a substitution would produce about a 10% difference in q_i or perhaps a 2 - 3% difference in the total calculated heating load of the house.

Regarding the estimation of combustion air requirements from the difference in infiltration rates in rows 1 and 4 of Table 3, we would rather see such an estimate based on measurements more explicity designed to measure this quantity.