APPLICATION OF TRACER GAS TECHNIQUES TO VENTILATION AND INDOOR AIR QUALITY INVESTIGATIONS

by

C.Y. Shaw

Institute for Research in Construction
National Research Council Canada

ABSTRACT

This paper reviews a selected number of tracer gas techniques which are suitable for use in ventilation studies and indoor air quality investigations in multi-storey office and residential buildings. Emphasis is placed on those techniques which have been successfully used by IRC researchers for such applications. Examples of using these techniques in field measurements are discussed.

INTRODUCTION

ASHRAE standard 62-1989 "Ventilation for Acceptable Indoor Air Quality" states that "acceptable indoor air quality is achieved by providing ventilation air of specified quality and quantity to the space" (ASHRAE 1989). For most buildings, the quality and quantity of ventilation air can be determined by measuring the minimum ventilation rate, air distribution patterns, contaminant flow patterns, and reentrainment of exhaust air. Tracer gas techniques using a single tracer gas are used for such measurements.

For buildings with complex floor plans, some areas may be overventilated and others may be inadequately ventilated, even though the total ventilation (outdoor air supply) rate is adequate. To ensure that every area (or room) receives the required amount of ventilation air, it may be necessary to measure the outdoor air supply rate to a particular room or zone of a building. Multiple tracer gas techniques are used for such measurements.

This paper reviews several tracer gas techniques which have been successfully used by IRC researchers for ventilation and indoor air quality studies. They include both single and multiple tracer gas techniques. Detailed instructions for using most of these techniques are included in an indoor air quality assessment manual for plant engineers which has been developed jointly by Public Works Canada and the Institute for Research in Construction.

SINGLE TRACER GAS TECHNIQUES

Minimum Ventilation Rate Ventilation air comes from two sources - outdoor air supplied directly by HVAC systems and air infiltration through cracks and unintentional openings in the building envelope (Shaw et.al 1991a and 1991b). As air infiltration is weather dependent, the minimum ventilation rate occurs when the weather is warm and the winds are calm, and the outdoor air dampers are set at their minimum position. A building's air change rate measured under these conditions is equal to its minimum ventilation rate.

As an example, tracer gas tests were conducted to measure the minimum ventilation rate of a fully air-conditioned eight-story office/library building in which the first four floors contain offices and the remaining four house library stacks. The building has a central core area housing passenger elevators, stairwells, washrooms, service shafts, study carrels, and small sitting areas. Except for the second and third floors, the floor space is fairly open, with very few individual offices. The building has nine air-conditioning systems identified as Systems 1 through 9 (Figure 1).

To obtain the minimum ventilation rate, the measurements were conducted on calm days with the outdoor air temperatures near 20°C and the outdoor air dampers at their minimum opening positions. A small amount of tracer gas, SF_6, was injected into every floor through the supply air ducts of systems 1, 2, 6, and 9. The total amount of tracer gas required was calculated from the equation

$$m = V * C_t$$

where

m = amount of tracer gas
V = building volume
C_t = maximum concentration (depending upon analyzer sensivity).

Based on a building volume of 80,000 m^3 and a maximum concentration of 50 ppb, the total quantity of pure SF_6 required was:

$$\begin{aligned} m &= 80{,}000\ m^3 * 1{,}000\ L/m^3 * 50 \text{ parts } SF_6 / 10^9 \text{ parts air} \\ &= 8 \times 10^7\ L * 50 \times 10^{-9} \\ &= 4\ L \text{ pure } SF_6. \end{aligned}$$

After about one hour (for mixing), samples were taken consecutively from each floor at the return ducts for another hour, using an automated sampling system. The samples were pumped continuously, one after another, to an electron capture gas chromatograph for analysis.

As adequate mixing of the tracer gas with the indoor air is important for such measurements, additional samples were collected manually at 10-minute intervals from two locations on each floor to evaluate mixing. These samples were collected as follows. Just prior to the sampling time, a 60-mL syringe was purged twice with air at the test location. At the designated time, 50 mL of air was collected in the syringe and injected into a 20-mL evacuated glass test tube with a rubber septum-stopper (the type used for blood sampling in medical laboratories). This meant that the sample was stored under pressure, which was relied upon later to drive the sample into the gas chromatograph for analysis.

The air change rate was obtained by plotting the logarithm of the measured concentrations at each sampling location against time in hours. The data were then fitted with a straight line and the slope of the line was the air change rate expressed in air changes per hour (ach). Figure 2 shows the measured SF_6 concentrations as a function of time for various sampling locations. It indicates that the air change rates from various sampling locations were similar. Concentrations in the occupied areas were also about the same, as were the concentrations in the return ducts. The tracer gas was lower, however, in the floor space than in the return ducts for most floors; suggesting that the concentrations in the floor space were higher near the return ducts than near the sampling locations. The average value of these air change rates was used as the mean air change rate (i.e., the minimum ventilation rate) of the building.

For buildings with adequate mixing, samples from the return ducts on each floor are drawn continuously through individual plastic tubes and mixed in a small manifold. A valve should be installed in each sampling tube to set and maintain identical flow rates from each location. The average air change rate can be determined directly from the samples drawn from the manifold.

Air Distribution For assessing air distribution within the above building, a small amount of SF_6 was injected into the main supply duct of HVAC system 9 (or the main supply duct of another system) to create a point source. The amount of tracer gas injected was similar to that used for air change measurements. Immediately following injection, tracer gas sampling began and continued at 10-minute intervals at the main return ducts on each floor, at eight locations on the first and second floors, and at four locations on each of the third, fourth, fifth, and sixth floors. Both the automated and manual sampling systems described above were used. The tracer gas concentrations of each sampling location were then plotted against time. Figure 3 shows a typical example of such a plot, in which the concentrations at all sampling locations reached a single level in approximately 80 minutes (Shaw et.al 1991a and 1991b). This time can be used to assess the performance of the air distribution systems.

In the absence of a formal guideline or standard and experimental data from similar buildings, a less rigorous criterion was used to assess the air distribution of this building. As indicated in Figure 3, tracer gas levels throughout the particular HVAC system zone were nearly equal within 30 minutes which is less than the 60 minutes typically allowed for achieving adequate mixing when conducting air change rate measurements in buildings with the tracer gas decay method. This suggests that the air distribution system of this building performed as well as those in other buildings where tracer gas decay tests have been conducted.

Reentrainment of Exhaust Air To determine whether exhaust air reenters this building, a small amount of SF_6 was injected into an exhaust system and samples were then taken at the outdoor air intake of each HVAC system using the syringe/test tube technique. All exhaust systems of the building were checked and the measured tracer gas concentrations were near 0, indicating that minimal reentry of exhaust air occurred (Shaw et.al 1991a and 1991b).

Air Change Efficiency and Ventilation Efficiency Recently, air change efficiency and ventilation efficiency have been used to assess the performance of a ventilation system. The air change efficiency is a measure of how quickly the air in a space is replaced. There are two definitions for this term. European researchers (Skaret and Sandberg 1985, AIVC 1990) define the air change efficiency as the ratio between the nominal time constant and the air exchange time for the room (the air exchange time for all the air in the room is equal to twice the room mean age of air). ASHRAE defines the air exchange effectiveness as the ratio between the mean age of air at the breathing height of one location and the average age of all the air in the room (ASHRAE 1992). The ventilation efficiency is defined as the ratio between the steady state concentration of contamination at the exhaust duct and the steady state mean concentration of the room (Skaret and Sandberg 1985, AIVC 1991). Both air change efficiency and ventilation efficiency are still an active research topic with a confusing range of definitions. Individual researchers have not always been consistent with terminology used in its description, and different authors have occasionally used different expressions to represent the same parameters (AIVC 1987). Thus, further work is needed before they can be used in routine ventilation and indoor air quality investigations.

Contaminant Flow Patterns Odours are a common problem in high-rise apartments. As an example, tracer gas decay tests were conducted to determine how a contaminant dispersed from the ground floor garbage room to other areas within a five-storey apartment building (Shaw et. al 1991c). This building has a basement, a ground floor and 4 typical storeys. The garbage room is located on the ground floor. Each typical storey has 12 apartment units, 6 on each side of a central corridor (Figure 4). The elevator shaft and enclosed garbage chute are located at the centre of the building. There are two stairways, one in each end of the building. The building has a central heating and ventilating system which supplies air to the corridor of each storey through two supply air registers. There are no return air grilles in the corridor. In each apartment unit, two exhaust fans which discharge room air from the kitchen and bathroom serve to draw the ventilation air into the apartment unit through the corridor.

To determine the odour migration patterns, a small amount of tracer gas, SF_6, was injected into the garbage room. Immediately after the injection, the tracer gas concentrations at each storey were measured at 10-minute intervals. The sampling locations were the centre of the corridor, the south stairwell, and 2 apartment units at each side of the corridor (indicated by solid dots in Figure 4). The measured tracer gas concentrations at each sampling location were plotted against time to indicate the magnitude and rate at which it dispersed to other locations.

Figures 5 and 6 show the contaminant dispersed from the ground floor garbage room to other areas within the building (Shaw et. al 1991c). The building's heating and ventilating system was operating normally. The wind blew from the South at 17 km/h and the outdoor air temperature was 11C during the test. The results indicate that immediately after tracer gas injection, the tracer gas concentrations in the corridor of every floor increased rapidly. The concentrations in individual apartment units also increased, but at a slower rate. This suggests that the heating and ventilating system was inadequate to overcome the stack action. As a result, the contaminant (tracer gas) dispersed into the corridor on every floor through the garbage chute, stair and elevator shafts. The contaminant then migrated into individual apartment units from the corridors. Due to the influence of the south wind, more contaminant got into the apartment units on the northeast side than on the southwest side. The tracer gas concentrations at most sampling locations reached their peak about 40 minutes after injection. The results suggest that any contaminant generated in the garbage room will migrate into individual apartment units via the garbage chute and the corridors. The extent and rate of this migration will depend on wind speed and direction, stack action and the use of exhaust fans in the apartment units.

MULTIPLE TRACER GAS TECHNIQUES

Standards such as the CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems (CSA 1991)" specify a minimum ventilation rate for each room of a house. To meet the requirement, it is necessary to measure the outdoor air supply rate for each room or zone of a house. The multiple tracer gas technique is often used for such measurements. It involves the injection of a different tracer gas into each of several interconnected spaces and the measurement of the tracer gas concentrations as a function of time. Based on the measured tracer gas concentrations, the interzonal airflows can then be calculated from the mass conservation equations for each tracer gas and the mass flow balance equations for the air (Sinden 1978, Perera 1983).

The application of the method is not straightforward (Enai et al. 1990a). To illustrate some of the problems, consider the simplest case, e.g., two interconnected rooms (Room 1 and Room 2) where the airflows between the two rooms are controlled and measured (Figure 7). If a tracer gas, g, is injected into Room 1 and another tracer gas, s, is released in Room 2, the rates of change in tracer gas concentrations in the two rooms can be described by the following equations, assuming that the tracer gas concentrations outside the rooms are negligible:

Room 1

$$V_1(dC_{g1}/dt) = -(F_{10} + F_{12})\cdot C_{g1} + F_{21}\cdot C_{g2} + Q_g \quad (1)$$

$$V_1(dC_{s1}/dt) = -(F_{10} + F_{12})\cdot C_{s1} + F_{21}\cdot C_{s2} \quad (2)$$

Room 2

$$V_2(dC_{g2}/dt) = -(F_{20} + F_{21})\cdot C_{g2} + F_{12}\cdot C_{g1} \quad (3)$$

$$V_2(dC_{s2}/dt) = -(F_{20} + F_{21})\cdot C_{s2} + F_{12}\cdot C_{s1} + Q_s \quad (4)$$

The mass flow balance equations for the two rooms are:

Room 1

$$F_{01} + F_{21} - (F_{10} + F_{12}) = 0 \quad (5)$$

Room 2

$$F_{02} + F_{12} - (F_{20} + F_{21}) = 0 \quad (6)$$

where

V = room volume
C = tracer gas concentration
t = time
F = airflow rate
Q = tracer gas release rate

The subscripts 0, 1, and 2 denote the outside, Room 1, and Room 2 respectively, and g and s refer to the tracer gases used. F_{10} indicates that the air flow is from Room 1 to the outside.

If a minimum of two tracer gases, g and s, are injected into Rooms 1 and 2, respectively, and their concentrations are monitored, the six unknowns, F_{10}, F_{12}, F_{01}, F_{20}, F_{02}, and F_{21}, can be evaluated from Equations 1 to 6. In this example, three tracer gases were injected. SF_6 and N_2O were introduced into Rooms 1 and 2, respectively, using the decay technique while CH_4 was injected into Room 1 using the constant injection mode. As CH_4 and SF_6 were introduced into Room 1 using different injection modes, it was possible to examine the effect of injection techniques on the calculated airflow rates.

Figure 8 shows a typical set of concentration profiles measured in the two rooms. Each set consists of six profiles, one for each tracer gas in each room. From such profiles, the concentrations of CH_4 and N_2O (representing a constant injection - decay test condition) corresponding to a sampling time six minutes after the injection of the tracer gases were selected and used to calculate F_{12} and F_{21} from Equations 1 to 6. This calculation was repeated using sets of concentration values measured at four-minute intervals for about two hours. Also, similar calculations were performed using the SF_6 and N_2O concentrations (representing a decay - decay test condition).

Figure 9 shows an example of the calculated interzonal airflow rates as a function of time (Enai et.al 1990a). The results indicate that:

1. For the same test, the calculated airflow rates based on different sets of concentration measurements (measured at different times) were not always the same.

2. The calculated airflow rates, based on the concentrations measured between approximately 30 and 70 minutes after injection, agreed with the measurement within 20% of the measured rates.

3. No clear evidence was found to suggest that the technique used to inject tracer gases (e.g., decay or

constant injection) has a significant or systematic effect on the calculated results.

These findings suggest that concentrations selected from only a certain portion of the measured profiles can give a good estimate of interzonal airflows. To determine the appropriate set of concentrations for calculating interzonal airflows, the following method has been proposed.

Because Equations 1 and 4 are similar, as are Equations 2 and 3, the solutions for the tracer gas concentration profiles (for tracer gas g) using Equations 1 and 3 will be similar to those for tracer gas using Equations 2 and 4. The basis for determining the appropriate tracer gas concentrations for use in interzonal airflow calculations can be derived by examining a typical pair of tracer gas concentration profiles for a single tracer gas released in one of the two rooms. Such profiles can be obtained analytically from Equations 1 and 3 or Equations 2 and 4.

By dropping the subscript g, Equations 1 and 3 become:

$$V_1(dC_1/dt) = -(F_{10} + F_{12})\bullet C_1 + F_{21}\bullet C_2 + Q \qquad (7)$$

$$V_2(dC_2/dt) = -(F_{20} + F_{21})\bullet C_2 + F_{12}\bullet C_1 \qquad (8)$$

Substituting for C_2 from Equation 7 into Equation 8, and letting $N_1 = (F_{12} + F_{10}) / V_1$ and $N_2 = (F_{21} + F_{20}) / V_2$, we have,

$$d^2C_1/dt^2 = -(N_1 + N_2)\bullet(dC_1/dt) - [N_1\bullet N_2 - F_{12}\bullet F_{21}/(V_1\bullet V_2)]\bullet C_1 + N_2\bullet Q/V_1 \qquad (9)$$

The solution to C_1 can be obtained by the method of Laplace transformation (Enai et.al 1990a). Thus,

$$C_1(t) = X_1\bullet \exp(-at) + Y_1\bullet \exp(-bt) + Z_1 \qquad (10)$$

<u>where</u>

$C_1(t)$ = tracer gas concentration in Room 1 at time t

$X_1 = [(b - N_1)\bullet C_1(0) + F_{21}\bullet C_2(0)/V_1] / (b-a)$

$Y_1 = [(N_1 - a)\bullet C_1(0) - F_{21}\bullet C_2(0)/V_1] / (b-a)$

$$Z_1 = [Q\bullet G_1\bullet b / (b-a)]\bullet[1 - \exp(-at)] - [Q\bullet G_1\bullet a / (b-a)]\bullet[1 - \exp(-bt)] + \{Q / [V_1\bullet(b-a)]\}\bullet[\exp(-at) - \exp(-bt)]$$

$$A = N_1 + N_2$$

$$B = N_1 \bullet N_2 - F_{12} \bullet F_{21} / (V_1 \bullet V_2)$$

$$a = [A - (A^2 - 4B)^{0.5}] / 2$$

$$b = [A + (A^2 - 4B)^{0.5}] / 2$$

$$G_1 = (F_{21} + F_{20}) / [(F_{12} + F_{10}) \bullet (F_{21} + F_{20}) - F_{21} \bullet F_{12}]$$

Similarly, $C_2(t)$ can be expressed by the equation,

$$C_2(t) = X_2 \bullet \exp(-at) + Y_2 \bullet \exp(-bt) + Z_2 \qquad (11)$$

<u>where</u>

$C_2(t)$ = tracer gas concentration in Room 2 at time t

$$X_2 = [(b - N_2) \bullet C_2(0) + F_{12} \bullet C_1(0)/V_2] / (b-a)$$

$$Y_2 = [(N_2 - a) \bullet C_2(0) - F_{12} \bullet C_1(0)/V_2] / (b-a)$$

$$Z_2 = [Q \bullet G_2 \bullet b / (b-a)] \bullet [1 - \exp(-at)] - [Q \bullet G_2 \bullet a / (b-a)] \bullet [1 - \exp(-bt)]$$

$$G_2 = F_{12} / [(F_{12} + F_{10}) \bullet (F_{21} + F_{20}) - F_{21} \bullet F_{12}]$$

If a single tracer gas (SF_6) is released in Room 1 using the decay mode, then $Q = 0$: $Z_1 = 0$, $Z_2 = 0$ and Equations 10 and 11 become,

$$C_1(t) = X_1 \bullet \exp(-at) + Y_1 \bullet \exp(-bt) \qquad (12)$$

$$C_2(t) = X_2 \bullet \exp(-at) + Y_2 \bullet \exp(-bt) \qquad (13)$$

Equations 12 and 13 define the tracer gas concentration profiles for a typical case of two interconnected zones. If all the airflows for such a case are known, the tracer gas concentration profiles can be calculated explicitly from these equations.

The approach proposed here, therefore, is to estimate the airflow rates from Equations 1 to 6 using a set of concentrations measured at some arbitrary time approximately 30 minutes after injection. These airflows are then used to estimate the concentrations for a later time from Eqs (12) and (13) (Enai et.al 1990b). These estimated concentrations are then compared with the corresponding measured concentrations, and if the agreement is not satisfactory, the procedure is repeated with a set of concentrations measured at a later time. This comparison is made for concentrations at two different times, five sampling intervals apart, to ensure that the agreement between the calculated and measured concentration profiles is not accidental (e.g., the two profiles cross each other at one time but do not agree in general). The final calculated airflow rates are achieved when satisfactory agreement between the measured and calculated concentrations is reached at the two points. The procedures have been successfully used to solve for interzonal airflows for cases of two and three interconnected rooms (Enai et.al 1990).

SUMMARY

This paper gives brief reviews of various tracer gas techniques which can be used in ventilation studies and indoor air quality investigations. Included are single tracer gas techniques for assessing the performance of HVAC systems of office buildings and measuring the contaminant-migration patterns within high-rise apartment buildings, and multiple tracer gas techniques for measuring interzonal airflows. All the methods discussed have been applied successfully in both residential and office buildings.

REFERENCES

AIVC. 1987. "A review and bibliography of ventilation effectiveness--Definitions, measurement, design and calculation," AIVC Technical Note 21, Air Infiltration and Ventilation Center, International Energy Agency

AIVC 1990. "A Guide to Air Change Efficiency", AIVC Technical Note 28, Air Infiltration and Ventilation Centre, UK.

AIVC 1991. "A Guide to Contaminant Removal Effectiveness", AIVC Technical Note 28.2, Air Infiltration and Ventilation Centre, UK.

ASHRAE. 1989. ASHRAE Standard 62-1989, "Ventilation for acceptable indoor air quality," American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta.

ASHRAE SPC 129P, 1992. "Working Draft for ASHRAE Standard Project Committee 129P, Ventilation Effectiveness", ASHRAE.

CSA. 1991. CAN/CSA-F326-M91, "Residential Mechanical Ventilation Systems," Canadian Standards Association. Toronto, Ontario, Canada.

Enai, M., Shaw, C.Y. and Reardon, J.T. 1990a. "On the multiple tracer gas technique for measuring interzonal airflows in buildings." ASHRAE Transactions, Vol. 96, Part 1.

Enai, M., Shaw, C.Y., Reardon, J.T. and Magee, R.J. 1990b. "Multiple tracer gas techniques for measuring interzonal airflows for three interconnected spaces." ASHRAE Transactions, Vol. 96, Part 1.

Perera, M.D.A.E.S. 1983. "Review of techniques for measuring ventilation rates in multi-celled buildings." Energy Conservation in Buildings - Heating, Ventilation and Insulation. D. Reidel Publishing Company, pp. 321-334. Dordrecht.

Shaw, C.Y., R.J. Magee, C.J. Shirtliffe, and H. Unligil. 1991a. "Indoor air quality assessment in an office-library building-Part I: Test Methods." ASHRAE Transactions, Vol.97, Part 2.

Shaw, C.Y., R.J. Magee, C.J. Shirtliffe, and H. Unligil. 1991b. "Indoor air quality assessment in an office-library building-Part II: Test results." ASHRAE Transactions, Vol.97, Part 2.

Shaw, C.Y., J.T. Reardon, M.N. Said and R.J. Magee. 1991c. "Airflow patterns in a five-storey apartment building". Proceedings of the 12th Air Infiltration and Ventilation Centre Conference on Air Movement and Ventilation Control, Ottawa, Canada.

Sinden, F.W. 1978. "Multi-chamber theory of air infiltration." Building and Environment, Vol. 13, pp. 21-28.

Skaret, E. and Sandberg, M. 1985. "Air Exchange and Ventilation Efficiency - New Aids for the Ventilation Industry", Norsk VVS (Norway), No.7, pp.527-534, OA Trans 2869.

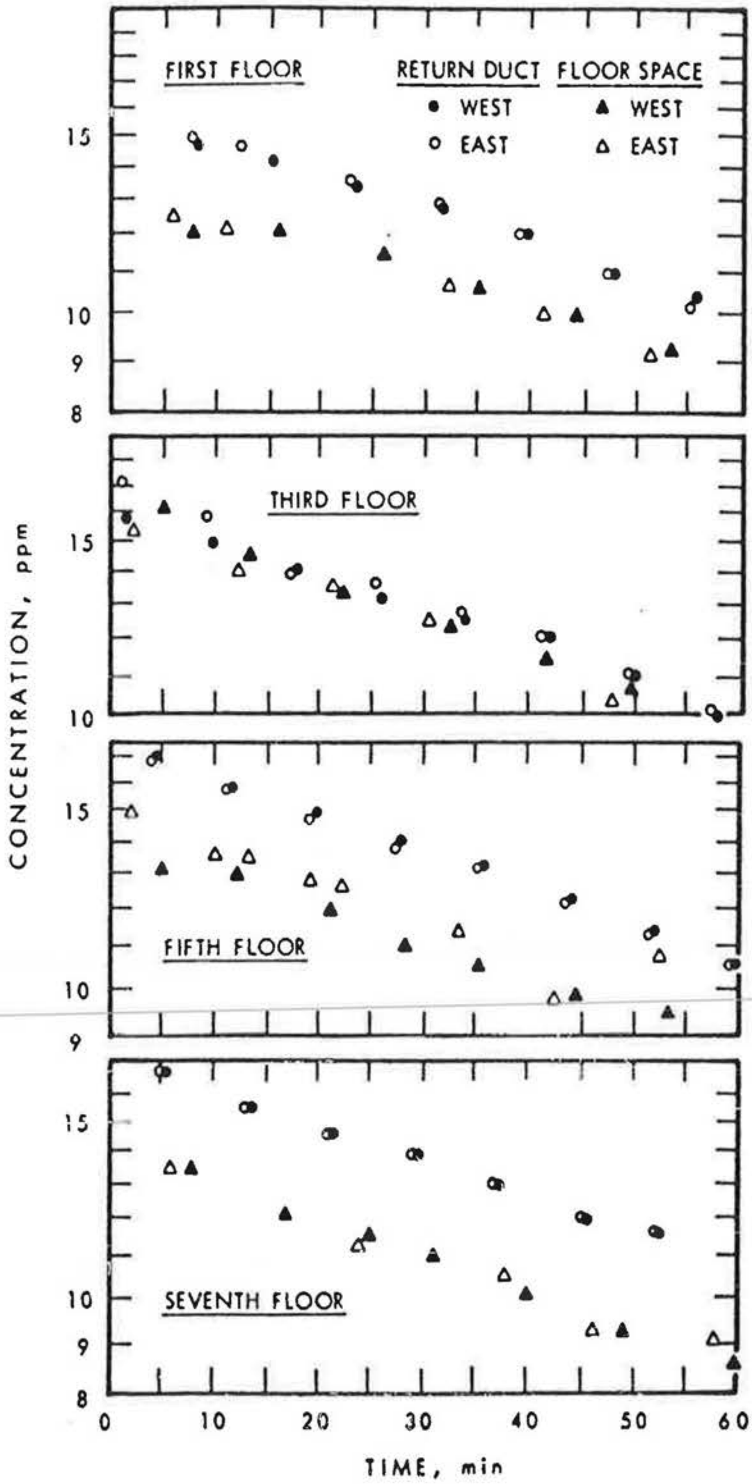

Figure 2 Air change rate measurements, SF_6 concentrations vs time for various sampling locations

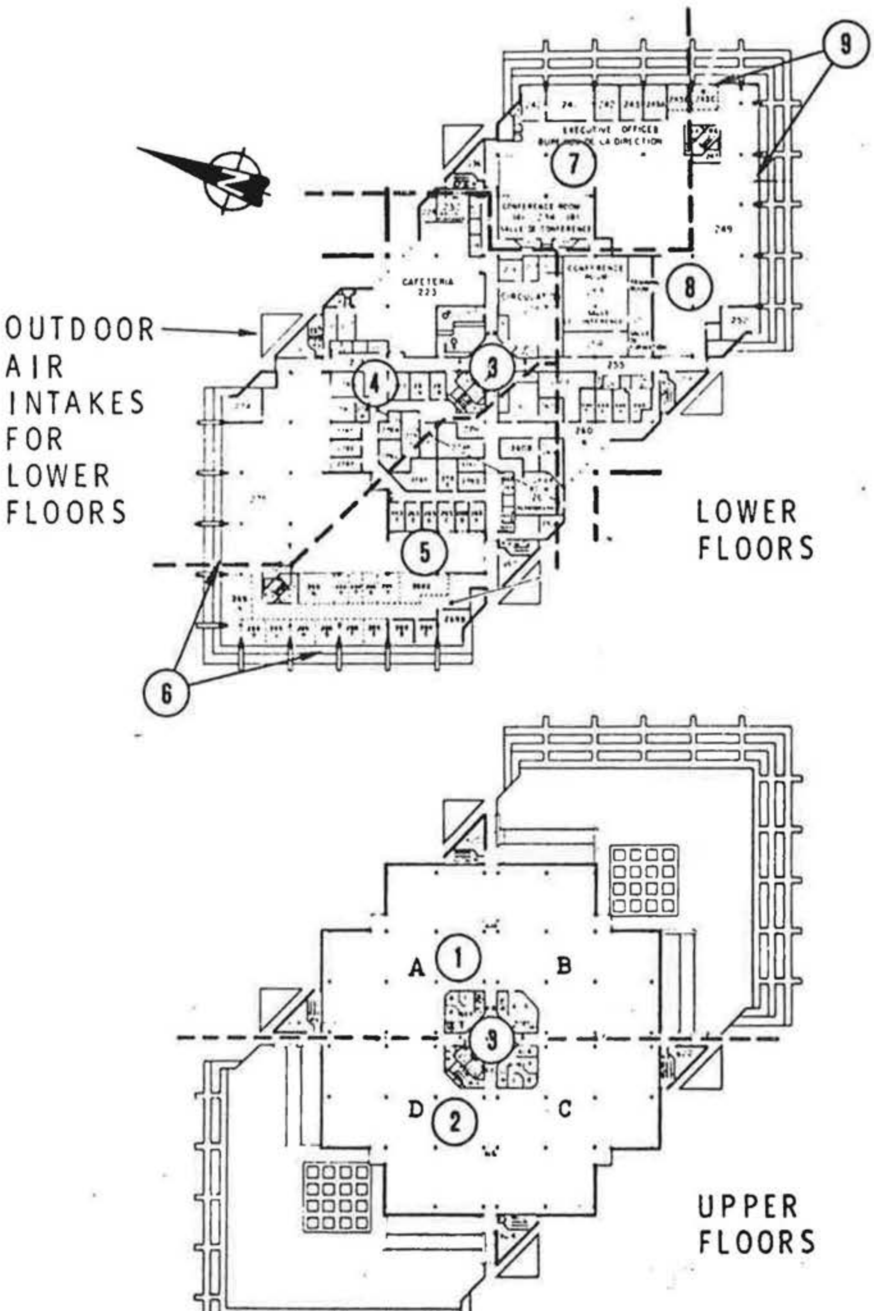

Figure 1. Typical floor plans showing the HVAC systems.

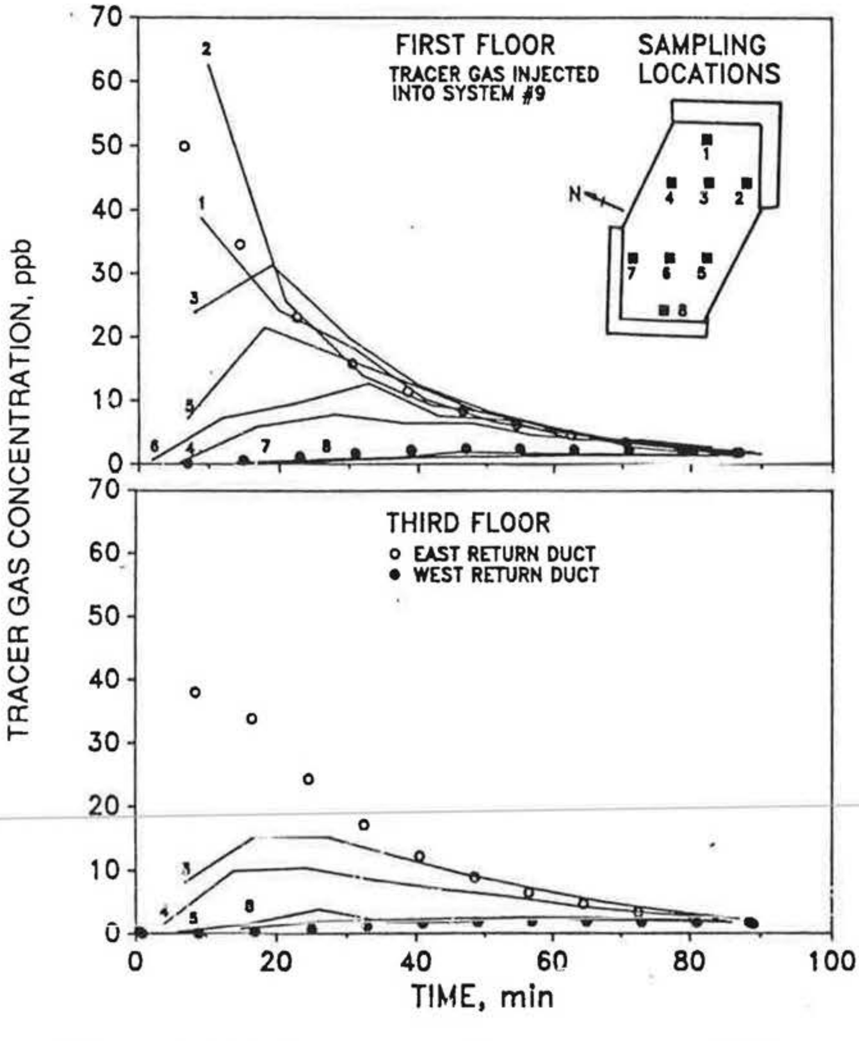

Figure 3 Air distribution patterns with the tracer gas injected into supply air ducts of system No. 9

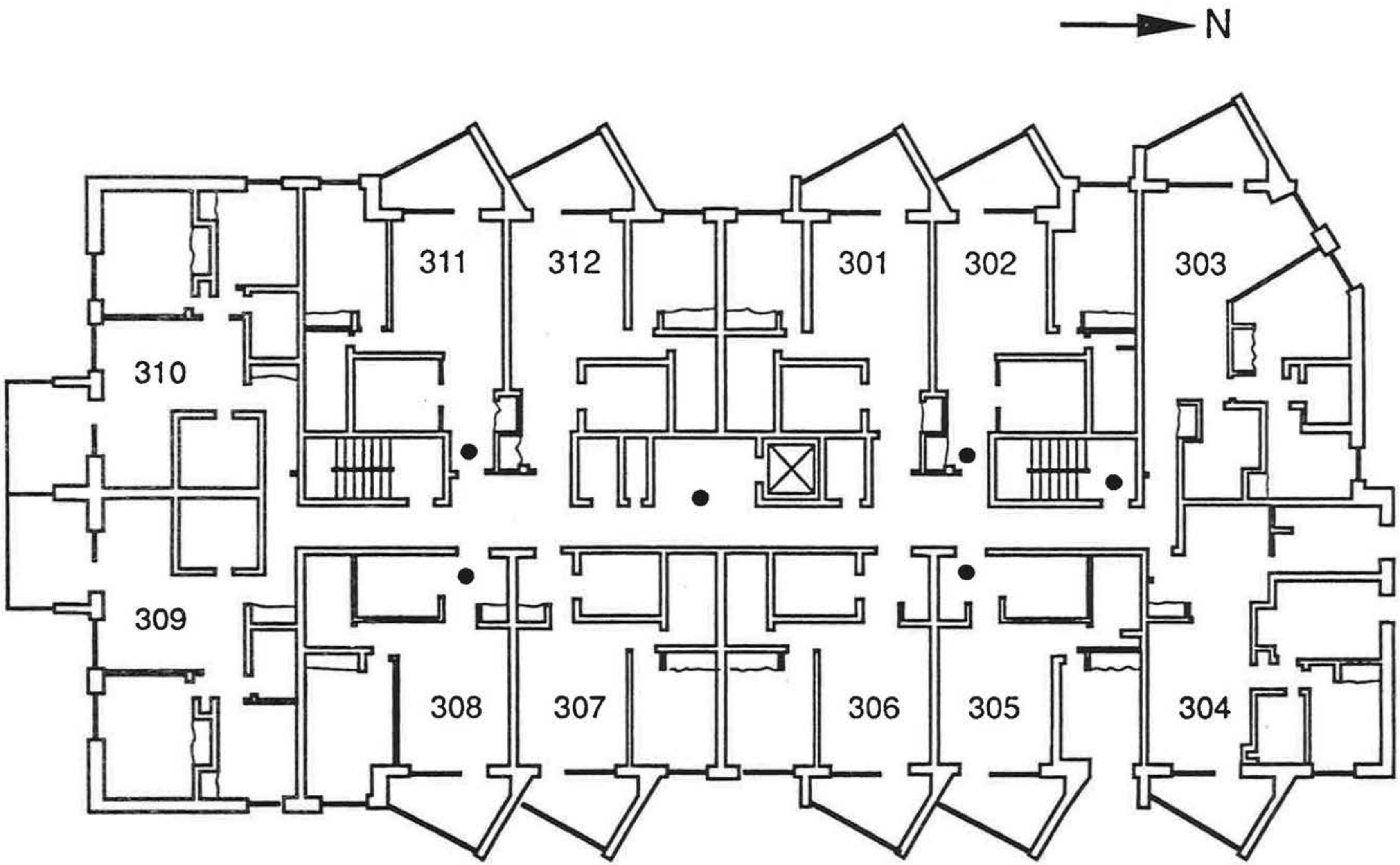

Figure 4

Floor plan of a typical floor showing tracer gas sampling locations

BR 7143-2

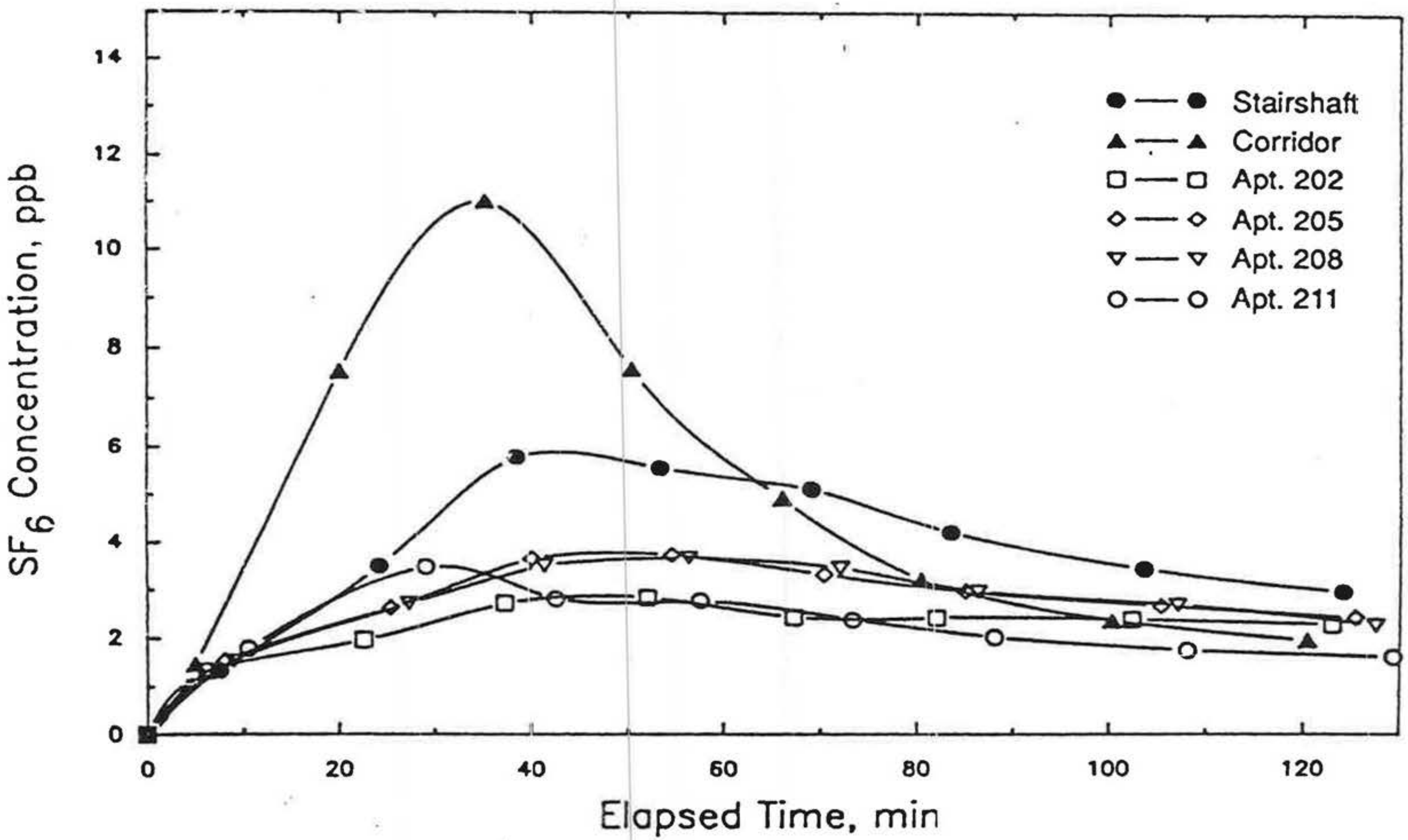

Figure 5

Contaminant dispersion patterns for the second floor with the ground floor garbage room as the source location; winter conditions.

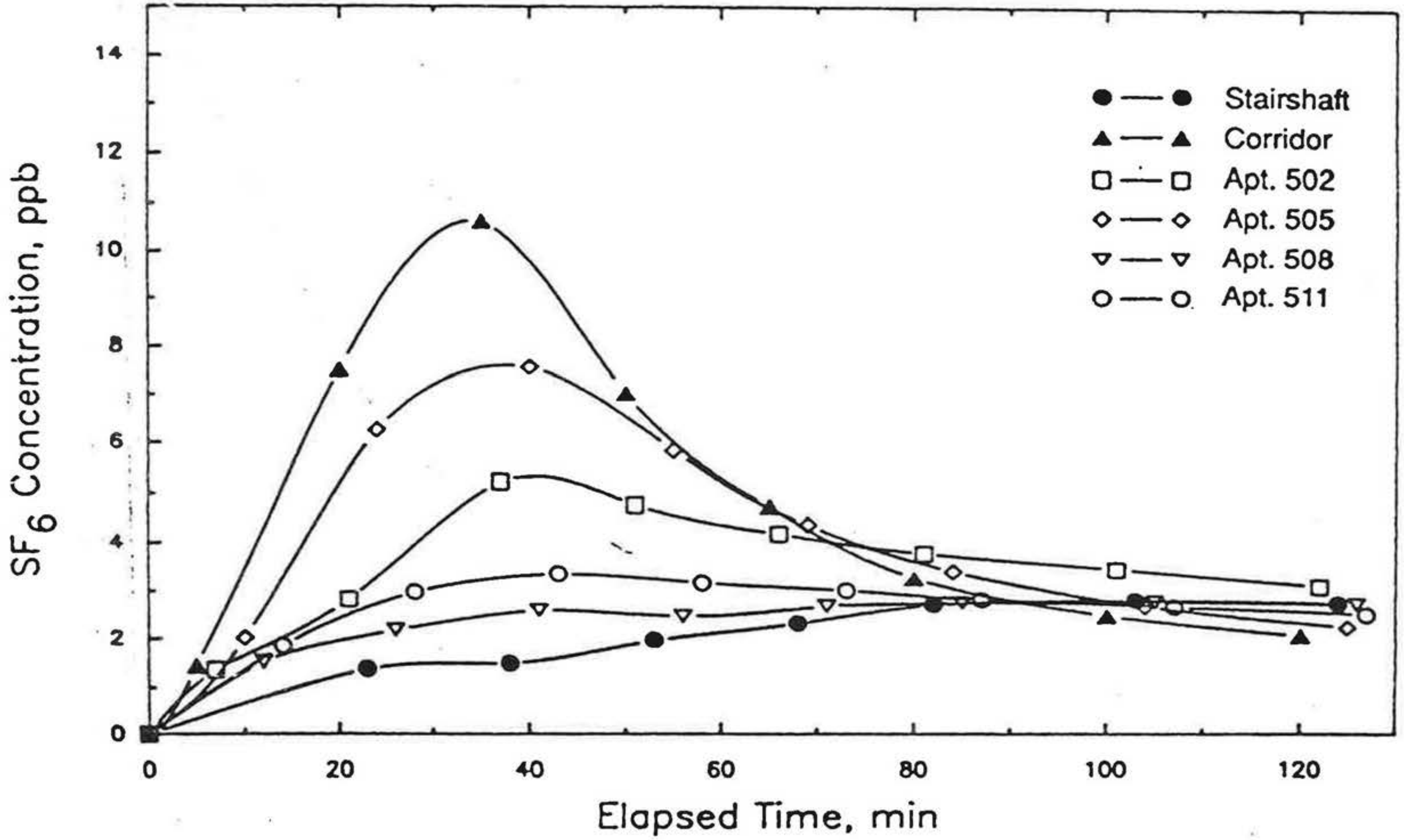

Figure 6

Contaminant dispersion patterns for the fifth floor with the ground floor garbage room as the source location; winter conditions.

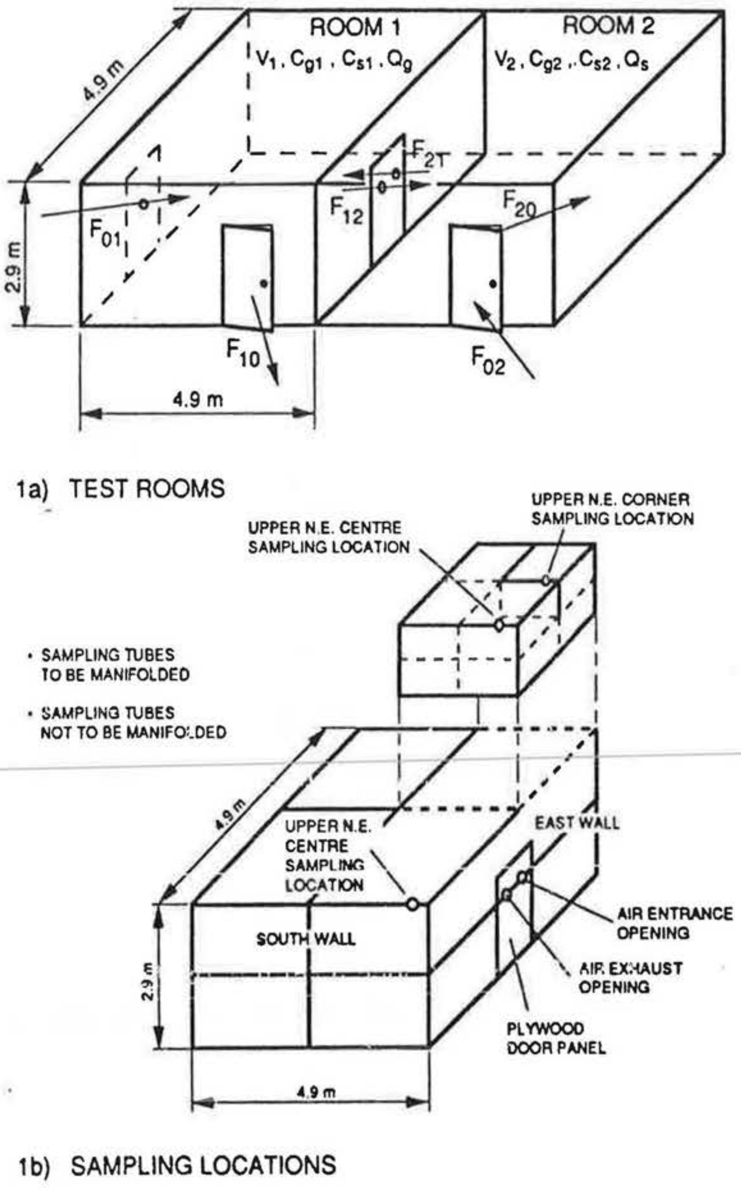

Figure 7 Test rooms and sampling locations

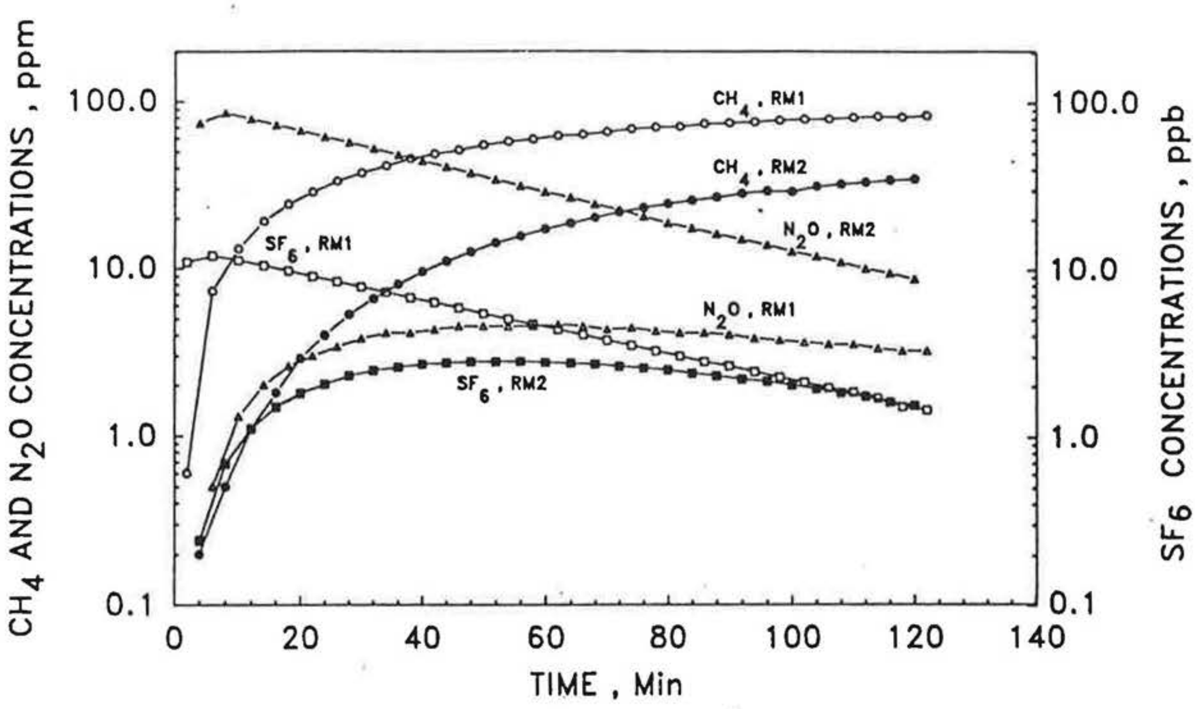

Figure 8 Typical tracer gas concentration profiles

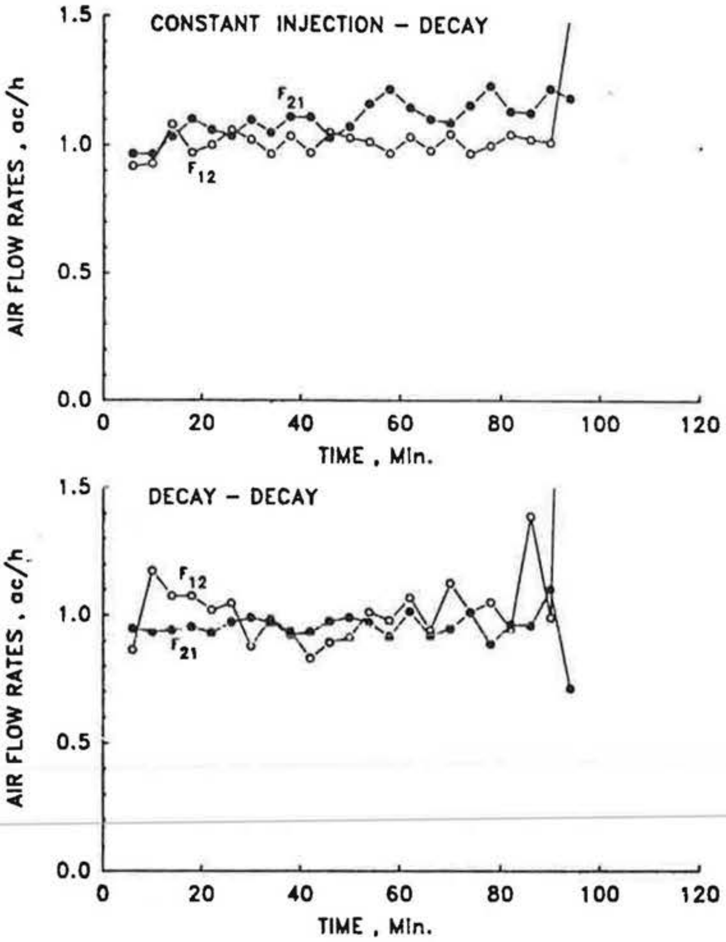

Figure 9 Calculated interzonal airflow rates; set airflow rates $F_{12} = F_{21} = 1$ ach