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PLACEMENT OF TRACER GAS SOURCES AND SAMPLERS TO MEASURE INFILTRATION RATE

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ABSTRACT

Two placement protocols of conservative tracer gas sources were compared in order to measure infiltration rates for residences. Perfluorocarbon was used as the conservative tracer gas, and diffused at a constant rate from a small aluminum capsule through a silicone rubber stopper. The tracer gas was passively sampled by a capillary absorption tube containing activated charcoal. The tracer gas concentration was determined by gas chromatography with an electron capture detector.

Ten homes in the Boston area including single family houses and multi-family homes, as well as single-floor homes and multi-floor homes were chosen as subject homes in this study performed in the late fall of 1984. Two different types of tracer gases were applied. In placement protocol 1, several sources of one type of the tracer gases were placed in the kitchen and tracer gas sources of the other type were placed in the master bedroom. In placement protocol 2, the sources of the secondary type were located in various rooms of the house except for the kitchen. Samplers were placed in the kitchen, living room, master bedroom and other bedrooms.

The most homes could be divided into a kitchen zone and a bedroom zone from distribution of the tracer gas concentrations. Therefore air flow rates into and from each zone were calculated from 2-zone mass balance equations under the assumption of complete mixing in each zone. When the secondary sources were located in various rooms in placement protocol 2, negative flow rates were obtained in many cases. This indicated that the complete mixing assumption was not met consistently or that some of the secondary sources might be located in the kitchen zone. We, therefore, propose a placement protocol of sources and samplers that sets the primary source in a kitchen, the secondary source in a master bedroom and samplers in each of these rooms.

1. INTRODUCTION .

Reduction of infiltration rate or air exchange rate may be required to save energy consumption for heating or cooling in homes. From the perspective of maintaining indoor air quality, too much reduction of the infiltration rate may cause adverse health effects by increasing exposures to certain air pollutants. Keeping moderate temperature in homes with less energy consumption while concurrently achieving lower levels of indoor air pollution has become a social demand. There are many factors taken into account when attempting to meet this demand, such as heat loss by conduction and by infiltration, source strength of air pollutants and their decay rates indoors, residence time of inhabitants, and the dose-health effect relationship.

Two measuring procedures for determining the infiltration rate have been devised. One is a blower door technique in which the house is pressurized by a calibrated fan and kept at a constant pressure. The infiltration rate is determined by measuring the air flow rate necessary to hold the pressure constant (1). This sampling method is simpler than most as the test duration is about one hour. The application of results, however, may be limited because air flow patterns during the experiment may differ from those typically observed. Also, if the use pattern of vents, windows, and doors differs from the usual activity, the results could be influenced significantly.

The second technique is a tracer gas method. By knowing the amount of tracer gas discharged in a house and the difference of tracer gas concentrations inside and outside of the house, the infiltration rate can be calculated from mass balance equations. Validity of the calculation is dependent upon uniformity of the tracer gas concentrations indoors and outdoors. If this is not so, the house is divided into several zones such that the uniformity requirement is satisfied in each. The infiltration rate is obtained differentially or integrally in this technique. In the differential method, sometimes called a decay method, the tracer gas is discharged within a short period and its decay rate is measured. The time constant of the change in response gives the air exchange rate. When the tracer gas is continuously discharged into the house at a constant rate, an average infiltration rate is calculated from the tracer gas concentrations and the emission rate. The air exchange rate is then obtained by dividing the infiltration rate by the house volume. The advantage of the tracer gas method is that the infiltration rate is measured under activity conditions which are typical for the occupants. A disadvantage is the requirement for uniformity of tracer gas concentration or complete mixing of the tracer gas within a defined "mixing volume".

Residential air infiltration rate is determined primarily by several physical parameters: wind velocity and direction, an opening of the building envelop and the indoor/outdoor temperature difference across the building envelop. These factors are modified by house structure and human activities, such as closing and opening of windows and doors, and use of combustion appliances and vents. Therefore, the air infiltration rate will vary among homes, as well as within a home, with time. The average air infiltration rate over a period of weeks to months is the most representative of long term conditions when considering energy consumption and impacts of indoor air pollution. The entire space within a residential unit does not exchange equally nor uniformly with outdoor air. The determination of internal air movement as well as whole-house air exchange is of interest to various energy and pollution studies. At present, however, there is no clear guidance on the proper use of constant emission source tracers and integrating collectors for the residential air exchange rate measurements.

This paper presents the results of a detailed study of air exchange and internal air mixing within 10 conventional homes. Perfluorocarbon tracer gas sources (PFT) and passive charcoal collectors were used in a variety of configurations over the several winter weeks of this study. The study concludes with practical consideration for protocol design for measuring air infiltration and internal air flows using the PFT system.

2. THEORETICAL MODEL

2.1 1-Zone, 1-Tracer Gas Model

If the air mass in the entire house is mixed completely, we can obtain a whole-house external air flow rate by using 1 tracer gas. The external air flow rate (F) and air exchange rate (E) are as follows:

$$F = S/C \qquad (1)$$

$$E = F/V \qquad (2)$$

Here C (ppt) : tracer gas concentration
E (1/hr) : air exchange rate
F (m^3/hr) : air flow rate
S (nl/hr) : emission rate of tracer gas
V (m^3) : mixing (house) volume

2.2 2-Zone, 1-Tracer Gas Model

If a house unit consists of two zones where complete mixing is assumed separately, but only 1 type of tracer gas is available (Figure 1), four independent equations are derived from mass balance assumption of air and tracer gas.

$$C_1F_2 + C_1F_5 - C_2F_6 - S_1 = 0 \quad (3)$$

$$F_1 + F_6 - F_2 - F_5 = 0 \quad (4)$$

$$C_2F_3 + C_2F_6 - C_1F_5 - S_2 = 0 \quad (5)$$

$$F_4 + F_5 - F_3 - F_6 = 0 \quad (6)$$

There are six unknown variables, F_1 through F_6, and 4 independent equations, so generally we cannot solve air flow rates for the unknown variables. However the range of the whole house external air flow rate (WHA $= F_1 + F_4$ or $F_2 + F_3$) can be obtained.

F_2, F_3, F_5 and F_6 are rewritten as a function of F_1 and F_4 from Eqs. (3) through (6) when C_1 is not equal to C_2.

$$F_2 = (-C_2(F_1 + F_4) + (S_1 + S_2))/(C_1 - C_2) \quad (7)$$

$$F_3 = (C_1(F_1 + F_4) - (S_1 + S_2))/(C_1 - C_2) \quad (8)$$

$$F_5 = (C_2F_4 - S_2)/(C_1 - C_2) \quad (9)$$

$$F_6 = (-C_1F_1 - S_1)/(C_1 - C_2) \quad (10)$$

In order to meet the conditions that all air flow rates (F_1 through F_6) are positive, F_1 and F_4 must be in the hatched domain on the F_1-F_4 plane as shown in Figure xx. The dotted line indicates the relationship of WHA $= F_1 + F_4$. The intercepts of the dotted line with F_1-axis and F_4-axis stand for WHA. Since the range of WHA is between $(S_1 + S_2)/C_1$ and $(S_1 + S_2)/C_2$, the range of WHA is narrower when C_1 and C_2 are closer each other. When C_1 equals C_2, WHA can be determined as $(S_1 + S_2)/(C_1$ or $C_2)$. If there are more than two zones in the house, we can get the same conclusion as the two zones' model, that is, the closer the tracer gas concentrations in each zone are, the narrower the range of WHA is.

Accordingly, it is important to determine the placement protocol of the tracer gas sources making the tracer gas concentrations uniform or close in the subject house.

2.3 2-Zone, 2-Tracer Gas Model

When two different types of tracer gas are used in a 2-zone house (Figure 2), 6 independent equations regarding mass balances of tracer gases and air are established and air flow rates into and from each zone can be calculated in general.

$$F_1 = \{S_{11}(C_{21} - C_{22}) - S_{21}(C_{11} - C_{12})\} / D \quad (11)$$

$$F_2 = \{-C_{22}(S_{11} + S_{12}) + C_{12}(S_{21} + S_{22})\} / D \quad (12)$$

$$F_3 = \{C_{21}(S_{11} + S_{12}) - C_{11}(S_{21} + S_{22})\} / D \quad (13)$$

$$F_4 = \{S_{22}(-C_{11} + C_{12}) + S_{12}(C_{21} - C_{22})\} / D \quad (14)$$

$$F_5 = \{-C_{12}S_{22} + C_{22}S_{12}\} / D \quad (15)$$

$$F_6 = \{-C_{21}S_{11} + C_{11}S_{21}\} / D \quad (16)$$

Where D is the determinant of the mass balance equations, that is, $D = C_{12}C_{21} - C_{11}C_{22}$. The suffixes on Cij and Sij refer to i-th type of tracer gas and j-th zone. Air exchange rates in zone-1, zone-2, and the entire house are defined as follows:

$$E_1 = (F_1 + F_6) / V_1 = (F_2 + F_5) / V_1 \quad (17)$$

$$E_2 = (F_4 + F_5) / V_2 = (F_3 + F_6) / V_2 \quad (18)$$

$$E = (F_1 + F_4) / (V_1 + V_2)$$
$$= (F_2 + F_3) / (V_1 + V_2) \quad (19)$$

If type one tracer gas sources are set only in zone one and type two in zone two, equations 11 through 16 can be simplified as follows:

$$F_1 = \{f_1(R_2 - 1)\} / (R_1R_2 - 1) \quad (11)'$$

$$F_2 = (-f_1 + f_2R_1) / (R_1R_2 - 1) \quad (12)'$$

$$F_3 = (f_1R_2 - f_2) / (R_1R_2 - 1) \quad (13)'$$

$$F_4 = \{f_2(R_1 - 1)\} / (R_1R_2 - 1) \quad (14)'$$

$$F_5 = -f_2 / (R_1R_2 - 1) \quad (15)'$$

$$F_6 = -f_1 / (R_1R_2 - 1) \quad (16)'.$$

Here f_1 and f_2 have units of air flow rate, and R_1 and R_2 are the ratios of the tracer gas concentrations in each zone, or $f_1 = S_{11}/C_{11}$, $f_2 = S_{22}/C_{22}$, $R_1 = C_{12}/C_{11}$ and $R_2 = C_{21}/C_{22}$.

3. METHODS AND MATERIALS

Two types of tracer gas, perfluoro-monomethyl-cyclohexane (PMCH) and perfluoro-dimethyl-cyclohexane (PDCH), were used in this study. These gases were released in a house through permeation tubes whose emission rates were gravimetrically measured prior to the study as 1700 nl/hr and 1100 nl/hr at 25 C for PMCH and PDCH respectively. Tracer gases were passively sampled by activated charcoal (Ambersorb 347) in capillary absorption tubes (CAT) which were placed in various locations throughout the house. After exposing CATs to indoor air for one week, the amount of the adsorbed tracer gases were analyzed with a GC/ECD following the procedure reported by Dietz et al. (2).

The homes of ten of our colleagues living in the Boston area were chosen as subject homes. Five out of ten houses were 1-floor homes and the others were 2-floor or more. Characteristics of these houses are summarized in Table 1. CATs were placed in a kitchen, living room, master bedroom, and other bedrooms. For this study, we have defined the master bedroom as the bedroom farthest from the kitchen. CATs were set approximately 1 meter off the floor and at least 2 meters from the tracer gas sources. Three more CATs were put in the living room as duplicates and to determine the vertical distribution of tracer gas concentrations. Two CATs were placed about 1.5 meters from the floor and one CAT was near the ceiling.

Two different protocols for the placement of tracer gas sources were compared. In placement protocol 1, 3 PMCH permeation tubes and several PDCH tubes were located in the kitchen and in the master bedroom respectively. The number of PDCH tubes ranged from 2 to 4 tubes according to the house volume. In each location they were placed at a doorway near the center of the house and at an elevation of about 1.8m. In placement protocol 2, one PDCH source was placed in the master bedroom and the others were distributed in several rooms other than the kitchen. The placement of PMCH tubes did not differ from that in protocol 1.

Weekly-averaged air flow rates were measured from October through December 1984 using these protocols. The measurements were performed four times in each house by repeating protocols 1 and 2.

4. RESULTS AND DISCUSSION

4.1 Reproducibility

A pair of CATs were placed 1 meter off the floor in the living room for examination of reproducibility. As shown in Figure 3, tracer gas concentrations measured by a pair of duplicated CATs agreed well and the correlation coefficients of 36 data points were 0.986 for PMCH and 0.996 for PDCH. The standard error of estimation was 1.7 (ppt) with a mean of 23.3 (ppt) and 0.8 (ppt) with a mean of 9.1 (ppt) for PMCH and PDCH respectively.

4.2 Vertical Profile of Tracer Gas Concentrations

In addition to the pair of the duplicated CATs in the living room, two more CATs were set at a few centimeters below a ceiling and at halfway up one wall. Vertical profiles were nearly uniform in most cases for PMCH and in all cases for PDCH. Vertical stratification of PMCH concentrations was found in some of the housing units which were single floor and relatively small. Average PMCH concentrations increased slightly with elevation of sampling height. Since PMCH tubes were located at the top of the doorway in the kitchen, it is possible that PMCH tracer gas might be dispersed in a plume from gas stoves with subsequent vertical stratification due to buoyancy. On the other hand, the buoyancy effect on PDCH tracer gas, for which sources were placed in rooms other than the kitchen, would not be expected hence the uniform profile.

4.3 Room to Room Variation of Tracer Gas Concentrations

A horizontal gradient of tracer gas concentrations was observed in both placement protocols (Table 2). Average PMCH concentrations of all measurements were 29.2 (ppt) in the kitchen, 23.0 (ppt) in the living room and 18.8 (ppt) in the master bedroom. The differences were statistically significant. The PMCH average in the kitchen, where the PMCH sources were located using both placement protocols, was the highest and that in the bedroom was the lowest. On the contrary, the average PDCH concentration, which also significantly differed, was highest in the master bedroom and that in the kitchen was the lowest. They were 7.5 (ppt), 9.2 (ppt) and 24.3 (ppt) in the kitchen, living room and master bedroom respectively. The tracer gas concentrations lowered with increase of the distance from the sources.

The locations of the PDCH sources differed between protocols 1 and 2. PDCH sources were placed in various rooms of the house by protocol 2 in order to achieve uniform PDCH concentration. However the averages of PDCH concentrations in each location were statistically different by both protocols, although concentration differences between the three locations in protocol 2 were smaller than those found in protocol 1 as expected.

In order to apply the multi-zone, 1-tracer gas model discussed in section 2.2, horizontal variability in tracer gas concentrations was assessed by using the coefficient of variation (CV) of the tracer gas concentrations measured in the various sampling locations (Table 3). Small value of this statistics suggest uniformity of concentrations and thus good mixing. Large values suggest poor mixing. For both protocols, PMCH displayed modest values, 26.2% and 29.2% for protocols 1 and 2. PDCH values were larger and differed between protocols: 71.0% and 41.0% for 1 and 2. This suggest poor mixing of PDCH tracer, especially under protocol 1. We speculate that the better mixing displayed for PMCH, of which sources were located in the kitchen only, may be due to the thermal-plume mixing of kitchen air with the whole-house air associated with cooking. And it may also be due to the relatively large openings in the kitchen zone. The larger CV's associated with PDCH may be due to the converse of this effect: placement of sources in rooms, such as bedrooms which mix less with the whole-house air.

When the sum of PMCH and PDCH concentrations were dealt with as one type of tracer gas, its average CV was significantly lower than that of PDCH ($p<0.001$) alone and slightly lower than that of PMCH alone (Table 3). The histogram of the coefficients of variation for the sum of PMCH and PDCH concentrations (CVMD) is illustrated in Figure 4. Thirty-three cases out of 36 had CVMD less than 50%. The CVMDs over 50% were observed in one house (home code E) where the concentrations of PDCH with sources placed on the second floor, were less than 1 (ppt) in the kitchen and living room located on the first floor, suggesting minimal down-mixing of second floor air. When CVMDs of this house were excluded from the calculation of the average, the average CVMD was reduced to 20.6% as shown in Table 3. As discussed in section 2.2, the range of WHA is the narrowest when the sum of PMCH and PDCH are used as the one type of the tracer gas.

4.4 Air Flow Rates Measured by One Tracer Gas

If the air in the house is completely mixed, one can calculate WHA with one type of tracer gas (Eq 1). This is not the case of our investigation. According to the theoretical consideration discussed in section 2.2, the narrower range of WHA is obtained when the horizontal distribution of the tracer gas concentrations is smaller. The coefficient of variation of the tracer gas concentrations in the house is one of the measures to evaluate how close the tracer gas concentrations are. The smallest average of the coefficient of variation for the tracer gas was obtained when the sum of PMCH and PDCH was dealt with as one type of tracer gas. The best estimate of WHA could therefore be obtained by the average concentration of the sum of the two tracer gases.

The best estimates of the external air flow rate of a whole house thus calculated ranged from 90.3 (m^3/hr) to 431.2 (m^3/hr) with a mean of 265.1 (m^3/hr) and standard deviation of 94.8 (m^3/hr) (Figure 5). No significant effects of the placement protocol and number of floors in a house were observed on them. The best estimates of each house seemed to be constant over the 4 weeks of the measurements (Table 4).

The best estimates of the external air flow rate of a whole house were compared with whole house external air flow rates calculated from average tracer gas concentrations obtained by various averaging methods (Table 5). When the average concentrations of PMCH alone or PDCH alone in the kitchen, living room and bedroom were used, the whole house external air flow rates calculated from the averages of PMCH concentrations correlated better with the best estimates than did the PDCH averages. Standard error of the regression of the whole house external air flow rate calculated from PMCH concentrations on the best estimates was about 60 (m^3/hr). The PMCH tracer gas indicated the external air flow rate of the whole house fairly well, even though the sources were located in the kitchen only.

When the tracer gas concentrations of the two sampling locations, kitchen and bedroom, were selected for averaging, the whole house external air flow rates calculated from the average of PMCH plus PDCH concentrations in these two locations correlated well with the best estimates. The standard error of the regression was about 25 (m^3/hr) and correlation coefficient exceeded 0.95. The values for whole-house external air flow rate and best estimate were nearly identical with the tracer gas sampling in the kitchen and living room. This information could reduce the burden of a future air exchange study under restrictions of cost and labor.

4.5 External Air Flow Rates Measured by Two Different Types of Tracer Gases

The external air flow rate between the inside and outside of the house and the internal air flow rate between zones were calculated using the tracer gas concentrations in the kitchen and master bedroom as representatives of zone one and zone two concentrations. Equations 11' through 16' were used under the assumption that the PMCH sources and PDCH sources were placed only in zone one and zone two respectively. One of the necessary conditions of the two zone model is that the concentration of tracer gas A in one zone, where tracer gas sources of A are placed, must be higher than the gas A concentration in the other zone.

Mathematically this implies that R_1 and R_2 in section 2.2 are equal to or less than 1. Seven cases out of 36 cases could not meet this necessary condition and six of them utilized protocol 2. Since PDCH sources were placed in various locations by protocol 2, some of them might have been located in the kitchen zone. As a result of the misclassification of PDCH source location, we found cases which could not meet the necessary condition. It is practically difficult, however, to classify PDCH sources placed at various locations of the house into the appropriate zone.

The other necessary condition of the two zone model is that all of the air flow rates (F_1 through F_6) must be positive or zero. There were 5 cases which satisfied the first necessary condition but did not fulfill the second one, that is, air flow rates from the kitchen zone to outside (F_2) in these cases were negative (Table 6). F_2 is calculated from the ratio of $(-f_1 + f_2R_1)$ to $(R_1R_2 - 1)$ (Eq. 12'). Since $(R_1R_2 - 1)$ is always negative, F2 becomes negative when -f1 is greater than f2R1. These five cases could be classified into 3 groups; a) both R_1 and R_2 were over 0.8 (case 1), b) R_2 was above 0.8 (case 2,3 and 5) and c) both R_1 and R_2 were less than 0.8 (case 4). In group a), it is possible that there is only one zone in the house, because both R_1 and R_2 were close to one. In fact the other measurement by protocol 1 in the house indicated high air flow rates between two zones, 1013.0 (m^3/hr) and 846.2 (m^3/hr) for F_5 and F_6 respectively. In group b) in which all cases were measured by protocol 2, R_2 and f_2 were relatively large. This implies that some PDCH sources must be considered as if they had been placed in the zone one (kitchen zone) and consequently, equation 11 through 16 should be used to calculate the air flow rates instead of equation 11' to 16'. In group c), f_1, R_1 and R_2 were relatively small. Further investigation is required for physical interpretation of this case.

The suitability of the two zone model to the subject houses were evaluated using cases which met the necessary conditions, because there is no definitive sufficient conditions of the two zone model. The external air flow rates of a whole house based upon the two zone model were compared with the best estimates. As shown in Figure 6, the external air flow rates of a whole house calculated from the two zone model, that is, the sum of F_1 and F_4 or the sum of F_2 and F_3, agreed well with the best estimates. The regression parameters of F_1 plus F_4 on the best estimates were 1.11 for the slope and -20.0 (m^3/hr) for the intercept, with a correlation coefficient of 0.886 and standard error of estimation of 48.9 (m^3/hr). When evaluating the placement protocols, the whole house external air flow rates by both protocols correlated well with the best estimates (Table 7). Eighteen cases out of 21 by protocol 1 and 6 cases out of 15 by protocol 2 could fit the two zone model.

4.6 Internal Air Flow Rates Measured by Two Different Types of Tracer Gases

The matrix of correlation coefficients between external and internal air flow rates calculated by the two zone model is shown in Table 8. The external air flow rates between the outside and each zone, and the internal air flow rates between two zones were well correlated. The correlation coefficients of the external air flow rates in zone one (F_1 and F_2) and zone two (F_3 and F_4) were 0.912 ($p<0.001$) and 0.650 ($p<0.001$) respectively. The internal flow rates between two zones (F_5 and F_6) had a correlation coefficient of 0.979 ($p<0.001$). This indicates that air flow rates passing through the same envelop were highly correlated but that they were independent of air flow rates passing through the other envelop.

The whole house external air flow rate by the two zone model, F_1 plus F_4 or F_2 plus F_3, was significantly correlated with only the kitchen zone external air flow rates, F_1 and F_2. This suggests that the external air flow rates of the kitchen zone dominated those of the bedroom zone. In fact the ratio of fresh air intake in the bedroom zone to that in the kitchen zone (F_4/F_1) was less than one with the exception of one case (Figure 7). The exceptional case, home code D, was a multi family house in which the kitchen and bedroom were located on the first and second floor respectively, and placement protocol 2 was used. Further investigation is required to interpret this case.

The summary statistics of the air flow rates obtained from the two zone model were shown in Table 9. In general, the external air flow rates in the kitchen zone were about 200 (m^3/hr). The external air flow rates in the bedroom zone and the internal air flow rates between two zones were around 100 (m^3/hr) which was about half of the kitchen zone external air flow rates.

5. CONCLUSIONS

Infiltration rate measurements of 10 residential houses using a perfluorocarbon tracer gas method were repeated 4 times varying the placement protocol for the tracer gas sources. We point out the following findings:

1) Vertical stratification of the tracer gas concentration was negligible, while the tracer gas concentrations were significantly different horizontally.

2) Tracer gas sources placed in a kitchen resulted in better dispersion than those set in other locations in a house.

3) The average concentration of two different types of tracer gases, with sources located in a kitchen and other locations in the

house, gave the best estimates of whole house external air flow rates.

4) Tracer gas sources placed in a kitchen yielded similar estimates of whole house external air flow rates to the best estimates.

5) Putting two different types of tracer gas sources in a kitchen and bedroom separately met requirements of the two zone model better than setting one type of source in a kitchen and spreading the other type in various places.

6) Average air flow rates in the kitchen zone to and from outside were about 200 (m^3/hr) and those of a bedroom zone were around 100 (m^3/hr). Internal air flow rates between a kitchen zone and bedroom zone were about 100 (m^3/hr).

Acknowledgement

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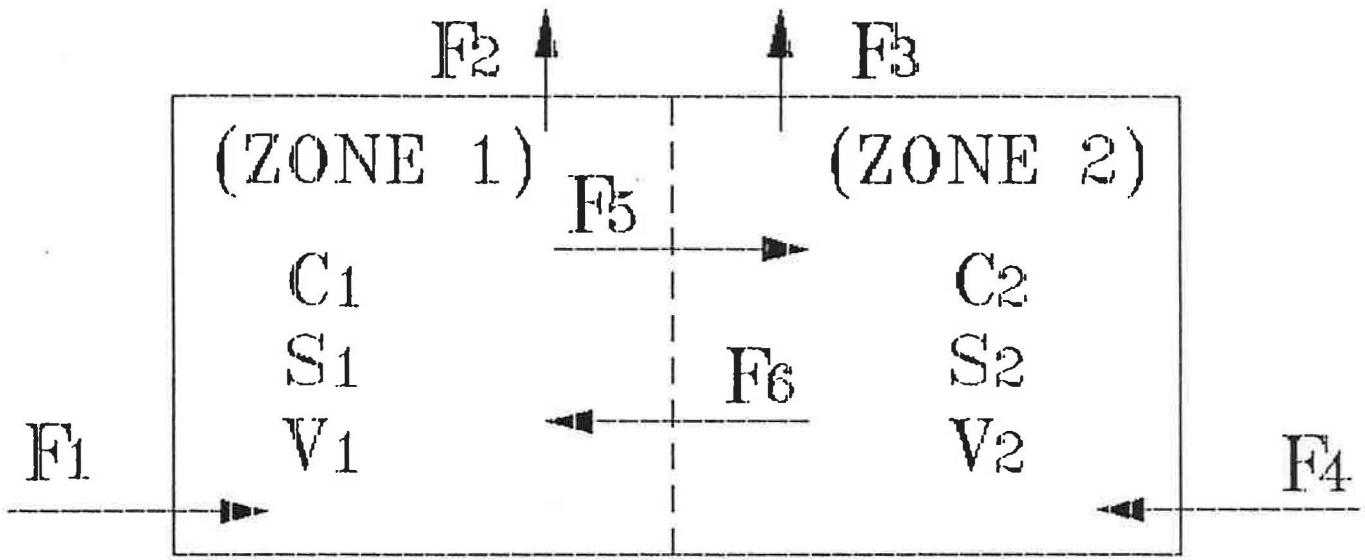
2. Dietz, R.N., and Cote, Z.A. (1982). Air infiltration measurements in a home using a convenient perfluorocarbon tracer technique, Environmental International, 8, 419-433

TWO-ZONE, ONE TRACER GAS MODEL



C : TRACER GAS CONCENTRATION

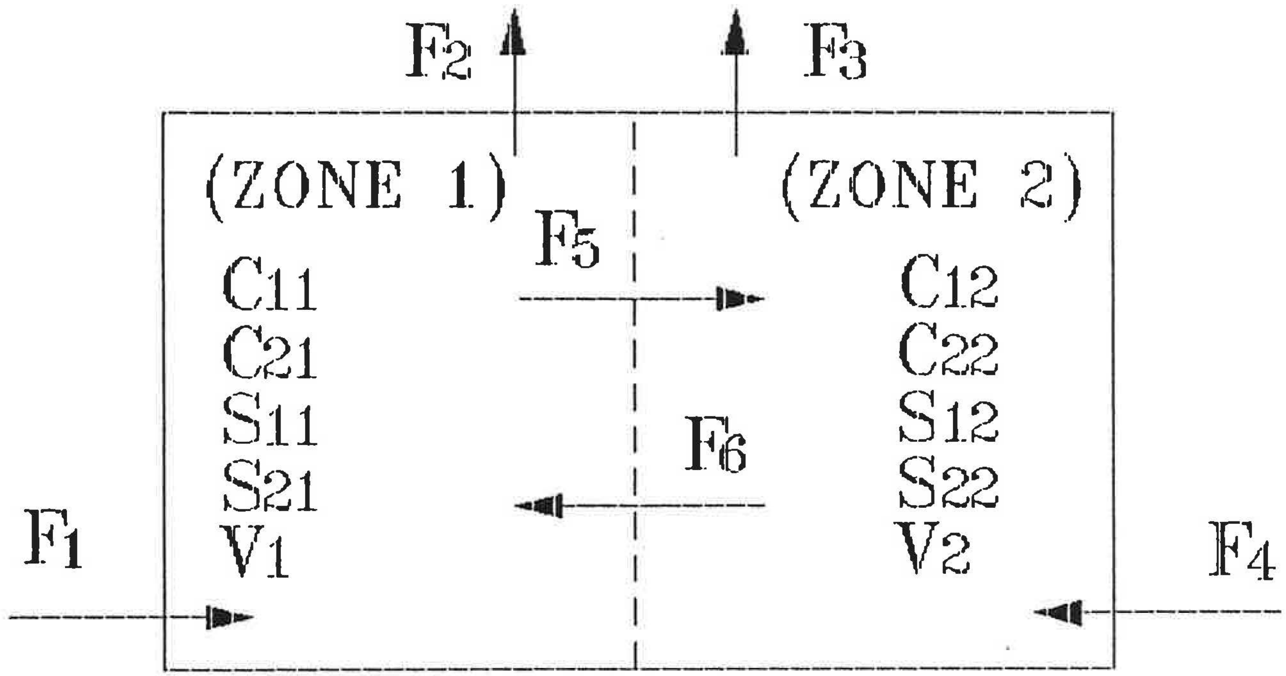
S : TRACER GAS SOURCE EMISSION RATE

V : VOLUME OF ZONE

F : AIR FLOW RATE

D:/TEN/FIG/TG1

TWO-ZONE, TWO TRACER GAS MODEL



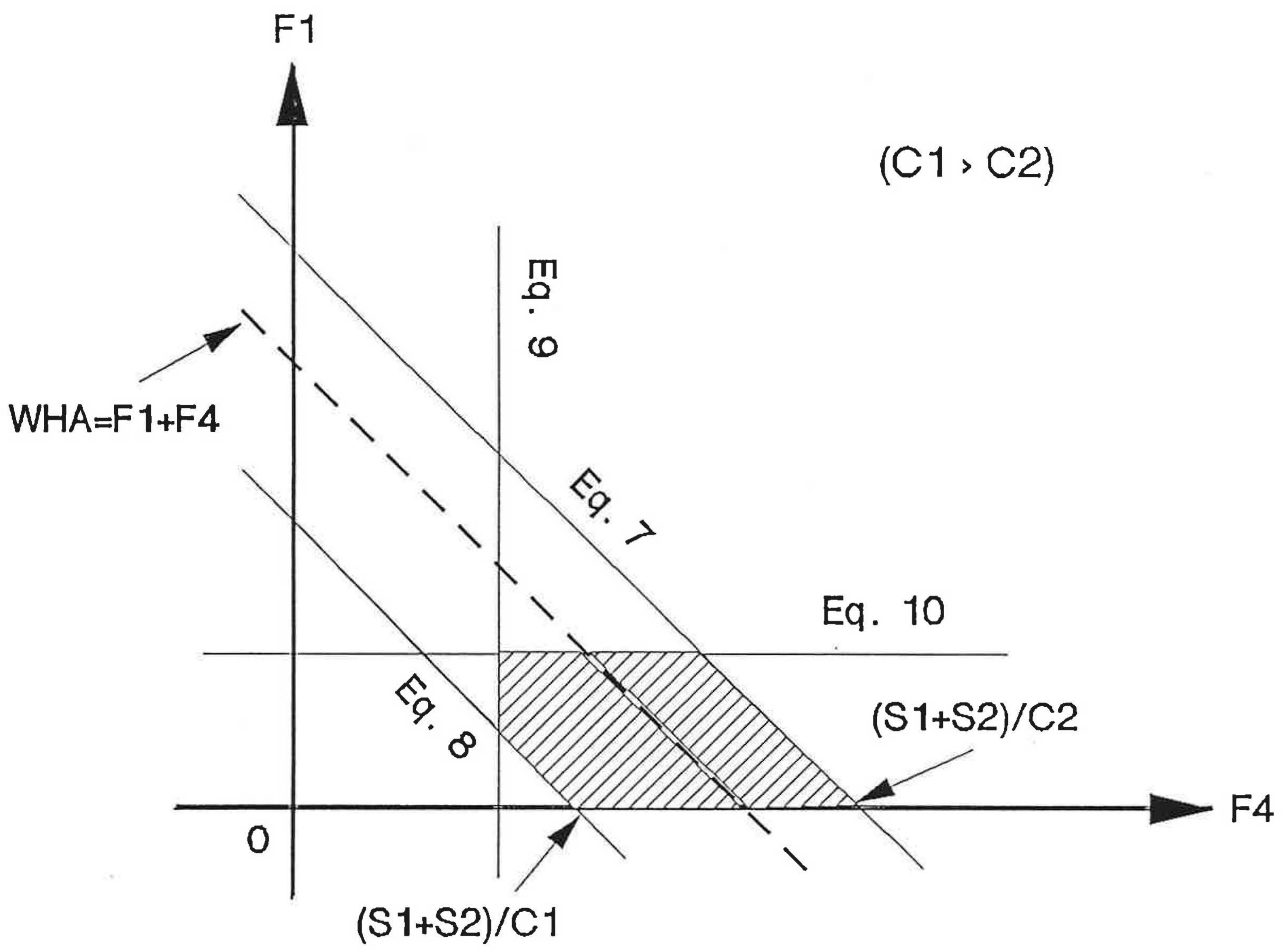
C : TRACER GAS CONCENTRATION

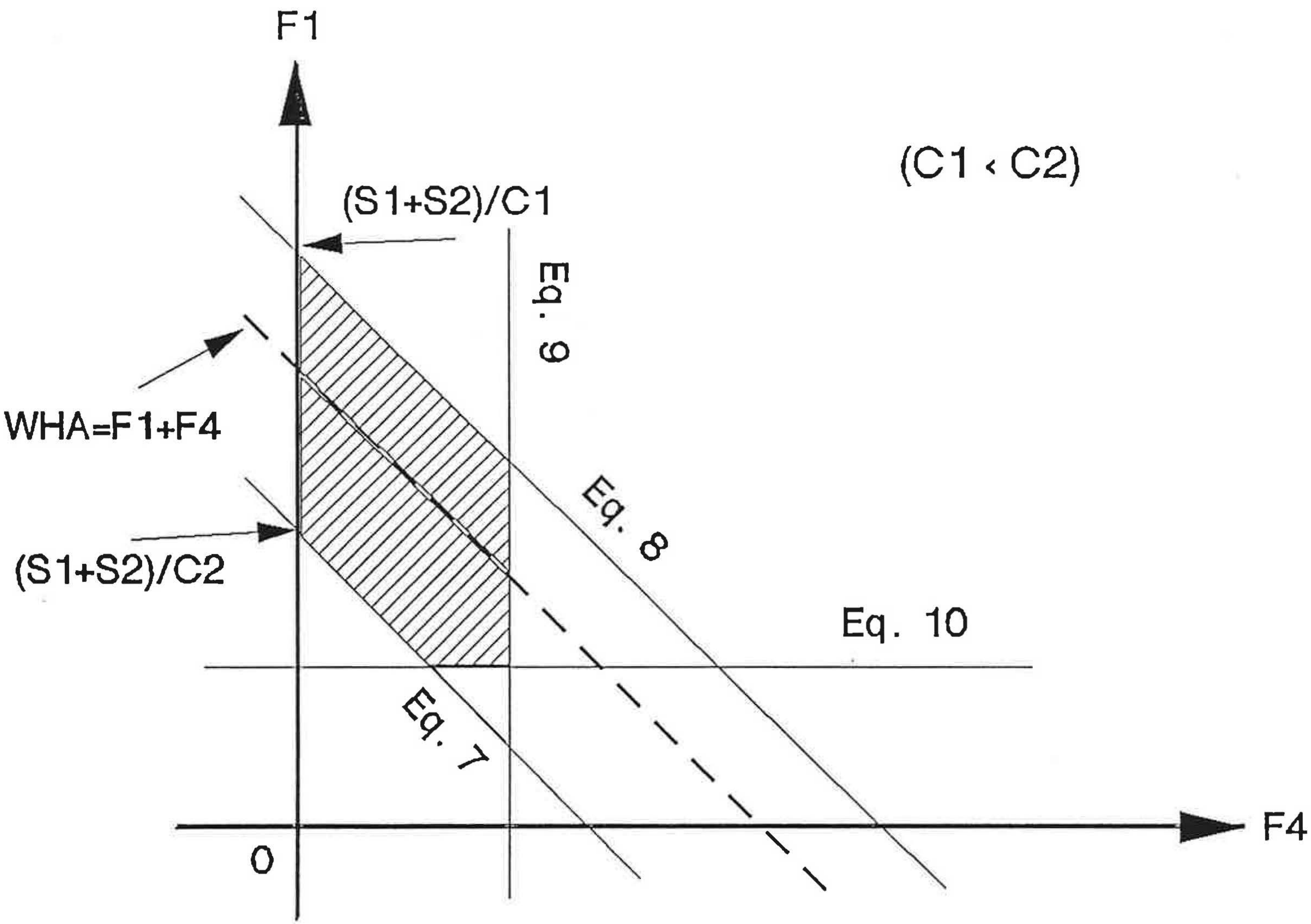
S : TRACER GAS SOURCE EMISSION RATE

V : VOLUME OF ZONE

F : AIR FLOW RATE

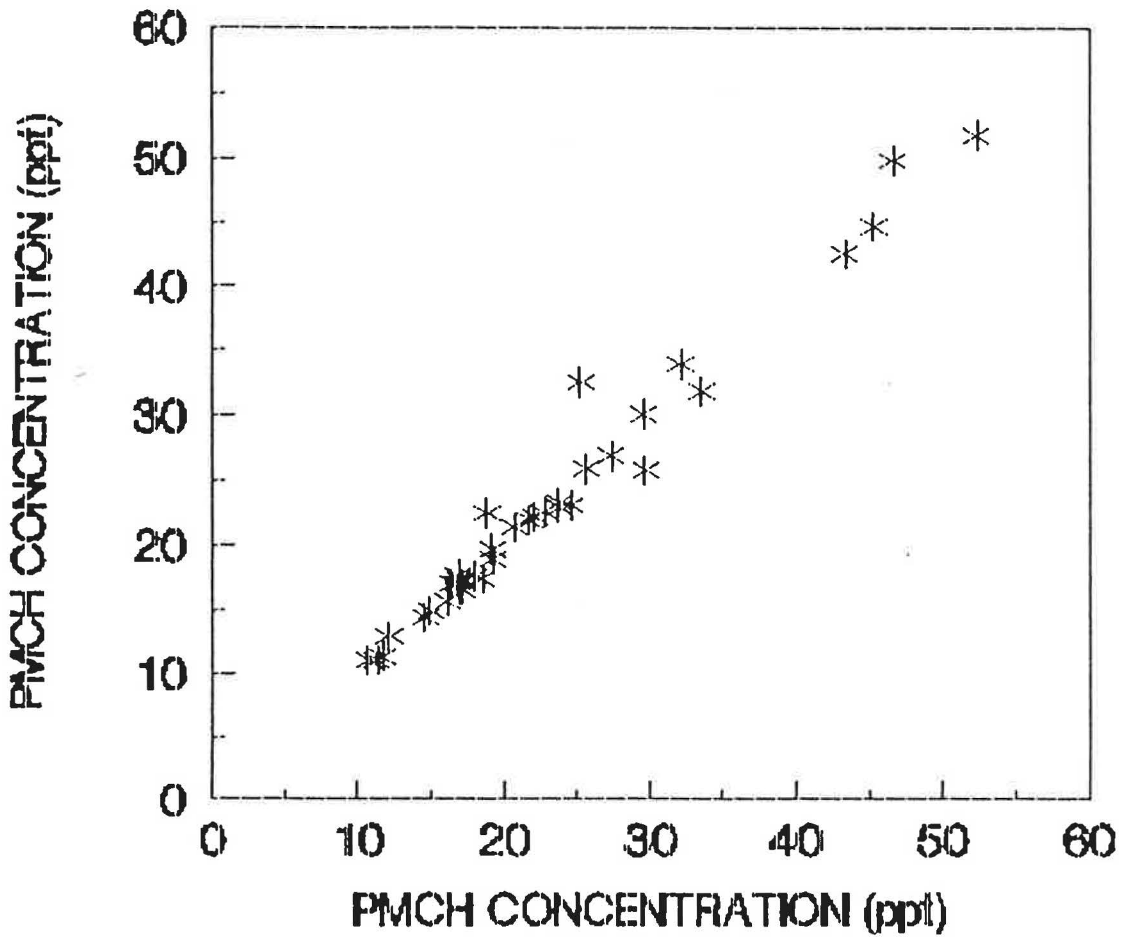
Cij & Sij : i-th TYPE OF GAS & j-th ZONE


F1
(C1 › C2)
Eq. 9
WHA=F1+F4
Eq. 7
Eq. 10
Eq. 8
(S1+S2)/C2
F4
0
(S1+S2)/C1

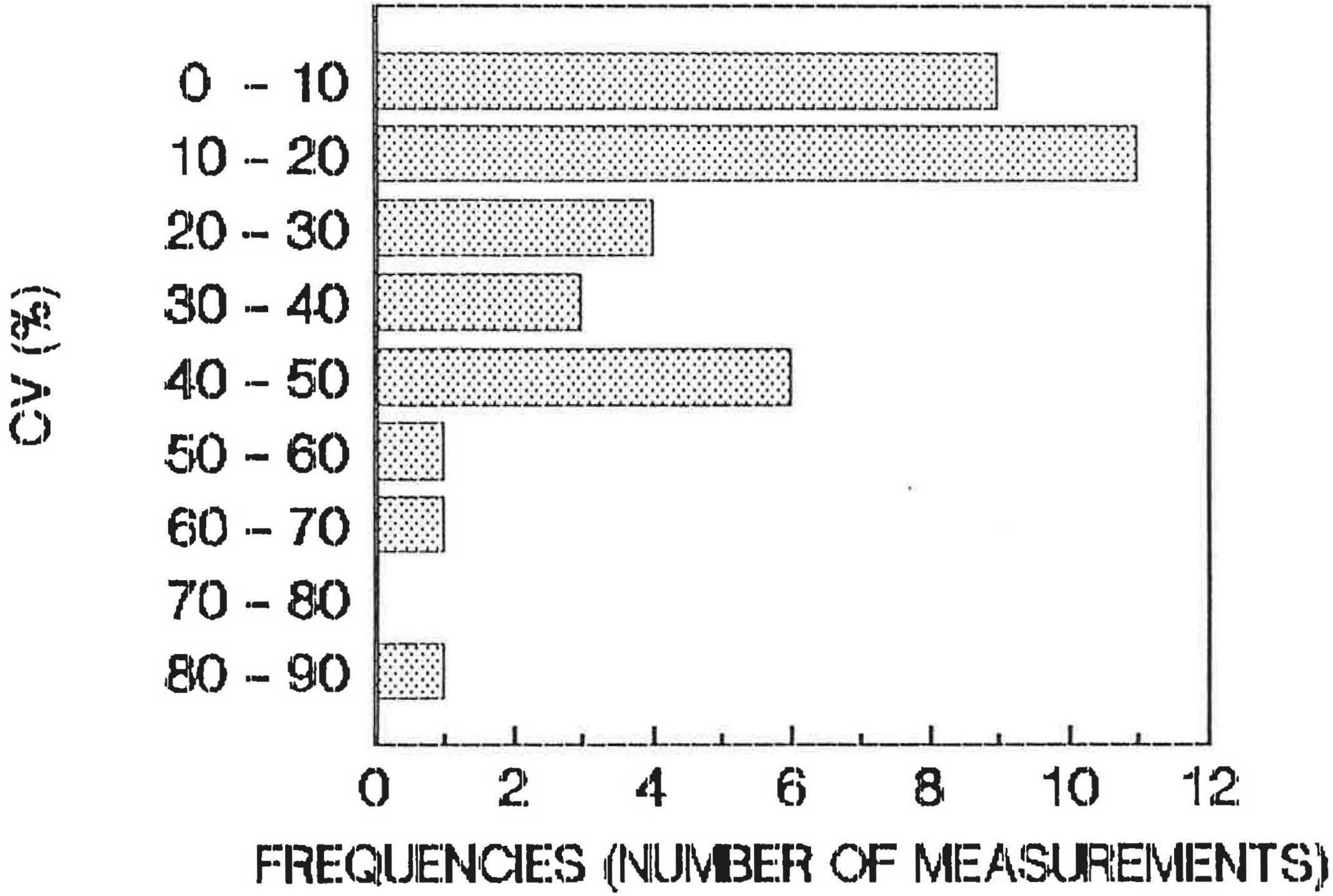


F1
(C1 < C2)
(S1+S2)/C1
Eq. 9
WHA=F1+F4
Eq. 8
(S1+S2)/C2
Eq. 10
Eq. 7
F4
0

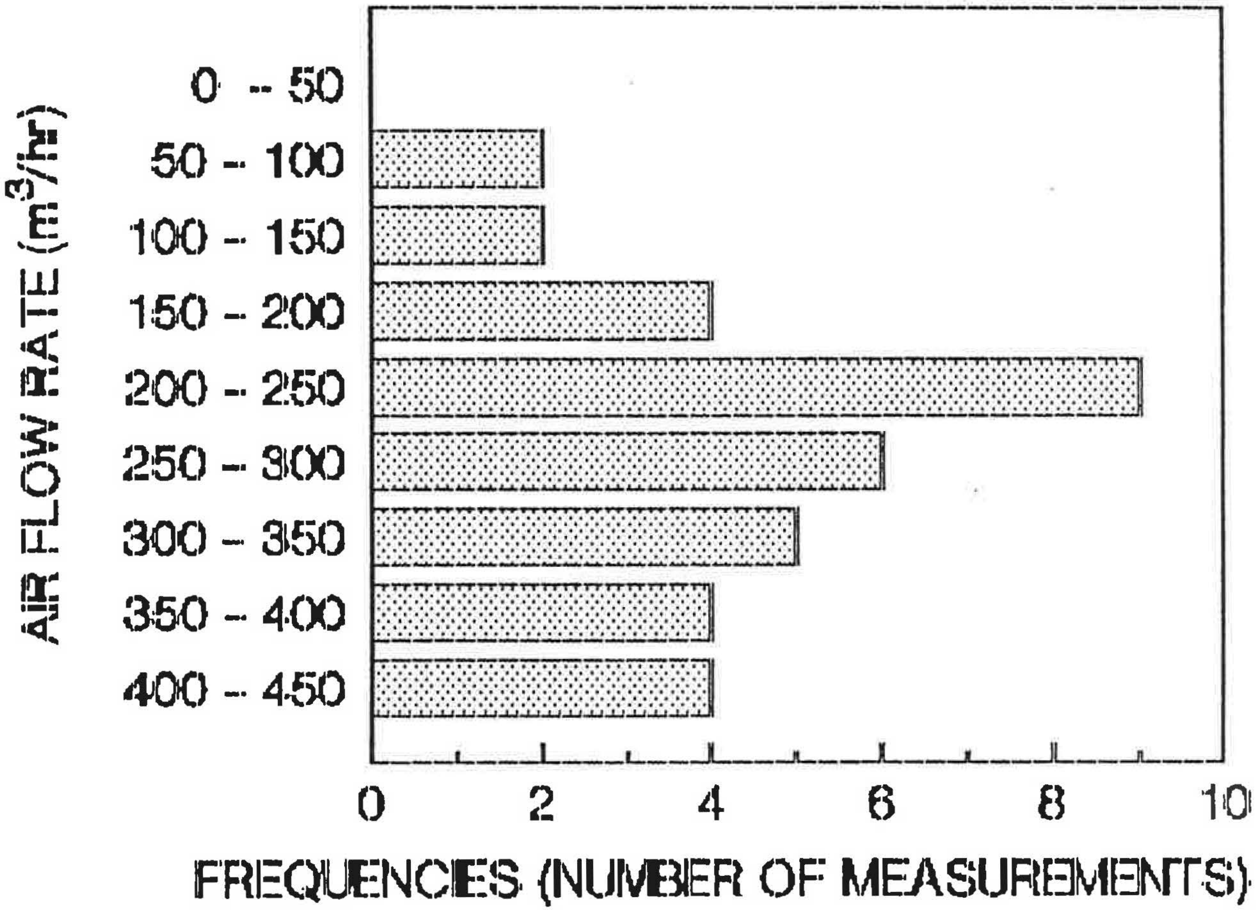
RELATION OF PAIRED PMCH MEASUREMENTS



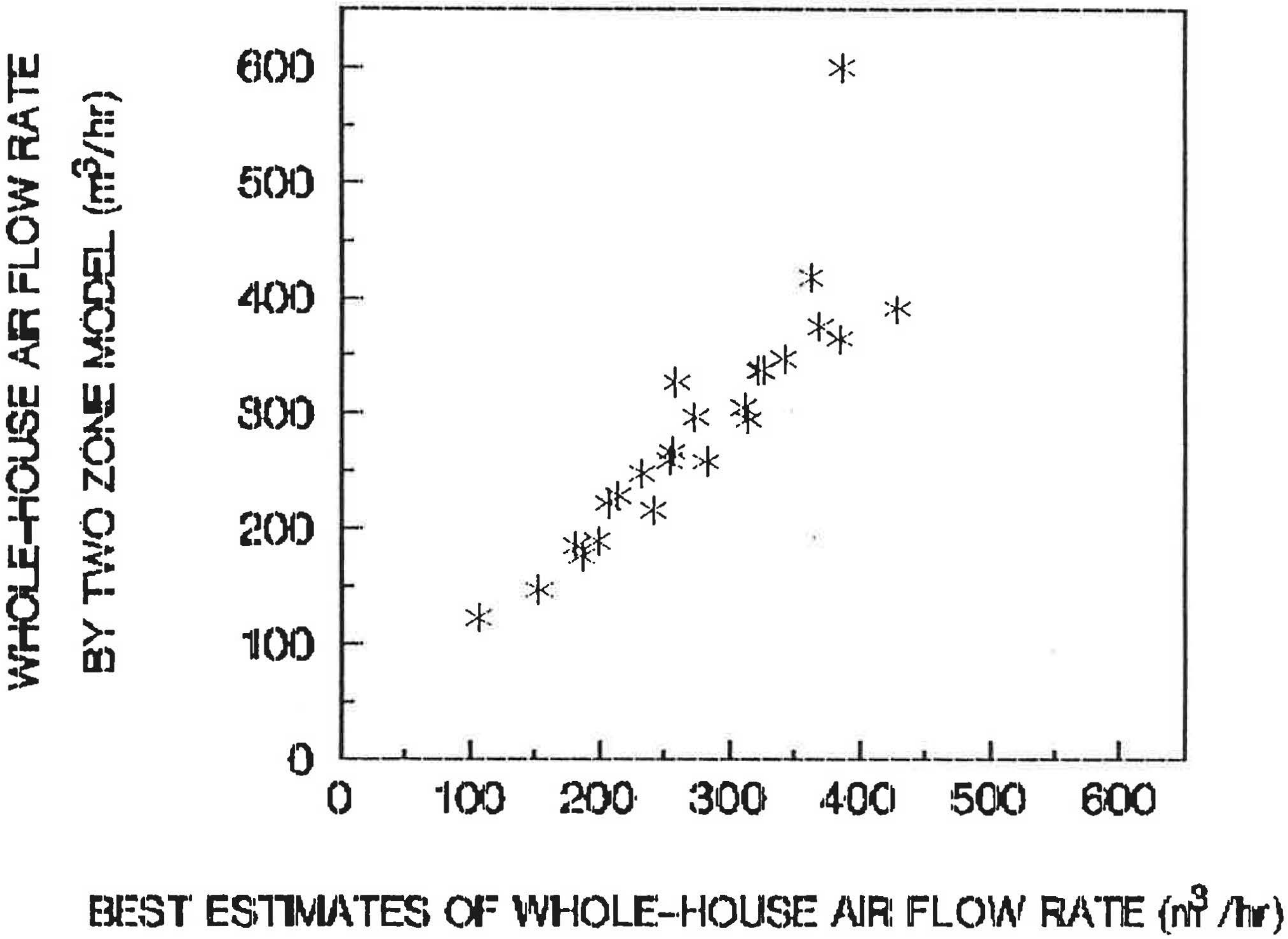
DISTRIBUTION OF CVs CALCULATED FROM
THE SUM OF PMCH AND PDCH CONCENTRATIONS



DISTRIBUTION OF WHOLE-HOUSE AIR FLOW RATE (BEST ESTIMATES)



COMPARISON OF WHOLE-HOUSE AIR FLOW RATES



DISTRIBUTION OF FRESH AIR INTAKE RATIO (BEDROOM ZONE TO KITCHEN ZONE)

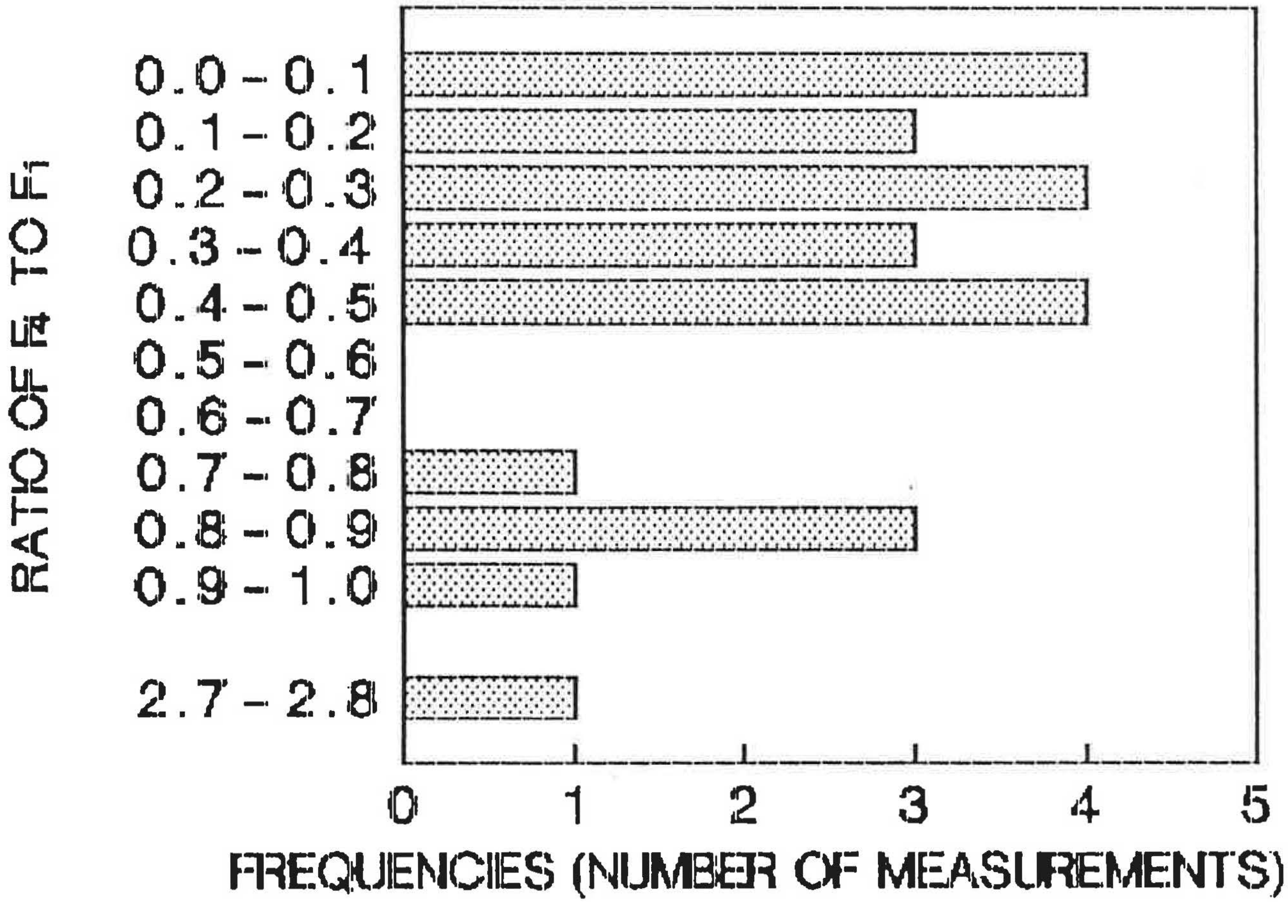


Table I Characteristics of subjects' home

HOME CODE	HOUSE TYPE	NO. OF FLOORS IN HOME	KITCHEN LOCATION	BEDROOM LOCATION
A	Single Family	2 fl. + basement + attic	1st floor	2nd floor
B	Single Family	2 fl. + basement + attic	1st floor	2nd floor
C	Single Family	2 fl. + basement + attic	1st floor	2nd floor + attic
D	Multi Family	2 fl. + basement	1st floor	2nd floor
E	Multi Family	2 fl.	2nd floor	3rd floor
F	Multi Family	1 fl. + basement	3rd floor	3rd floor
G	Multi Family	1 fl.	1st floor	1st floor
H	Multi Family	1 fl.	1st floor	1st floor
I	Multi Family	1 fl.	3rd floor	3rd floor
J	Multi Family	1 fl.	3rd floor	3rd floor

Table 2 Horizontal Distribution of Tracer Gas Concentrations

Type of gas	Placement protocol	Average Concentrations (ppt) Kitchen	Living room	Bedroom
PMCH	all data	29.2	23.0	19.7
	protocol 1	27.2	21.9	17.7
	protocol 2	32.0	24.5	22.4
PDCH	all data	7.5	9.2	25.6
	protocol 1	5.7	6.8	29.3
	protocol 2	10.0	12.7	20.5

Table 3 Coefficient of Variance among Tracer gas concentrations of kitchen, living room and bedroom

Type of gas	Placement protocol	Coefficient of Variance (%)				
		Average (mean)	Average (median)	Standard deviation	Minimum	Maximum
PMCH	all data	27.4	24.6	15.4	4.1	56.0
	protocol 1	26.2	24.9	14.8	4.1	54.6
	protocol 2	29.2	20.8	16.5	6.9	56.0
PDCH	all data	58.5	51.5	39.4	9.1	141.4
	protocol 1	71.0	66.2	41.5	12.2	141.4
	protocol 2	41.0	28.7	29.1	9.1	97.2
PMCH	all data	24.3	18.1	18.7	2.5	83.6
		(20.6)*	(17.3)	(14.0)	(2.5)	(46.1)
+	protocol 1	25.5	17.3	22.5	3.3	83.6
		(18.9)	(12.3)	(15.6)	(3.3)	(46.1)
PDCH	Protocol 2	22.7	18.4	12.1	2.5	43.4
		(22.7)	(18.4)	(12.1)	(2.5)	(43.4)

* excluding three cases having over 50% of CV

Table 4 AIR FLOW RATE IN EACH HOUSE

HOME CODE	EXTERNAL FLOW RATE (PMCH + PDCH) MEAN (m3/hr)	STD	CV (%)
A	112.3	30.2	26.9
B	217.0	43.5	20.0
C	233.5	29.6	12.7
D	270.8	49.9	18.4
E	396.2	27.4	6.9
F	202.9	23.4	11.5
G	300.3	54.1	18.0
H	390.1	48.1	12.3
I	300.5	36.8	12.2
J	238.7	71.9	30.1

Table 5 Comparison of external air flow rates calculated from average concentrations of PMCH plus PDCH in kitchen, living room and bedroom with external air flow rates obtained by various average tracer gas concentrations

Type of Gas	Sampling locations	Placement protocol	Regression parameters Slope	Intercept	R	SE	Number of data
	kitchen	all data	1.09	-16.3	0.868	61.1	36
PMCH	living room	protocol 1	1.23	-41.6	0.880	61.4	21
	bedroom	protocol 2	0.93	6.3	0.883	55.5	15
	kitchen	all data	1.01	27.4	0.652	114.8	36
PDCH	living room	protocol 1	0.77	69.5	0.599	94.7	21
	bedroom	protocol 2	1.27	-10.1	0.730	133.5	15
	kitchen	all data	1.20	-35.4	0.819	82.3	36
PMCH	bedroom	protocol 1	1.40	-70.8	0.837	84.4	21
		protocol 2	0.98	-3.8	0.841	70.7	15
	kitchen	all data	1.27	-42.6	0.555	186.9	36
PDCH	bedroom	protocol 1	0.47	105.8	0.377	107.2	21
		protocol 2	2.15	-176.2	0.769	200.0	15
PMCH	kitchen	all data	0.98	-6.1	0.958	28.8	36
+	bedroom	protocol 1	0.85	17.3	0.954	24.6	21
PDCH		protocol 2	1.11	-27.3	0.985	21.7	15

Table 6 Summary of cases which have negative air flow rate

Case Number	House Code	Placement protocol	Preconditions not satisfied	R1	R2	f1	f2
1	J	1	F2 (- 77.8)	1.00	0.81	175.9	191.5
2	H	2	F2 (-173.9)	0.67	0.88	350.5	625.1
3	B	2	F2 (-248.4)	0.40	0.95	107.2	653.9
4	B	1	F2 (- 53.2)	0.29	0.67	87.5	447.4
5	B	2	F2 (-195.6)	0.46	0.96	107.2	467.1

Table 7 Regression of external air flow rate by two zone model on the best estimate

Placement Protocol	Regression parameters Slope	Intercept	R	SE	Number of data
all data	1.11	-20.0	0.886	48.8	24
protocol 1	1.13	-23.2	0.872	56.0	18
protocol 2	0.95	11.1	0.983	14.8	6

Table 8 Correlation coefficient matrix among air flow rates

	F1	F2	F3	F4	F5	F6	F1+F4	BE
F1	1.0000	.9117**	-.1226	-.3142	.0747	.0511	.9180**	.7422**
F2		1.0000	-.4121	-.2723	-.2046	-.1592	.8428**	.6837**
F3			1.0000	.6501**	.3620	.2274	.1430	.2428
F4				1.0000	-.2078	-.2208	.0882	.2571
F5					1.0000	.9793**	-.0085	.0394
F6						1.0000	-.0386	.0240
F1+F4							1.0000	.8861**
BE								1.0000

Number of cases = 24 (* = p (0.01, ** = p (0.001)
BE = the best estimate of external air flow

Table 9 Summary statistics of air flow rates calculated from two zone model (24 CASES, m3/hr)

LOCATION	MEAN	STANDARD DEVIATION	MINIMUM	MAXIMUM
F1	213.2	108.1	61.0	567.1
F2	181.0	111.9	24.8	507.4
F3	106.1	60.9	8.7	241.1
F4	73.9	43.1	2.9	166.6
F5	137.9	198.0	12.1	1013.0
F6	105.6	170.5	0.0	846.2
F1+F4	287.1	103.0	122.4	599.0