Passive Tracer Gas Measurement of Air Exchange in a Large Multi-Celled Building in Alaska

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ABSTRACT

A 2963 m^3 residence for transient military personnel at Fort Richardson, AK, was subjected to a passive perfluorocarbon tracer gas measurement of air exchange for three days. The building was treated as having three separate zones corresponding to the three floors. Each zone received constant tracer gas emission sources of the same type of gas unique to that zone. The concentrations of each tracer gas were measured throughout the building. As a consequence, it was possible to calculate the average air exchange of each zone with each other zone and the outdoors.

The measurement took place during a period when the average temperature of -19°C varied approximately 5°C up or down. The first and second floors had air exchange rates of 0.21 and 0.28 ach (air changes per hour), respectively, whereas the basement had 0.70 ach. The higher exchange rate for the basement was attributed to the configuration of the main entry doors and interior doors, which allowed cold air to descend to the basement, but discouraged mixing on the first floor.

The measurement was significant because it represents the upper end of building size and complexity that lends itself to this measurement technique. Measurement precision was good. The accuracy depended on adequate mixing and on minimum variation of wind and outdoor temperature. Both objectives were met reasonably well.

INTRODUCTION

Passive Perfluorocarbon Tracer Gas Technique

The use of perfluorocarbon compounds as a passive source of a constant-emission-rate tracer gas for measuring air exchange rates in buildings dates from before 1982 (Dietz and Cote 1982). The technique, which has been developed primarily for detached residential buildings, employs small metal tubes (hereafter called "sources") for dispensing any of four possible tracer gases at an essentially constant rate. Small glass vials (hereafter called "samplers") absorb the tracer gases at a rate that is proportional to their concentrations. Sources and samplers are each smaller than a cigarette and are typically distributed at a density of one per 113 m^3 (4000 ft^3) of building volume.

This technique has been evaluated (Leaderer et al. 1985) in a well-defined environmental chamber under conditions when the air exchange rate varied periodically and, separately, when the temperature varied periodically. With a threefold variation in ventilation rates, the technique resulted in a 10% negative bias in the calculated air exchange rate as determined by the tracer gas measurement.

Passive perfluorocarbon tracer gas (PFT) air exchange measurements were performed on three houses on Long Island (Dietz et al. 1985a) with the samplers being changed and analyzed twice monthly. The calculated air exchange rates varied by a standard deviation from 12% to 26% of the mean air exchange rates for these houses for the seven-month period of measurements.

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Measurement of air exchange rates in multiple zones within dwellings increases accuracy (D'Ottavio and Dietz 1985). Treatment of a dwelling as a single, well-mixed zone was shown to result in errors of 10% to 20% if the basement is included in the model of air movements in and out of multiple zones within the dwelling.

The technique of using multiple tracer gases in multiple zones was improved to include larger buildings (Dietz et al. 1985b). The assumptions were that each floor is a single well-mixed zone and that little direct airflow occurs between floors. The assumption that each zone is well mixed is often not valid because of the presence of individual rooms and closed doors. However, adjusting the emission rate of the tracer gas in each compartment in proportion to the compartment areas to be included in a zone can compensate for this problem. Mixing by natural convection within zones of this size has been shown to be adequate (Dietz et al. 1986).

By 1986 a fairly complete description of the technique was published (Dietz et al. 1986). It includes equations necessary to account for the flows of air bearing three tracer gases among three zones and the outdoors.

Of greatest concern to those using the technique is the potential for bias in the calculation of air exchange rates, based on long-term average tracer gas concentrations (Sherman 1987). Passive perfluorocarbon tracer gas may be used over several months; however, this leads to potential estimates of the air exchange rate that are 15% to 35% below the true average. This problem occurs because air exchange rates are calculated from the inverse of the average concentration. In order to avoid this bias, the calculation would have to be based on the average of the inverse of the concentration. This latter value is unobtainable without frequent changes of the samplers to obtain time series of the concentrations. This problem is diminished to the extent that the temperature and wind speed do not fluctuate, so that the inverse of the average concentration is near the average of the inverse of concentration.

Sherman (1987) also illustrates the importance of using multiple injection and sampling points, especially in multi-story buildings, because the stack effect tends to defeat good mixing within the building among zones that are on separate floors.

Military Residential Buildings in Alaska

A large number of military housing units for bachelor quarters and transients are wood-framed two-story buildings with hydronic heating systems and no central ventilation system. Many of these have been retrofitted with insulation, siding, windows, and doors.

Of the possible tracer gas methods for evaluating air exchange rates in such buildings, the tracer-decay method (ASTM E 741) offers the strongest competition to the passive PFT technique. Successful application of either technique requires good distribution of the tracer gas within the building. For the tracer-decay method, this can be done by simultaneously releasing the gas at several points within the building in proportions designed to obtain a uniform initial concentration. Simultaneous injection of tracer gas is a problem in a building with multiple rows of locked doors.

PROCEDURE

Test Building

Building 57 at Fort Richardson, AK, near Anchorage, a two-story frame building (Figure 1) on a full-height partially finished basement, was the subject of our study. The building is 11 m (37 ft) wide by 46 m (152 ft) long. The first and second floors have double-loaded corridors with five suites on each side. Each suite comprises two equal rooms with closets and a bathroom between them. The basement includes a large unfinished space, a laundry room, a washroom, a multi-purpose room, and several locked storage areas.

Building 57 has a baseboard hot water heating system and bathroom vent fans. There is no central air-handling system.

The building serves as quarters for transient military personnel and civilians conducting military business. It is like a hotel in many respects, complete with daily maid service.

Distribution of PFT Sources and Samplers

The passive PFT air exchange measurement technique was developed at a national laboratory and has been licensed for commercial use (NAHB, n.d.). The vendor's guidelines for placement of PFT sources depend on the anticipated air exchange rates in the building. In order to sample a high enough concentration for accurate analysis, a minimum number of sources per unit volume are required. The higher the air exchange rate, the higher the minimum number of sources required.

The PFT sources per floor were placed at a density of two per 84.2 m^3 (2974 ft^3) bedroom suite. Some suites on each floor had only one source. The sources were placed on a window casing at about 1.5 m (4.4 ft) above the floor. The basement received an equal number of sources. Hallways on the first and second floors received no sources.

Each bedroom suite had at least one sampling tube. The samplers in the same space were well removed from the source tubes. One sampler was placed in the entryway to each bedroom suite. One room had four samplers to establish the standard deviation of the measurement process. The hallways on the first and second floors each had three samplers. The two stairways had a sampler at each floor.

Meteorological Conditions

The sampling period lasted for 52 hours. During this period the difference in temperature between indoors and outdoors (ΔT) varied between a maximum of 45.8°C and a minimum of 34.2°C (82.4° and 61.6°F) with a mean and standard deviation of 41.6°C ± 12% (74.9°F). The weather data plot (Figure 2) shows that the wind was calm for all but nine hours, and that when present, it was less than 1.0 m/s (2.2 mph).

Analysis of Results

Gas Concentrations. The PFT sources emit gas at an essentially constant rate for a given temperature. Small fluctuations of indoor temperature in a controlled building have a minimal effect on tracer gas source rates (Dietz et al. 1986).

The samplers absorb the different tracer gases at known rates. Thus, when a collector is heated for analysis and the amount of each gas is determined with a gas chromatograph, it is possible to determine the average concentration present during the sampling time. To calculate the average concentrations in the space, one must know the absorption rate for each tracer gas, the time period of the measurement, and the absolute amount of each tracer gas that was collected.

Calculation of Air Exchange Rated. Consider the simple case of a single-zone building. The air exchange rate is a function of the concentration of the tracer gas, as follows:

$$A(t) = \frac{S}{C(t)} - \left[\frac{1}{C(t)}\right]\left[\frac{d\ C(t)}{dt}\right] \qquad (1)$$

where

$A(t)$ = air exchange rate (h^{-1})
S = tracer gas source rate (m^3/m^3h)
$C(t)$ = tracer gas concentration (m^3/m^3)

Even in this single-zone case, the passive monitoring approach cannot track a changing $C(t)$. It can only represent the average concentration, $\overline{C}$. Since $S/\overline{C} \neq \overline{A}$, the average air exchange rate (unless $dC(t)/dt = 0$), the technique is biased to the extent that concentration varies.

The combination of low air exchange rates and a brief measurement period hinders determination of the steady-state concentrations in the building. Under essentially constant wind and temperature conditions, the air exchange rate in a single-zone building may also be assumed to be essentially constant, $A(t) = a$, and Equation 1 may be solved as:

$$C(t) = \frac{S}{a}(1 - e^{-at}) \qquad (2)$$

The exponential term becomes small with time at a rate that depends on a. If the air exchange rate is low, then the transient effect remains longer, as demonstrated in Table 1.

Table 1 illustrates how long to wait after starting the tracer emission process before collecting air samples. However, this measurement was done on a compressed time schedule whereby the samplers were deployed soon after the initial release of the tracer gas. Since 1) the concentration was initially zero and 2) the samplers represent an average concentration during this transient period, one must calculate the steady-state concentration from the average concentration measured from the samplers.

Calculation of the steady-state concentration may be done by 1) taking the average value of $C(t)$ by integrating Equation 2, according to Equation 3, and 2) adjusting a until $\bar{C}$ equals the measured value from the sampler:

$$\bar{C} = \frac{\int_0^T C(t)dt}{T} = \left(\frac{S}{aT}\right)\left[T - \left(\frac{1}{a}\right)(1 - e^{-aT})\right] \quad (3)$$

where

T = completion time of the measurement (h).

As a result of this calculation, the steady-state value of C can be obtained by dividing a into S, as indicated by Equation 2 for large t.

Interzonal Flows. For the three-zone case in this study each floor had its own type of perfluorocarbon tracer gas. Tracer gas 1 (basement) was PDCH[2], tracer gas 2 (first floor) was PMCH[3], and tracer gas 3 (second floor) was PMCP[4]. The samplers on each floor gathered tracer gas from each type of source in proportion to the ambient concentration of each. The sources' rates of emission are well defined as a function of temperature. The indoor temperature was essentially constant during the period of measurement.

RESULTS

Gas Concentrations

Table 2 summarizes the source strengths, the average concentrations during the transient period, and the calculated steady-state concentrations of each tracer gas in each zone. The steady-state concentrations of the tracer gases in their zones of origin are between 3% and 12% higher than the average concentrations.

The weighted averages of the concentrations for each zone were calculated to represent each floor as a single zone. Figures 3, 4, and 5 illustrate the distribution of each tracer gas in each zone as a function of location in the building.

Tracer gas flows and airflows in and out of each zone can be related in a 12 by 12 matrix. Solution of the matrix gives formulas for the 12 airflows among zones and in exchange with the outside air. Nonuniform distribution of the tracer gas and variations in the airflow rate introduce errors in this solution that would require a suitable model or an independent measurement technique to assess.

Airflows

With a calculated steady-state concentration for each tracer gas available for each zone, together with the source strengths for each zone, we could calculate the flows among zones and between each zone and the outdoors. Substitution of the concentrations of each tracer gas in each zone into the analytical solution for interzonal flows gave the values shown in Figure 6.

The results were analyzed with an alternative assumption about zonal boundaries. Our basic assumption was that each floor represented a separate zone. However, since the stairwells and halls were contiguous and contained no tracer gas sources, the alternate assumption was that these were part of a zone including the basement, and that the upstairs rooms on either side of the hall on each floor constituted the other two zones. The two different assumptions about zone boundaries resulted in total assumed flows in and out of the building that were 6% different from each other.

DISCUSSION

Causes of Airflow Patterns

Figure 6 shows that the bulk of the air exchange in the building is in the basement zone. Given the lack of wind and the high ΔT, the entry doors were probably the source of this air exchange, since the entry door presents a path for warm air to escape from the basement and for cold outside air to displace the escaped warm air. The entry door would not have as strong an effect on air exchange on the first and second floors because of stability of the air mass above the entry-level plane.

Within the building, a significant amount of air goes directly from the basement to the first and second floors, but very little goes from the first floor to the second. The hallway doors into the stairway entry area from the first floor were usually closed; the movement from the basement, to the first floor is hard to explain. From Figure 3 it is evident that the concentration of tracer gas 1, which originated in the basement, is not significantly higher in the first-floor hallway than it is in the rooms. On the second floor the concentrations of tracer gas 1 are even more uniform between the rooms and the hall.

The stack effect is the probable cause of about 130 m^3/h (77 ft^3/min) of air exfiltration through the second floor. Given the lack of significant wind, it is surprising that the infiltration of the second floor is on the order of 100 m^3/h (59 ft^3/min).

Precision of the Measurement from Replicates

Room 4 was the site of replicate samplers to determine the precision of the measurement of concentration, given the uncontrolled aspects of the procedure. The hallways, stairways, and basement areas offer some replication, although the samplers were placed quite far from each other in the same space. The stairways indicate the potential for vertical mixing and the hallways show potential for horizontal mixing.

The range of standard deviations as a percentage of the mean was between 16% and 3% for the three tracer gases in Room 4, as seen in Table 3. The halls showed better mixing and replication than did Room 4, despite the distances between samplers. The halls' standard deviations were between 3.7% and 13% for the three tracer gases in two halls. The basement had a minimal spread in standard deviations of mean airflows from 2.5% to 9.2%. The stairways, with standard deviations of about 40%, did not represent well-mixed zones, probably due to the stack effect between zones.

Accuracy of the Measurement

There was no direct check of the accuracy of the measurement. Given the size of the building, some other tracer gas technique might have been possible. However, the reasonably constant ΔT, the brevity of the measurement, and the reasonably good distribution of tracer gases within zones suggest that the resulting overall air exchange of 0.24 ach may be believed to be one significant figure and that the interzonal flow may be believed to one-half an order of magnitude.

CONCLUSIONS

Ventilation Implications for the Building

ASHRAE Standard 62-1981 (ASHRAE 1981a) specifies a minimum ventilation rate that would require at least 8.5 m^3/h per occupant of a building for sedentary activities and normal metabolisms. Overall, the test building would meet this standard handily, since two occupants per suite and 20 suites would require only 340 m^3/h. However, since most of the air exchange occurs at the basement level, the requirement is not met as easily as might be assumed. The first floor receives about 104 m^3/h from the basement level and about 72 m^3/h from outdoors. This roughly meets the 170 m^3/h requirement for the 10 suites on each floor. The second floor receives about 140 m^3/h from the basement and 105 m^3/h from outside. Since the basement has very little potential to produce carbon dioxide, the basis for this minimum ventilation standard, the building may be adequately ventilated if no other sources of pollution present a problem.

For energy consumption the measured air exchange rates are very low in the test building. Surveys of North American housing indicate that 0.2 ach is at the low end of the spectrum (ASHRAE 1981b). The individual zones of the test building had air exchange rates with all

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TABLE 1

Time, t, (h) to Achieve 95% of the Steady-State Concentration, Using Equation 1, as a Function of Air Exchange Rate, a (h^{-1}).

a	t = [ln(0.05)] / a
1.0	3
0.5	6
0.2	15
0.1	30

TABLE 2

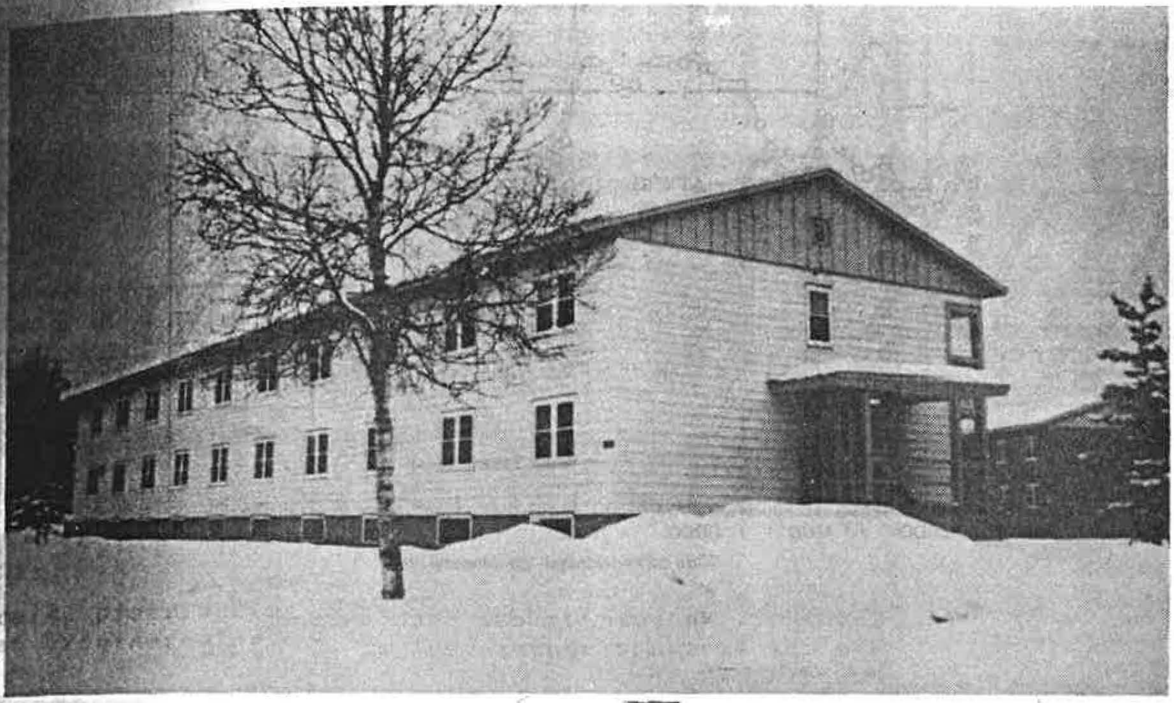
Tracer Gas Concentrations During the 52-Hour Measurement Period. (S = tracer gas emission rate per unit volume in the zone ($1/10^{12}\ m^3/m^3h$). $\bar{C}$ = average concentration ($1/10^{12}\ m^3/m^3$) obtained from samplers. CSS = steady-state concentration ($1/10^{12}\ m^3/m^3$) obtained by adjusting a in Equation 3 and substituting in Equation 2 with $t \to \infty$).

		Gas 3	Gas 2	Gas 1
S		26.55	17.85	8.525
$\bar{C}$	Floor 2	97.72	8.80	7.37
	1	7.10	88.19	7.60
	Basement	3.05	4.17	12.75
CSS	Floor 2	105.83	8.89	7.50
	1	7.14	98.68	7.74
	Basement	3.06	4.19	13.14

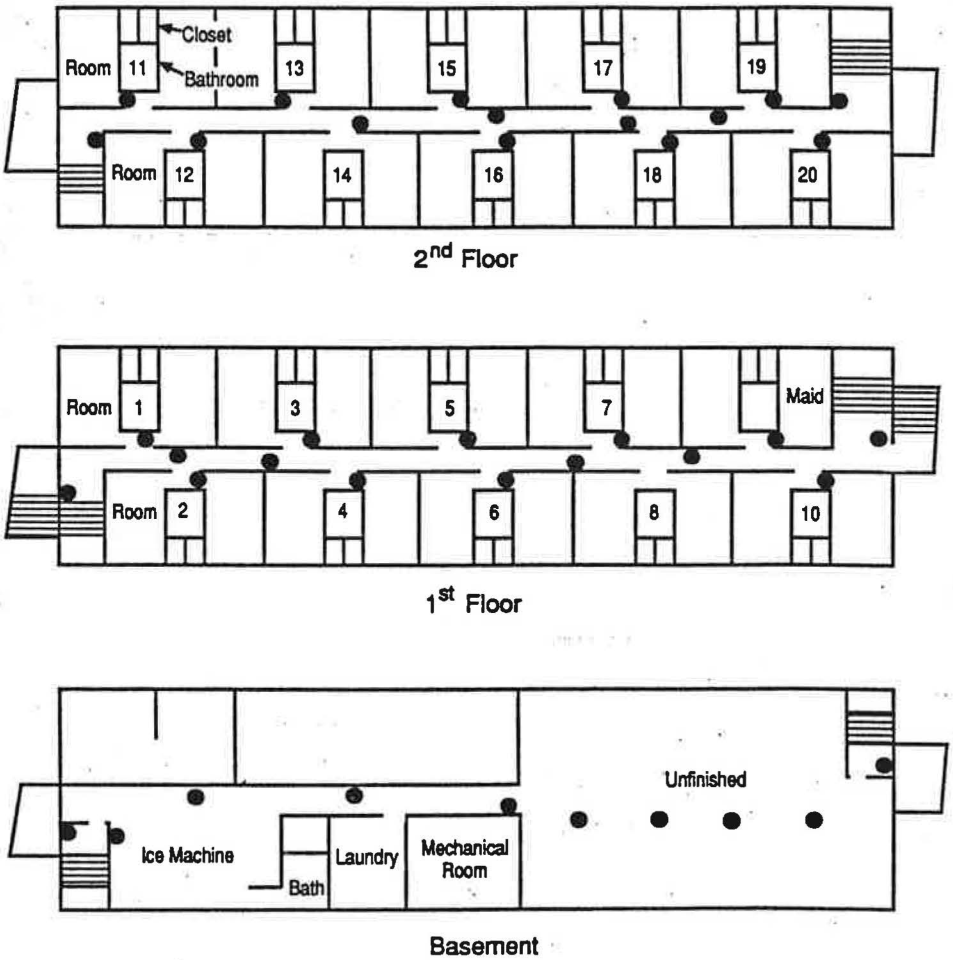
TABLE 3

Standard Deviation as a Percentage of the Mean Value for Each Tracer Gas in Different Parts of the Building. (Values marked with an asterisk (*) indicate that the tracer gas originated in the same zone.)

Floor	Room	Gas 3	Gas 2	Gas 1	#Samplers
1	4	10	3.2*	16	6
2	Hall	13*	7.2	3.7	4
1	Hall	8.1	5.7*	5.2	4
Basement	1	5.0	2.7	9.2*	3
Basement	3	3.2	5.0	2.5*	4
Stairway	North	42	38	47	3
Stairway	South	44	63	47	3



a)



b)

Figure 1. Building 57, Ft. Richardson, AK. Transient quarters subject to passive PFT air exchange measurement

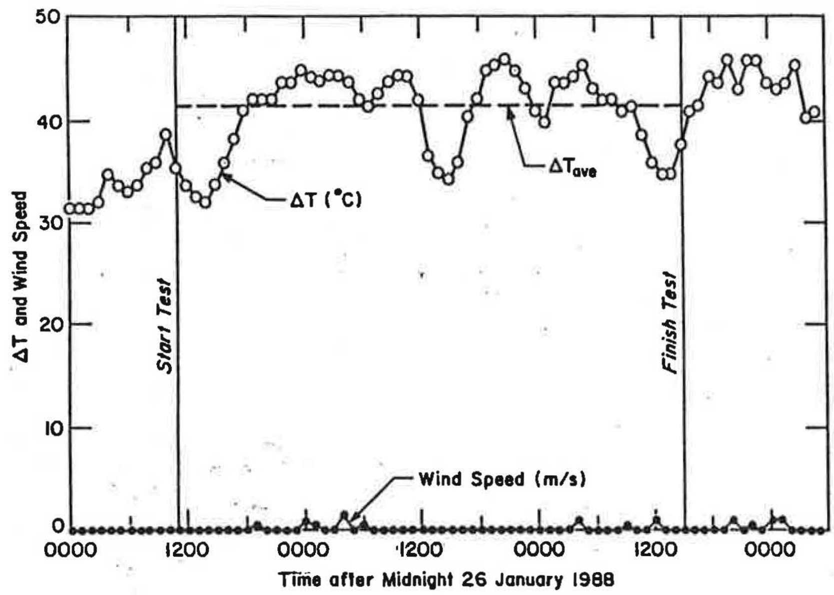


Figure 2. *Meteorological data during the air exchange measurement of Building 57*

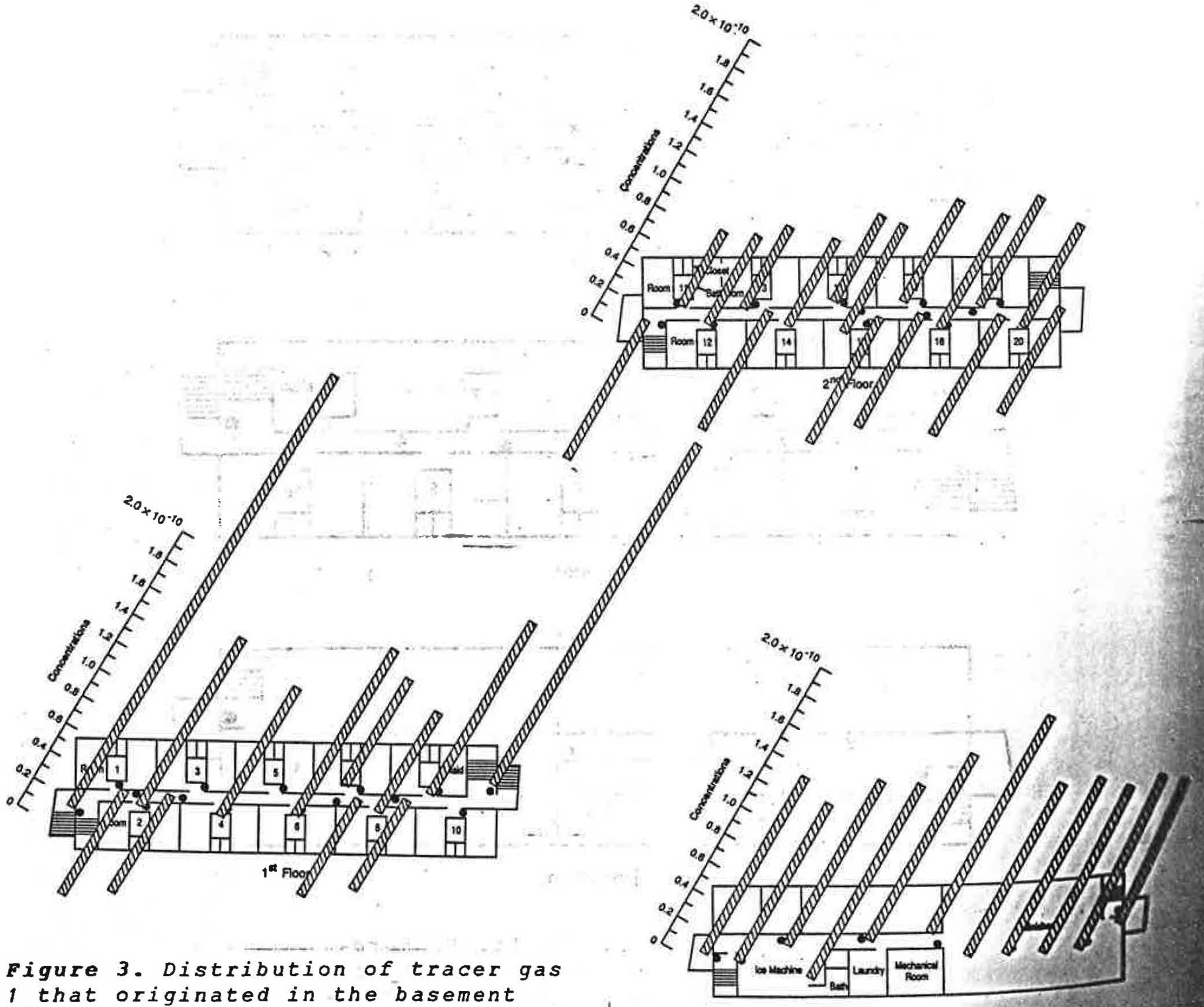


Figure 3. *Distribution of tracer gas 1 that originated in the basement*

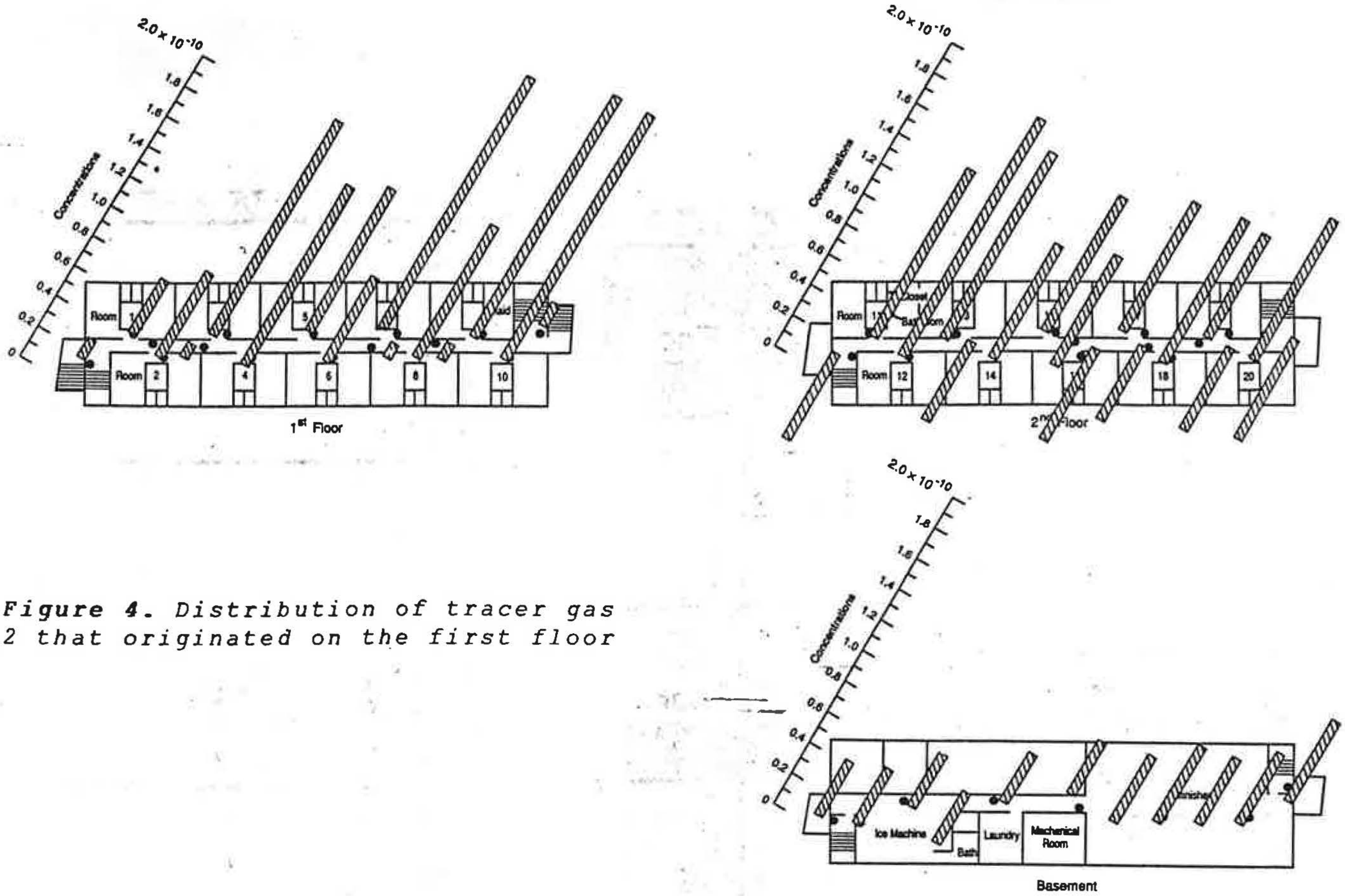


Figure 4. Distribution of tracer gas 2 that originated on the first floor

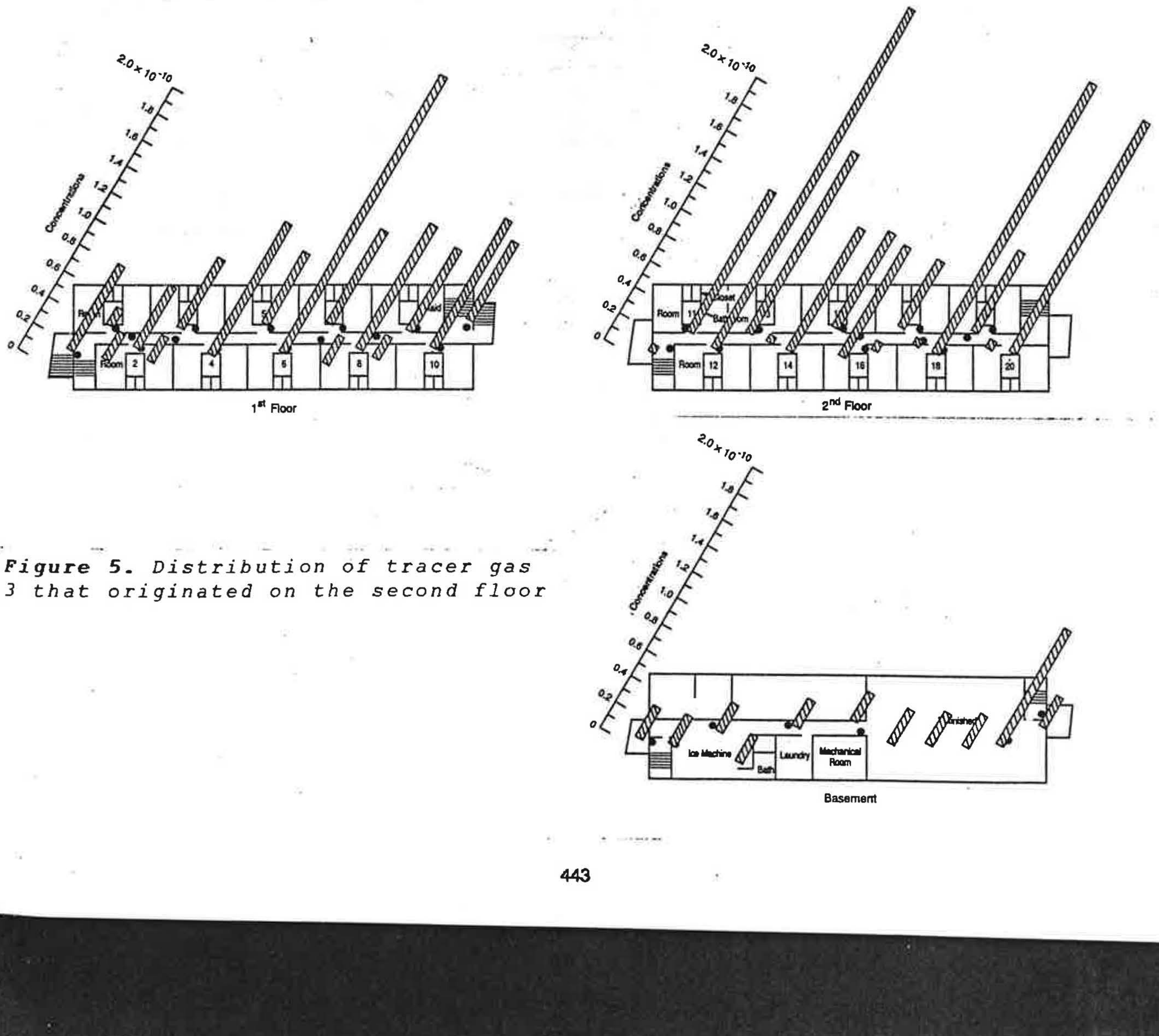


Figure 5. Distribution of tracer gas 3 that originated on the second floor

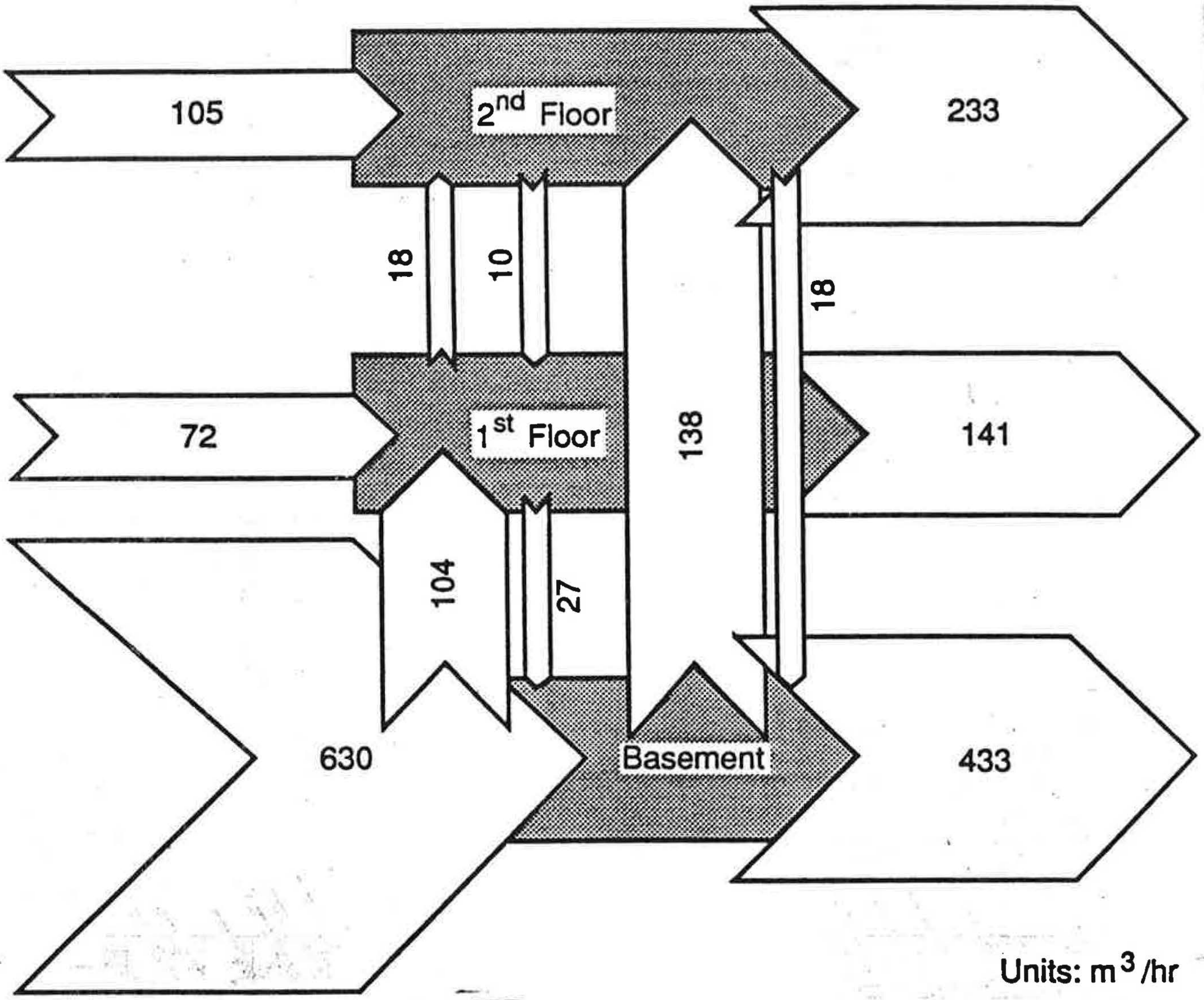


Figure 6. Interzonal airflows