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NATURAL VENTILATION IN LARGE AND MULTICELLED BUILDINGS:

- THEORY, MEASUREMENT AND PREDICTION -

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OVERALL OBJECTIVE OF RESEARCH

To broaden the area of knowledge of natural ventilation to include types of buildings other than dwellings. In particular, large and more complex (e.g. multicellular) buildings such as offices.

SUMMARY

In this programme of work, methodologies for determining infiltration rates of large and complex buildings have been established. Solutions to this, hitherto, intractable problem have been obtained using a combination of theoretical and experimental studies.

Theoretical considerations suggested that comprehensive information regarding interzonal air movements might be obtained from experimental techniques using multiple tracer gases. Field measurements to determine interzonal flows were carried out in office buildings using automated measurement systems developed for this purpose.

It was recognised that, in most circumstances, simpler techniques, which would give less comprehensive but nevertheless useful information, were needed. Such a simplified technique has been developed. Theoretical and experimental work showed that, with this technique, it is probably sufficient to seed part of a complex building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.

Prediction models have also been used to determine the effectiveness of draughtstripping windows on the energy consumption of an office building. The predicted infiltration rates compared well with measured values. Energy calculations showed that, for this particular building, draughtstripping windows has reduced by 21% the seasonal gas consumption.

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CHAPTER 1

INTRODUCTION

1. PROBLEM OF DETERMINING INFILTRATION RATES IN LARGE AND COMPLEX BUILDINGS

Despite the fact that the majority of buildings, whether for commercial, public or domestic use, are naturally ventilated, infiltration and natural ventilation are among the least well understood aspects of building design. The need to conserve energy has provided the stimulus to reduce levels of fresh air supply to the minimum necessary to ensure health, safety and comfort. This has led to the demand by designers and building users for data on ventilation rates in existing buildings, for the development of methods for assessing the effects of remedial measures in over-ventilated buildings and for improved methods for predicting natural ventilation rates.

Research effort has consequently concentrated on three main areas:

- The development of experimental techniques for measuring ventilation rates and leakage characteristics of buildings.
- Construction of computer-based simulation models.
- The collection of experimental data on ventilation rates and associated independent variables.

By far the greater part of this effort has, however, been concentrated on dwellings to the exclusion of larger and more complex buildings, such as offices. This had lead to a dearth of experimental data on natural ventilation and infiltration rates on such buildings. Investigations in these had been deterred by problems of scale and lack of appropriate measurement techniques.

The most widely used conventional technique is to disperse a tracer gas throughout a building and then measure the rate at which the concentration of the tracer decays. Two conditions are, however, required to be satisfied before the decay rate from any measurement is judged to be a valid representation of the ventilation rate of the building, i.e.,

- the tracer has to be initially dispersed uniformly throughout the building and,
- there must be perfect mixing of tracer and internal air during the whole of the measuring period.

These conditions can be fully satisfied in mechanically ventilated single-celled buildings. Departures from these conditions occur as,

- the building becomes multicelled,
- the building becomes large in size, and
- the building becomes naturally ventilated.

The problems of using the conventional tracer technique, and the deviation of the decay rate from representing the ventilation rate, increase in the following order:

Problems/departures	Building		Ventilation
	Size	Complexity	
least	small	single-cell	mechanical
↓	large	single-cell	mechanical
	small	multicell	mechanical
	small	single-cell	natural
	large	single-cell	natural
most	large	multicell	natural

In buildings which are mechanically ventilated, the air handling unit can be used to disperse the tracer to a uniform concentration throughout the building and then, subsequently, to keep the tracer well mixed during measurements.

In small, naturally ventilated buildings (such as dwellings), portable mixing fans can be used to disperse and mix the tracer gas. This approach becomes impractical, if not impossible, for logistic reasons when measurements of a similar nature are required in large, multicelled, naturally ventilated buildings like offices.

The difficulties of carrying out single tracer gas in such buildings are therefore significantly greater than those in dwellings. This perhaps explains the dearth of reported measurements in the literature.

2. OBJECTIVES OF THE PRESENT PROGRAMME OF WORK

The overall objective of this work was to broaden the area of knowledge of natural ventilation to include types of buildings other than dwellings, in particular, large, complex, multicellular buildings such as offices.

As steps in achieving this, the following subsidiary objectives were identified:

- The development and validation of appropriate measurement techniques.
- The use of these to obtain results in typical buildings.
- The application of results in the context of energy use in buildings, including the determination of the effectiveness of ameliorative measures.

3. POSSIBLE BENEFITS

In 1980, the heating and lighting of public administration and commercial buildings accounted for 15% of the total primary energy consumption of the United Kingdom, at a cost of £3,320M [1]. Over a quarter of this may be attributed to ventilation and infiltration emphasising the need for better control of ventilation and for the reduction of infiltration.

This is further illustrated by a report [2] dealing with a programme of retrofit measures in Government office buildings. Although a significant reduction in annual fuel costs was achieved over the programme as a whole, particular difficulty was found in reducing consumption in a number of high energy using buildings. A common feature of these was that occupants judged them to be generally cold and draughty, suggesting excessive ventilation and infiltration. Subsequent calculations for a typical building indicated that a reduction in ventilation rate from 3 to 1 air changes per hour (ach) could reduce energy consumption by 17% and heating plant operating time by 18%. A field trial undertaken on a large office building in London demonstrated a reduction of 22% in energy consumption by improving the tightness of windows by weather-stripping. However, the cost-effectiveness of measures such as this can only be assessed if methods are available for determining existing infiltration and ventilation rates in such buildings.

4. PROGRAMME OF WORK

In order to achieve the objectives stated in Section 2 above, the work programme was arranged in four overlapping stages.

Stage 1 Carry out a review and feasibility study of techniques that might be used.

Stage 2 Carry out controlled experimental studies to develop and prove possible techniques and to obtain information on limits of application, accuracy and reliability, complexity of installation, cost etc..

Stage 3 Carry out field measurements in offices.

Stage 4 Analyse results, compare with theoretical predictions and determine contribution of natural ventilation to energy consumption.

The results of the programme are set out in the Report. Chapter 2 sets out the theoretical background needed to the measurement of both ventilation rates and interzonal flows in multicelled buildings. Appropriate and easily applied experimental methods are reviewed in Chapter 3. Arising from the considerations set out in Chapters 2 and 3, four automated systems were considered suitable for further examination and Chapter 4 describes the construction, development and operation of these. The resulting field measurements using these systems are set out in Chapter 5.

As a result of these measurements, the advantages and disadvantages of each of these systems were identified and the need for a simpler approach became apparent. Chapters 6 and 7 describe the theoretical and experimental development of such a method. Consistent with this approach, Chapter 8 deals with the development and testing of simpler methods of tracer gas sampling. This enables analysis to be carried out in the laboratory, thereby dispensing with the need to have on site complex and expensive equipment.

One productive application of the measurement of ventilation rate in real buildings is to validate computer predictions based upon theoretical models. Chapter 9 describes a comparison between prediction and field measurements, made as part of the programme, in one building and also demonstrates the energy savings achieved by the use of window-draughtstripping in reducing infiltration rates.

REFERENCES

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CHAPTER 2

THEORETICAL BASIS FOR MEASURING VENTILATION RATES IN MULTICELLED BUILDINGS

1. INTRODUCTION

It is not easy to predict air movement within buildings, especially if the building is large and multicelled. The movement of air can, however, be determined by using tracer gases to map these flows.

The detail to which these flows need to be known will determine the choice of measurement technique and the sophistication of approach. If a broad and overall ventilation rate is required, then a single tracer gas 'decay' measurement may be sufficient. If, however, interzonal airflows are required as well, then an approach involving multiple tracer gases would need to be considered.

In this Chapter, we discuss the theoretical basis underlying a wide variety of measurement techniques. The detail to which the airflows will be looked at will range in complexity and will cover interzonal airflows, fresh air infiltration into various zones and overall infiltration rates.

Section 2 looks at the equations governing tracer gas concentrations in multicelled buildings. The 'direct' solution of these equations, i.e. the manner in which tracer is dispersed given that the airflows are known, is considered in Section 3.

In Section 4, the 'inverse' problem of determining airflows by measuring tracer concentrations within cells is considered. It is shown that if interzone airflows need to be determined in an N-zone building, then N-sets of N tracer gas equations need to be set up and solved. Possible experimental strategies for constructing these equations are discussed in Section 5.

It does not matter how the tracer gas equations are set-up experimentally as long as all the tracer concentration and generation terms are measured. It is, however, experimentally easier to have procedures which fix one or more of these terms to predetermined values. This can reduce the mathematical effort needed to solve the various tracer gas equations.

These procedures of 'decay', 'constant concentration' and 'constant injection' as well as 'long term averaging' are discussed fully in Section 6 in the context of a multicelled building. For completeness, the manner in which the tracer gas equations are simplified for a single cell building is considered in Section 7 together with a brief discussion on the use of the experimental procedures for such a building.

The implications for interpreting tracer gas measurements in a building when the tracer mixes imperfectly with air in a cell is discussed in Section 8. Analysis of errors incurred in carrying out these experimental methods is then discussed in Section 9.

The Chapter concludes with a general summary is drawn and suggestions for specific experimental procedures to be implemented within the present programme of work.

2. GOVERNING EQUATIONS

The basic equations of all tracer gas methods can be derived by considering the general equations governing tracer gas concentrations in multiple-connected spaces (i.e. cells) using an approach similar to that given by Sinden [1] and Sherman et al [2].

The following assumptions are made:

- The building is composed of N cells in which the air and tracer is perfectly mixed.
- Q_{ij} and Q_{ji} are the volume flow rates between cells i and j where the two flow rates are not necessarily equal.
- $C'_i(t)$ is the concentration of the tracer in the i^{th} cell at time t
- Volume of each cell is V_i
- Production of the tracer in any cell is $f_i(t)$.

Suffix 'O' refers to the air space outside the building.

The conservation of the mass of tracer gas gives the following set of equations:

$$V_i \frac{dC'_i}{dt} = f_i + \left[Q_{oi}.C_o + \left\{ \sum_{j=1}^{N} Q_{ji}.C'_j(1 - \delta_{ij}) \right\} \right] - \left[Q_{io}.C'_i + \left\{ \sum_{j=1}^{N} Q_{ij}.C'_i(1 - \delta_{ij}) \right\} \right] \tag{1}$$

for i = 1, 2, ..., N and j = 1, 2, ..., N. the independent variable t has been dropped from $C'_i(t)$ and $f_i(t)$ in the above equation for clarity. The Kronecker delta,

$$\delta_{ij} = 1 \text{ for } i = j$$

and $$= 0 \text{ for } i \neq j$$

The conservation of mass (neglecting small changes in density) of air gives another set of equations.

$$\underset{\text{(inflow)}}{Q_{oi} + \sum_{j=1}^{N} Q_{ji}(1 - \delta_{ij})} = \underset{\text{(outflow)}}{Q_{io} + \sum_{j=1}^{N} Q_{ij}(1 - \delta_{ij})} \tag{2}$$

If S_i is defined as the outflow of air from cell i to the outside, then from Equation 2,

$$S_i = Q_{io} + \sum_{j=1}^{N} Q_{ij}(1 - \delta_{ij}) \tag{3}$$

If

$$C(t) = C'(t) - C_o(t)$$

then Equation 1 reduces to

$$\{K\} = [Q] \cdot \{C\} \tag{4}$$

where the elements of column matrix $\{K\}$ are given by,

$$k_i = V_i \dot{C}_i - f_i$$

and those of the square matrix $[Q]$ by

$$q_i = S_i . \delta_{ij} + Q_{ji}(1 - \delta_{ij})$$

The elements along the principal diagonal of $[Q]$ are all negative. In this matrix, if elements in any row or column are summed, the result is the negative value of either Q_{0i} or Q_{i0} respectively.

3. DIRECT SOLUTION OF THE TRACER GAS EQUATION

Given the initial condition,

$$\left\{C\right\}_{t=0} = \left\{C(0)\right\} \tag{5}$$

and knowing the intercell flows $[Q]$, the concentrations $\{C(t)\}$ at time t can, in theory, be determined by solving the set of equations given by Equation 4.

Although not normally needed in ventilation measurements, the solution to Equation 4 has some relevance as it allows strategies to be developed for dispersing the tracer in multicelled buildings and subsequently collecting various samples for analysis.

Pipes and Hovanessian [3] offer the solution,

$$\left\{C(t)\right\} = e^{\left[Q\right]t} . \left\{C(0)\right\} + e^{\left[Q\right]t} . \int_0^t e^{-\left[Q\right]t'} . f_i(t')dt' \tag{6}$$

where the elements in the exponential matrix are formed by replacing each element q_{ij} in matrix $[Q]$ by $e^{q_{ij} . t}$. This solution is rather difficult to evaluate except in very simple cases.

Sinden [1] has considered the case when $\{f\} = 0$. Equation 4 then reduces to the form

$$\left[V\right]\left\{\dot{C}\right\} = \left[Q\right]\left\{C\right\} \tag{7}$$

subject to the condition of Equation 5. A basic property of the system of differential equations given by Equation 7 is that, for certain special initial concentrations, the solution has the simple form

$$\left\{C(t)\right\} = \left\{C(0)\right\} e^{\lambda t} \tag{8}$$

In general, there are N such special solutions, each with its own characteristic (or eigen) value of λ. The special solutions can be written as

$$\left\{C^{(0)}\right\} e^{\lambda_0 t}, \left\{C^{(1)}\right\} e^{\lambda_1 t}, \ldots, \left\{C^{(N-1)}\right\} e^{\lambda_{N-1} t}$$

where $C^{(k)}$ is the eigen-vector corresponding to eigenvalue λ_k. Every other solution is then a combination of these such that,

$$\left\{C(t)\right\} = \sum_{k=0}^{N-1} \alpha_k \left\{C^{(k)}\right\} e^{\lambda_k t} \tag{9}$$

To find the eigenvalues λ_k and the corresponding eigen-vectors $\{C^{(k)}\}$, Equation 8 has to be substituted in Equation 7 to give,

$$\lambda \left[V\right]\left\{C\right\} = \left[Q\right]\left\{C\right\} \tag{10}$$

Values of λ for which Equation 10 has a solution,

$$\left\{C\right\} \neq \left\{0\right\}$$

are the eigenvalues of matrix $[Q]$ and the corresponding solutions of

$$\{C\} \neq \{0\}$$

are the eigenvectors of $[Q]$ corresponding to that particular λ.

At the moment, analytical solutions of the form of Equation 9 can be derived only for the simplest multicellular flows. Computer programs using numerical algorithms have now been written [4] which extends the solutions to problems involving complex but more realistic flows.

4. INVERSE PROBLEM OF DETERMINING INTERCELL AIRFLOWS FROM CONCENTRATION MEASUREMENTS

The inverse problem of determining intercellular flows Q_{ij} from observations of gas concentrations $C_i(t)$ are encountered in ventilation studies.

The quantities $\{\dot{C}\}$, $\{C\}$, $[V]$ and $\{f\}$ of Equation 4 are either known or can be measured. There are, however, (N^2-N) unknown values of Q_{ij} and Q_{ji} (for $i \neq j$) together with 2N unknown values of Q_{i0} and Q_{0i}. To determine this total of (N^2+N) unknown values, we have at our disposal N equations each from Equations 2 and 4.

By satisfying N unknowns by the N equations of Equation 2, there are only N equations left from Equation 4 to satisfy the remaining N^2 unknowns. The only way these unknown values can be found is by generating a further (N-1) independent sets similar to Equation 4.

The g^{th} generated set of Equation 4 can be written as,

$$\left\{K\right\}^{(g)} = \left[Q\right] . \left\{C\right\}^{(g)} \tag{11}$$

where g = 1, 2, ..., N. The elements of the column vector $\{K\}^{(g)}$ are given by

$$k_i^{(g)} = V_i . \dot{c}_i^{(g)} - f_i^{(g)}$$

for i=1, 2, .., N.

By algebraically manipulating the N^2 equations given by Equation 11, we can write the unknown airflows Q_{ji} in column form and the concentration matrix $\{C\}$ in square form so as to form a system of equations given by

$$^{(l)}\left\{Y\right\} = \left[A\right] . {}^{(l)}\left\{X\right\} \tag{12}$$

In the expression above, equations relating to a cell l is denoted by the raised prefix (l) where l = 1, 2, .., N. the i^{th} element of the column matrix $^{(l)}\{Y\}$ and j^{th} element of $^{(l)}\{X\}$ are given by,

$$^{(l)}y_i = V_l \dot{C}_l^{(i)} - f_l^{(i)} \tag{13}$$

$$^{(l)}x_j = q_l^{(i)} = - S_l \delta_{lj} + Q_{jl} (1 - \delta_{lj})$$

and the a_{ij} element of square matrix $[A]$ by,

$$a_{ij} = C_j^{(i)} \tag{14}$$

Note that the raised prefix (l) refers to the 'set of equations' relating to the l^{th} cell whilst the lowered suffix l refers to a 'quantity' relating to the l^{th} cell.

Given $^{(l)}\{Y\} \neq \{0\}$, Equation 12 may be regarded as a non-homogeneous system of N linear equations in the N unknowns, $^{(l)}\{X\}$. The system has a unique solution, if and only if, the determinant of $[A]$ is not equal to zero, i.e.

$$|A| \neq 0 \tag{15}$$

Thus, knowing

V_l	volume of cell l
$\dot{C}_l^{(i)}$	time derivative of the tracer concentration in cell l during the i th generation of the experiment for i = 1, 2, ..., N
$f_l^{(i)}$	tracer production in cell l during the i th generation for i = 1, 2, ..., N
$C_j^{(i)}$	tracer concentration in cells j (= 1, 2, ...,N) for i (= 1, 2, ..., N) generation of the experiment

and provided Equation 15 is satisfied, the unknown flow quantities,

S_l	total outflow/inflow of air into cell l
Q_{jl}	flow from cell j (= 1, 2, ..., N but j = l) to cell l

can be calculated by solving Equation 12 for any cell l (= 1, 2, .., N).

Once the flows S_l and Q_{jl} (excluding j=l) are solved for all l, the exchange of air between any cell l and the outside, Q_{0l} and Q_{l0}, can be calculated from Equation 2.

5. POSSIBLE STRATEGIES IN CONSTRUCTING N-SETS OF CONSERVATION OF TRACER GAS EQUATIONS

N sets of Equation 11 can be generated by any one of three possible strategies or by a hybrid of these. The sets can be formed either by,

- observing $\{K\}$ and $\{C\}$ at N different time points
- varying the injection rates $\{f\}$ a total of N times
- using N different tracer gases

5.1. Observing at N different time points

Sinden [1] highlights some of the problems associated with constructing N sets of Equation 11 at N different times as follows;

- Observations of $\{C(t)\}$ tend to be unreliable because of their sensitivity to noise.
- The matrix $[A]$ of Equation 12 will be badly determined if the times t_k $(k = 1, 2, \ldots, N)$ are close together. With wider intervals, it is doubtful whether the intercell flows in $\{X\}$ will remain constant over that period.
- If initial conditions of Equation 5 coincide with an eigenvector, then Equation 11 generated at different times will be the same, thereby giving only N independent equations.

Problems of noise can be minimised by integrating Equation 4 over N time intervals of either fixed or varying periods such that,

$$V_i\left[C_i(t_2) - C_i(t_1)\right] - \left[f_i(t_2) - f_i(t_1)\right] = - S_i\int_{t_1}^{t_2} C_i(t).dt + \sum_{j=1}^{N} Q_{ji}.(1 - \delta_{ij}).\int_{t_1}^{t_2} C_j(t).dt \qquad (16)$$

The two other remaining problems can, in theory, be minimised by choosing appropriate time intervals, but the mathematical approach to do this is still not clear and requires further thought [1].

5.2. Varying the injection rate $\{f\}$ a total of N times

By a careful choice of injection rates $\{f\}$, it is possible to construct a well-determined concentration matrix $[A]$, given in Equation 12. One possible strategy would be to inject one cell at a time whilst maintaining zero injections in the others. The set of corresponding equations, Equation 11, can then be constructed. This process of injection is then repeated for the remaining cells. At each injection sequence, the injection can be continuous for the duration of each test or, an initial injection of tracer before taking measurements may be sufficient.

The increased length of this single-gas, multi-injection procedure can be prohibitive which means that the intercell flows given by $\{X\}$ may not remain constant during the experiment. If, however, invariancy is assumed, and the duration of the complete experiment is not prohibitve, then this multi-injection procedure is a valid technique to use [5].

5.3. Injecting N different gases

As Sherman et al [2] point out, it is simpler to use N different gases to give the required N^2 equations for Equation 12 than the length of the experiment. This reduces operator effort and ensures that changes in external weather conditions do not violate too strongly the time invariancy of the inter-cellular flows, $\{X\}$. The main disadvantage of this procedure is that it requires sophisticated multi-injection and sampling hardware as well as analytical equipment.

The concentration matrix $[A]$ will be non-singular if each gas is injected into one, and only, one cell. In this case, element $^{(1)}y_i$ of Equation 13 is modified to

$$^{(1)}y_i = V_1\, \dot{C}_1^{(i)} - f_1^{(i)}\delta_{1i} \qquad (17)$$

6. EXPERIMENTAL IMPLEMENTATION OF TRACER EQUATIONS

It does not matter how the tracer gas equations are set-up experimentally as long as all the tracer concentration and generation terms in Equation 12 can be measured. It is, however, easier experimentally to have procedures which fix one or more of these terms to predetermined values. This can reduce the mathematical effort needed to solve the various tracer gas equations so as to determine intercell airflows.

Three techniques utilising tracer gas are commonly used to determine ventilation rates and airflows within single- or multicelled buildings. These are techniques of 'decay', 'constant concentration' and 'constant flow'. A fourth technique, of recent origin and still not in widespread use, is that of 'long term' averaging.

6.1. Tracer decay

In this technique, quantities of the tracer gas are released within each test space, mixed as thoroughly as possible with the internal air and is then allowed to decay by interchange with the other spaces and the outside air. The element $f_1^{(i)}$ can then be dropped from Equation 13 which then reduces to.

$$^{(1)}y_i = V_1 . \dot{C}_1^{(i)} \qquad (18)$$

6.2. Constant concentration

In this case, the concentration of a tracer gas is held constant in each cell. If N different tracer gases are used, and the injection is one gas to each cell, the $^{(1)}$vector matrix $\{C\}$ drops out of Equation 12 reducing the term $^{(1)}y_i$ in Equation 13 to

$$^{(1)}y_i = - f_1^{(i)} \delta_{1i} \tag{19}$$

The direct infiltration rates, Q_{O1} $(1 = 1, 2, \ldots, N)$ from the outside to the 1 cells can be found from only one set of Equation 12 by carrying out a special experimental procedure. This is done by using one gas as the tracer and keeping the concentration of this gas at a constant value C in all cells. Equation 12 then reduces to the set of equations,

$$- f_1 = C \sum_{f=i}^{N} \left[- S_1 \, \delta_{1j} + Q_{j1}(1 - \delta_{1j}) \right] \tag{20}$$

for cells $1 = 1, 2, \ldots, N$. The raised suffix (i) is dropped since only one tracer is used.

Substituting Equations 2 and 3 in Equation 20, we have

$$Q_{o1} = f_1/\bar{c} \tag{21}$$

for $1 = 1, 2, \ldots, N$.

The overall infiltration rate into the building is then simply,

$$\sum_{1=1}^{N} Q_{o1} \tag{22}$$

6.3. Constant flow

The essence of this technique is to inject, at a constant flow rate, a tracer into each cell. This is a simpler experiment than that of constant concentration but it still requires the solution of N sets of Equation 11. This means that N different tracer gases must be used with each being injected into only one cell at a time.

If injections are continued until equilibrium concentrations are reached, the elements (given by Equation 13) of matrix $^{(1)}\{Y\}$ in Equation 12 are simplified to

$$^{(1)}y_i = - F_1^{(i)} \, . \, \delta_{1i} \tag{23}$$

where F is the constant injection rate. A disadvantage is the long time needed before equilibrium concentrations are reached as no allowance is made in the conservation equations for changes in the airflow rates [Q] during the test period.

6.4. Long term averaging

In some circumstances, it may be necessary to determine the long term averages of airflows in a building where the averaging period is about a month. Sherman et al [2] point out that, in principle, the three techniques considered above could be used over this period but that this would tie-up equipment which are both expensive and complex. A simpler system, which could determine the averaged terms of the corresponding equations in a straightforward manner, would be preferable.

If the long-term averages are denoted by an overbar, Equation 11 can be simplified to

$$- \left\{\bar{f}\right\}^{(g)} = \left[Q\right].\left\{\bar{C}\right\}^{(g)} \qquad (24)$$

7. SINGLE CELL BUILDINGS

If all cells in a multicell building are connected to form a single space and a tracer gas is mixed perfectly with the air within that space, then the two governings Equations 1 and 2 reduce to

$$V \dot{C}(t) = f(t) - Q_o.C(t) \qquad (25)$$

where Q_0 is the fresh air infiltration.

7.1. Tracer decay

In the tracer decay mode

$$f(t) = 0 \quad \text{for} \quad t > 0$$

and Equation 25 reduces to

$$V \dot{C}(t) = - Q_o.C(t) \qquad (26)$$

which can be solved to give

$$C(t) = C(0) . e^{-(Qo/V)\ t} \tag{27}$$

The fresh air infiltration I defined by,

$$I = Q_o/V \tag{28}$$

can then be determined graphically by fitting a straight line to the decay curve of Equation 27 plotted in the form of ln(C) versus elapsed time t. If t is in hours, the units of I are in air change per hour (ach).

Alternatively, I can be detemined on a point by point basis so that,

$$I = \left[\ln(C_1/C_2)\right]/(t_2 - t_1) \tag{29}$$

where C_1 and C_2 are the concentrations corresponding to times t_1 and t_2 respectively.

7.2. Constant concentration

If a constant concentration $\bar{C}$ is maintained in the single cell building, Equation 25 reduces to

$$f(t) = Q_o\ \bar{C} \tag{30}$$

from which the infiltration rate I can be determined.

7.3. Constant flow

If F is the constant flowrate at which the tracer gas is injected into the single cell building, then Equation 25 is modified to

$$V.\dot{C}(t) = - Q_0.C(t) + F \tag{31}$$

which, given the initial condition C(0)=0, can be solved to give

$$C(t) = (F/Q_0).\left[1 - e^{-(Q_0/V)t}\right] \tag{32}$$

Equation 32 shows that the time taken to approach steady state concentration is inversely proportional to the infiltration rate, I. For example, at 2 ach, it takes 2.3 hours to reach 99% of the final concentration. If the infiltration rate is reduced to 1 ach, the time is doubled to 4.6 hours.

7.4. Long term averaging

For long term averaging, Equation 25 can be rewritten as.

$$\overline{(V/Q_0).\dot{C}(t)} + \overline{C(t)} = \overline{f(t)/Q_0} \qquad (33)$$

where the overbar denotes time averaged values.

If the tracer flow is kept constant at F and the averaging interval is long (so that the concentration reaches an equilibrium value), then Equation 33 reduces to

$$\overline{(1/Q_0)} = \bar{C}/F \qquad (34)$$

According to Sherman et al [2], if the infiltration $Q_0(t)$ is not constant over the long term, then

$$\overline{(1/Q_0)} = k/\bar{Q}_0 \qquad (35)$$

where the correction factor

$$k = \sqrt{1 + 2\sigma^2} \qquad (36)$$

contains the fractional standard deviation σ, of either the infiltration or the inverse infiltration. By analysing a large data set relating to dwellings, they found that

$$k \simeq 1$$

Hence the average infiltration rate from Equation 34 is simply,

$$Q_0 = F / C \qquad (37)$$

8. PROBLEMS OF IMPERFECT MIXING IN CELLS

One of the main problems that can arise during air change measurements is imperfect mixing between tracer and internal air. Even with perfect initial mixing, with the use of fans, there is no guarantee that this will persist during measurement. In all cases of imperfect mixing, the location of the sampling points will determine the air change rates that are measured.

Hunt[6] describes three extreme cases in which the tracer does not mix perfectly with the room air. In the first case, some of the air in the test space stagnates even after initial perfect mixing of the tracer. For example. if the air in the lower half of the chamber is stagnant whilst air is passed through the upper half at 2 ach, then the overall average airchange is 1 ach. If the sampling is averaged over the whole volume, the poor mixing would destroy the expected logarithmic decay and the resulting logarithmic graph would be curved upwards.

In the second case, the space behaves as two separate parts with different airchange rates. If the air in the two chambers were sampled independently and then blended together, the logarithmic curve would show a slight downward curvature. Air change rate evaluated from this curve would be about 3 to 4% less than the expected average value.

The third case of imperfect mixing occurs when entering air displaces the air already present without mixing with it. The concentration of the sample which is obtained by blending together samples from the entire chamber would then give a non-linear logarithmic curve. This would curve downwards and the severity of the curvature would depend on the flow rate of air entering the chamber.

Poor mixing affects the tracer gas equations insofar that the flow matrix $[A]$ will give incorrect values of intercell flow rates if measured values of $\{C\}$ and $\{\dot{C}\}$ are used. The only recourse then open [2] is not to assume that $[V]$ represents the diagonal matrix with the measured volumes of the cells as its elements but that it is yet another unknown matrix containing off-diagonal elements as well.

9. ERROR ANALYSIS

The total error in any measurement can be made made up from errors of accuracy and precision. Precision errors are defined as the standard deviation of results from repeated trials under identical conditions whilst accuracy relates to the expected value of the measurement from the true value.

Standard techniques of error analysis can be used to estimate the errors involved in determining airflow rates in multicell ventilation measurements.

9.1. Multicell airflows

If Δx_i and Δa_{ij} are the absolute standard errors of x_i and a_{ij} in Equation 12, then

$$\Delta y_i \approx \sum_{j=1}^{N} a_{ij}\, \Delta x_j + \sum_{j=1}^{N} \Delta a_{ij} . x_j \tag{38}$$

where Δy_{ij} are the corresponding errors in y_i.

Equation 38 can be put into matrix notation, from which

$$\{\Delta X\} = [A]^{-1} \{\Delta Y\} - [A]^{-1} [\Delta A] \{X\} \tag{39}$$

The elements in the error matrices $\{\Delta Y\}$ and $\{\Delta A\}$ are given by

$$\Delta Y_i = \sqrt{(\dot{C}_1{}^{(i)}\, \Delta V_1)^2 + (V_1 . \Delta\dot{C}_1{}^{(i)})^2 + (\Delta f)^2} \tag{40}$$

where

$$\Delta C = \sqrt{(\Delta C_2^2 + \Delta C_1^2)}/\delta t \quad + \quad \delta C \sqrt{\Delta t_1^2 + \Delta t_2^2}\, /(\delta t)^2 \tag{41}$$

in which

$$\begin{aligned} \delta t &= t_2 - t_1 \\ \delta C &= C_2 - C_1 \\ \Delta a_{ij} &= \Delta C_j{}^{(i)} \end{aligned} \tag{42}$$

For large values of δt, Equation 41 reduces to

$$\Delta C \approx \sqrt{C_2^2 + C_1^2}\, /\delta t \tag{43}$$

9.2. Single cell airflow

The infiltration rate, I, in a single cell building can be found by determining the slope of the tracer decay curve written in the form

$$\ln\{C(t)\} \approx \ln(C_0) - (Q_0/V) . t \tag{44a}$$

which represents a linear equation of the form

$$y = a_0 + a_1 . x \tag{44b}$$

The problem then is to calculate the values of a_0 and a_1 to give a best straight line fit through the N sets of experimental data points of ln.C(t). and t corresponding to y and x in Equation 44b. To resolve this, techniques of linear regression are used.

According to Chatfield [7], the best estimates of a_0 and a_1 can be determined using the linear regression method of 'least squares' which gives

$$\hat{a}_0 = \bar{y} - \hat{a}_1 \bar{x} \tag{45}$$

and

$$\hat{a}_1 = \sum_{i=1}^{N} (x_i - \bar{x}) y_i / \left[\sum_{i=1}^{N} (x_i - \bar{x})^2 \right]$$

where

$$\bar{x} = \left(\sum_{i=1}^{N} x_i \right) / N$$

If $t_{\alpha/2;(N-2)}$ is the value of the Student-t distribution for (N-2) degrees of freedom at the 100(1 - α/2) percentage point, then the 100(1 - α) confidence interval for a_0 is given by

$$\hat{a}_0 \pm t_{\alpha/2;(N-2)} \cdot S_{y|x} \sqrt{\left\{ (1/N) + (\bar{x}^2) / \sum \left[(x_i - \bar{x})^2 \right] \right\}} \tag{46}$$

for a_1 by

$$\hat{a}_1 \pm t_{\alpha/2;(N-2)} \cdot S_{y|x} / \sqrt{(x_i - \bar{x})^2} \tag{47}$$

and for the straight line

$$y_0 = a_0 + a_1 x_0$$

by

$$\hat{a}_0 + \hat{a}_1 x_0 \pm t_{\alpha/2;(N-2)} \cdot S_{y|x} \sqrt{(1/N) + (x_0 - \bar{x})^2 / \sum (x_i - \bar{x})^2} \tag{48}$$

In the above equations, $S^2_{y/x}$ is the unbiased estimate of the residual variance and is given by

$$S^2_{y|x} = \left[\sum y_i^2 - \hat{a}_0 \; y_i - \hat{a}_1 \; x_i y_i\right] \tag{49}$$

where the summation in Equations 46 to 49 are carried out for all i (= 1, 2, ..., N).

Note that the confidence interval for y_0 given in Equation 48 is smallest when

$$x_0 = \bar{\bar{x}}$$

This means that in the linear portion of the decay curve, it is better to take more observations at the ends and reduce those in the middle. As Chatfield [7] points out, this will increase the value of $(x_i - \bar{x})^2$ and so decrease the standard error of all the above estimates.

An important statistcal parameter which must be given in all linear regression analysis is the correlation coefficient, r, given by

$$r = \sum(x_i - \bar{x})(y_i - \bar{y}) / \left\{\left[\sum(x_i - \bar{x})^2\right]\left[\sum(y_i - \bar{y})^2\right]\right\} \tag{50}$$

which measures the degree of correlation between the two variables x and y. It can be shown [7] that r^2 gives the ratio of the variation of the points $\hat{y}_i$ from the regression line to that of the total variation of y_i from the mean value $\bar{y}$. The remaining $(1 - r^2)$ then indicates the amount of variation unaccounted by any linear dependence of x on y.

10. CONCLUSIONS

In this Chapter, we have examined the theoretical background underlying the measurement of airflows in multicelled buildings.

The equations governing the dispersion of tracer gas in multicelled buildings has been set out. It has been shown that these equations form a set of simultaneous differential equations. There are two approaches to solving these. The first of these would give the 'direct' solution whereby the movement and concentration level of the tracer can be predicted once the airflow pattern within the building was known. This was not, however, what is required in the present context since what we need is the 'inverse' solution whereby the airflows can be determined by measuring concentration levels of the tracer.

The 'direct' solution is, however, relevant as it provides a powerful tool with which to determine strategies for both dispersing and sampling tracer gas in complex, multicelled buildings. It has been shown that an analytical solution is very difficult for this case. A computer program using numerical algorithms has, therefore, been written to provide 'direct' solutions. This has been used extensively in Chapter 7 to develop a 'simplified' technique.

For the present, however, the 'inverse' solution is of immediate importance. It has been shown that the number of equations generated by a single tracer gas are insufficient to determine in full the air movement between cells. Possible strategies for constructing these additional equations have been considered. Three approaches were examined and, arising from these, it was shown that a strategy involving multiple tracer gases should be the most effective and appropriate.

In such an approach, complete intercellular flows can be determined by seeding each cell with a different tracer. If, however, certain neighbouring cells can be assumed to behave in a similar manner then they can be grouped together to form a zone. The number of tracers can then be reduced.

The manner in which this 'multiple tracer' approach can be implemented experimentally has been discussed as have the the techniques of 'decay', 'constant concentration', 'constant flow' and 'long term averaging' in the context of multicelled buildings. As an adjunct to the item on 'constant concentration', it has been shown that if only the fresh air infiltration into each cell that is required, then a single tracer gas is sufficient.

With regard to the experimental work necessary for the present programme of work in multicelled buildings, this Chapter indicated that the most appropriate approach would be to use multiple tracers in the 'decay' mode to determine interzonal air movements. This Chapter also showed that the technique involving a single tracer gas and operating in a 'constant concentration' mode will also provide valuable information regarding fresh air infiltration into cells of a multicelled building.

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CHAPTER 3

REVIEW OF EXPERIMENTAL TECHNIQUES

1. INTRODUCTION

This Chapter reviews existing experimental techniques for measuring infiltration rates considered as being of direct interest to the present work. Those of a more general nature can be found in References 1 and 2.

Infiltration rates can be determined either measured directly or indirectly. In techniques involving an 'indirect' approach, as in the 'pressurisation' technique, a parameter such as the 'leakiness' of the building is measured. A ventilation rate is obtained by using these leakiness characteristics, together with parameters such as building type and external surface pressure coefficients, in prediction algorithms.

In contrast to the 'indirect' method, we are concerned exclusively in this Chapter with those methods which use tracer gases to give a direct measure of the infiltration rates and interzonal airflows.

Section 2 begins the review by discussing the properties required from an ideal tracer from both the viewpoints of necessity and desirability.

Attention is then focussed in Section 3 on analytical methods which we deem suitable for our programme of work. These have been chosen on the basis of previous experience, ease of use both in the laboratory and in the field and the capability of measuring (to the accuracy we require) the tracer gases that are to be of use to us. Within each of the analytical methods, the tracers that could be used are also discussed.

In Section 4, discussion will be centred on those tracer gases which are, in practice, used in ventilation measurements. Attention will be focussed on two aspects of the physical characteristics of these tracers which may affect ventilation measurements.

Section 5 concerns itself with 'off line' measurement techniques. In the present context, 'off line' measurements are those which do not tie up complex, automated systems during the course of the experiment. 'Off line' techniques usually involve manual dispersion of the tracer and their subsequent collection in suitable containers for subsequent analysis in the laboratory. Variations to these can occur as, for example, an analyser being set up to measure the tracer concentration at a fixed point during the course of the experiment with the output being written onto a Y-t (i.e. output versus time) chart recorder.

The previous Chapter came to the conclusion that multiple tracer gas measurements are necessary if interzonal flows in complex, multicelled buildings are to be measured. It also came to the conclusion that if information regarding fresh air infiltration is only needed, then an experimental procedure involving the 'constant concentration' method would be the most appropriate.

Experiments involving multiple tracers require each zone to be scanned and concentrations of all gases in each of these zones to be measured. Similarly, the single tracer 'constant concentration' technique requires the tracer concentration of each cell to be maintained at a fixed value.

In both of these experimental methods, it is very difficult (if not impossible) to manually carry these operations and, as such, requires suitable automated systems to do these operations. In Section 6, automated systems built prior to our programme of work are discussed. These do not, however, necessarily incorporate features that we are looking for in our work but gives an indication of what is possible.

Section 7 then concludes this Chapter with a brief summary and suggests lines of experimental technique which would be useful to our programme of work.

2. REQUIRED PROPERTIES OF TRACER GASES

Gases as tracers are preferred to particulate and liquid aerosols because of the relative ease of dispersion, collection and analysis [3]. Many authors [1,3,4,5] have set out the properties required of an ideal tracer, but no single gas can satisfy all these. A compromise has to be made by choosing the most suitable for any particular application. In general, and if possible, a tracer gas should have properties which are both necessary and desirable.

2.1. Necessary properties

The following properties of a tracer gas are necessary:

i. For compatability with the theoretical basis of tracer gas techniques:

- Methods should be available to measure suitable levels of tracer concentrations.
- The tracer should not be created in an unquantifiable way within a space (e.g. radon is not acceptable, but carbon dioxide, CO2, from occupants or combustion may

be quantified).

- It should not be removed from the space except by air movement (i.e. not by absorption or chemical change).
- Its presence in the ambient air should be known and/or be in measurable concentrations.
- It should be capable of mixing readily with air.

ii. For operational reasons:

- Methods should be available for determining its concentration free from interference by other constituents of the air from which it can be separated.
- It shall not damage health or cause discomfort (e.g. irritation or odour) to occupants or operators.
- It should be non-flammable.

2.2. Desirable properties

The following properties are desirable in a tracer gas:

- Tracer gas and measuring equipment should be inexpensive.
- Equipment and gas containers should be readily portable.
- It should be possible to easily disperse the tracer gas at a measured rate.
- It should be possible to accurately measure the tracer at very low levels of concentration.
- The tracer should have approximately the same molecular weight as air. This is less important if convection plays a bigger role than molecular diffusion [4] and if the tracer is initially well diluted with air.

3. ANALYTICAL METHODS FOR DETERMINING TRACER GAS CONCENTRATIONS

References 2 and 6 give a comprehensive list of gases, as well as methods of detection and analyses which have been used to trace air movement and air exchange. In this Section, gases and methods of analyses which are relevant to the present context are discussed. We shall primarily discuss two types of analysis, namely infrared and electron-capture, and the tracer gases that could be used with them.

3.1. Nondispersive infrared analysers

The basic principle of infrared (IR) analysis is that of a source emitting IR radiation which is measured by an appropriate detector. When an IR absorbent gas flows between the source and the detector, radiation reaching the detector is reduced. The size of reduction is determined primarily by the concentration of the gas in air.

Most common gases and organic vapours can be detected using IR analysers. The exception to these are the simple nonpolar diatomics (e.g. oxygen, hydrogen, nitrogen) and the inert gases. The absorption spectra of detectable gases show peaks at well defined wavelengths. Absorption data and the wavelength locations of the strongest peak for over 400 gases can be obtained from Reference 7. Absorption spectra for a wide range of gases are also presented in Reference 8.

The IR absorption is proportional to both the concentration of the gas being measured and to the pathlength of the sample cell. This pathlength can be varied by,

- physically varying the distance between the source and the detector, or
- by varying the optical pathlength of the IR beam and also by a system of multiple reflections.

In this way, detection range can be varied to suit the concentration of gas to be measured. In general, IR analysis is suitable for tracers operating in the ppm range.

Two tracers, widely used in ventilation work with IR analysers, are sulphur hexafluoride (SF6) and nitrous oxide (N20). In occupied premises and in situations requiring long term exposures, however, N20 is now less frequently used as a tracer because of possible health hazards [9]. In the USA, the recommended threshold limit value, TLV, is 50 parts per million (ppm) but, in general, a limit of 25 ppm is applied. Nevertheless, this tracer can still be used, with discretion, in unoccupied areas.

Sulphur hexafluoride, SF6, is emerging as the most useful tracer gas for ventilation measurement studies. It is odourless, non-flammable and has a threshold limit value (TLV) of 1000 ppm; Commercially available analysers can be set up to detect this gas in the 5 to 200 ppm range. In certain circumstances, this IR detectable range can be lowered down to 1 ppm.

3.2. Electron capture detection with gas chromatography

Electron capture (EC) detection is probably one of the most sensitive and specific gas analysis techniques [3] and works with gases and vapours which absorb electrons. In general, these are molecules which contain electronegative atoms like bromine (Br), chlorine (Cl), fluorine (F), iodine (I) and oxygen (O2).

The principle of operation [10] is to inject air containing the tracer into a flowing stream of some inert carrier gas such as argon. A chromatographic column is then used to separate tracer material from the oxygen and other electron-attaching substances in the air. The isolated tracer, diluted in carrier gas, is then presented to the detector.

In the detector, a small DC voltage applied across the cell induces a radioactive foil to irradiate the carrier gas with weak beta radiation. Ionisation of the carrier gas produces a constant current, and when the voltage across the cell is gradually increase, the ionisation current also increases up to a constant saturated value. All available electrons in the cell are now discharged at the anode and if the tracer is introduced, it reacts rapidly with the gaseous electrons and the saturation current decreases. This decrease is a sensitive indicator of the tracer concentration.

Clemons and Altshuller [11] measured the response (Table 1) of many halogenated substances to electron capture. They noted that the response of the detector, and hence the sensitivity of detection, increased in the order;

fluorine, chlorine, bromine, iodine

as well as the number of these atoms in the molecule of the substance.

Electron-capturing halogenated tracers were originally used in meteorology for long distance dispersion experiments. Collins et al [3] used SF6 and Freon 12 (dichloro difluoro methane, CCl2F2). In addition to SF6, Saltsman et al (Ref 12) used two other fluorocarbons, Freon 13B1 (bromo trifluoro methane, CBrF3) and Freon C313 (octafluoro cyclobutane). In these experiments, SF6 was measured down to concentrations of 0.01 ppb (limit set by background level) whilst the Freons were measured down to 0.3 ppb. SF6 and the Freons discussed here are inert, non toxic, odourless, non flammable and non corrosive. They can also be liquified at room temperature for ease of storage.

More recently, Lovelock and Ferber [10] have discussed the use of perfluorocarbons as atmospheric tracers since they can be detected at concentrations of 10^{-12} parts per volume (ppv). Ferber [13] has also showed that these tracers may be collected and concentrated by a factor of 1000 thereby increasing the sensitivity of detection to 10^{-15} ppv.

The perfluorocarbons are derivatives of parent fluorocarbons which contain only carbon and fluorine. It has been shown [10] that the reactivity of these tracers to electron capture increases with

- increasing molecular weight, and
- linking structure of carbon atoms.

That is, at a given molecular weight, compounds with at least one carbon atom linked directly to three or more carbon atoms, or alternatively with carbon atoms linked by double or triple bonds forming part of aromatic ring systems, are better as sources of potential tracer compounds than those with their carbon atoms linked in a simple chain or closed ring. Reactivity of the compound is drastically reduced if any oxygen or nitrogen atoms are included within the fluorinated compound.

According to Lovelock and Ferber [10]. the perfluorocarbons are some of the very few tracers which do not readily attach to solid surfaces nor are absorbed by water. They are in liquid form at room temperature but can be dispersed either by flash-heating [14] or by allowing them to diffuse from an impregnated fluoroelastomer source [15]. Suitable perfluorcarbons are included in the list of tracers in Table 2.

It should be impressed that their present low ambient background level (see Table 2) requires these tracers to be used carefully and discriminantly so as not to raise significantly (i.e. contaminate) this level.

4. CHARACTERISTICS OF TRACERS WHICH MAY AFFECT VENTILATION MEASUREMENTS

Two important characteristics required of a tracer are,

- it should mix evenly throughout the space without stratification and,
- it should not be either adsorbed nor absorbed by the surrounding surfaces.

These are considered in more detail in the following subsections.

4.1. Intercomparison of tracers with different molecular weights

Shaw [16] carried out tracer 'decay' measurements in a tightly sealed room in which the air leakage rate was maintained at a constant rate with an exhaust fan. He compared methane (CH4), carbon monoxide (CO), carbon dioxide (CO2), nitrous oxide (N2O) and sulphur hexafluoride (SF6) as the tracers. With the exception of SF6, which was measured at ppb levels, all the tracers were used at ppm concentration levels.

In this experiment. a flame-ionisation detector was used to measure CH4 whilst CO, N2O and CO2 were all measured with infrared analysers. An electron capture detector coupled to a gas chromatograph was used to determine the SF6 concentrations.

No conclusive, systematic difference was found between the air change rates measured using the different gases. The SF6 measurements underpredicted the air change rate by about 10% but was not significantly different to the general observed scatter of the measurements.

An experiment to compare directly the tracers SF6, CH4 and N2O in measuring air infiltration rates in buildings was reported by Grimsrud et al [5]. It was concluded that the air change rates measured using a heavier gas are generally slightly higher than those measured using a lighter gas. The differences were, however, found to be small and were contained within the 5 to 10% range of uncertainity expected in any tracer gas measurement. They further note that even if these differences are real and can be accounted for by a mechanism not yet determined, it should not preclude the use of one gas in preference to another when choosing a tracer.

4.2. Adsorption or absorption of tracer gas

Adsorption or absorption of a tracer gas by the surrounding surfaces can present a problem in ventilation measurements. In adsorption, the tracer adheres thinly to the surface of a solid substance with which it is in contact. Absorption, however, allows the tracer to permeate into the substance.

Hartmann et al [17] investigated the absorption of nitrous oxide (N2O) by surfaces such as woodboard, gypsum board, wallpaper, carpet, paint, plastic surfaces of various kinds and plastic tubes used for tracer sampling but found them to be insignificant. Gale [18] suggests that N2O can be absorbed to a certain degree by soft furnishings such as beddings and curtains but offers no direct evidence. Grimsrud et al [5] found insignificant absorption of N20 by water vapour during their measurements in an unoccupied dwelling.

Saltzman et al [12] stored SF6, Freon 13B1 and the heavier molecule Freon C-318 in Teflon, Mylar and Saran bags over a period of a few days. Before and after measurements indicated very small changes in concentration levels.

A typical example from Saltzmzan et al is a 'storage' test on a mixture of the three gases being contained in a Teflon bag over a period of eight days. Before and after concentration measurements showed the following changes;

- SF6 from 8.0 ppb to 7.5 ppb
- Freon 13B1 from 100 ppb to 91.8 ppb, and
- Freon C-318 from 250 ppb to 248 ppb.

These changes, with the exception of Freon 13B1, are however small and can be assumed to fall within the limits of experimental error. Freon 13B1 indicated a loss rate of about 1% per day. To all intent, however, these measurements offers no definite conclusion regarding possible loss of tracer through 'sampling' bags.

They also found that the walls of the container bags in all cases were not contaminated even with high concentrations of the tracers, and that these three tracers did not react with water vapour or with common atmospheric pollutants.

Clemons and Altshuller [11] similarly found that SF6 was not adsorbed by the inner lining of Mylar bags. With the much heavier tracer, dibromodifluoromethane (CBr2F2), they found that if they desorbed a bag which had contained 10 ppb of the tracer then they could detect in the residue approximately 3% of the original concentration.

Polyethylene bottles [3, 19] and sample lines [20] can, however, adsorb SF6. Gale [18] suggests that SF6 can be absorbed by soft furnishings to a greater degree than N20 but again cites no evidence. Recent work by Shaw [16], using SF6 at ppb concentration levels, to measure ventilation rates in a carpetted and an uncarpetted office room have shown no significant difference between the two sets of measurements.

5. OFF-LINE VENTILATION MEASUREMENT TECHNIQUES

The essential feature of off-line measurement procedures is the intermittent nature of tracer sampling and subsequent off-site analysis. After the tracer has initially been distributed, air samples are collected from various locations at various times using suitable containers. These are then sent or taken back to a central laboratory for analysis.

This approach gives a broad indication of the magnitude of air infiltration in a single cell building or of local ventilation rates in different zones of a complex building. It is suitable for use by relatively unskilled personnel and is particularly appropriate in energy-audit or retrofit programmes when a large number of buildings or buildings, say in remote locations, need to be monitored.

5.1. Distributing the tracer

The tracer can initially be distributed straight from the gas cylinders, or from pre-packed containers. For the latter, a known quantity of tracer gas is withdrawn from a supply cylinder and injected into containers for dispatch to the site. These containers could either be graduated syringes [21] or flexible, polyethylene bottles [22]. The volume of tracer in each container should be approximately set to a level determined by,

- the volume of the space,
- the expected air change rate, and
- the dynamic range of the instruments that will be used to analyse the collected samples.

The concentration in each container does not need to be known with great accuracy nor do they need to be precisely equal to one another because the aim is to measure only the relative concentrations which occur during collection of samples.

According to Grot [21] the tracer can be distributed by walking slowly around the building and injecting into each separate space an amount of tracer proportional to that volume. Mechanical ventilation systems, when available, should either be switched on for a short while to provide initial mixing or run at full recirculation throughout the test. Otherwise, small table fans placed on the floor are useful. Grot [21] suggests that half to one hour is required for adequate mixing to take place.

5.2. 'Grab' sampling

'Grab' samples are those taken in suitable containers during filed measurements for subsequent off-line analysis in the laboratory. These containers can be purpose-built sample bags made from FEP Teflon, Saran or Mylar [11, 12]. They can be filled with the sampled air by using either a hand pump or a small battery-powered pump. As an inexpensive alternative, polyethylene bottles could be used. Ten successive squeezes, each yielding 50% contraction in volume, of 500 ml polyethylene bottles provide a valid sample of the tracer concentration in a sampled space [12]. According to Drivas et al [19], SF6 can remain up to two weeks in polyethylene without any appreciable loss.

Recently, Tamura and Evans [23] have reported the use of 20 ml evacuated glass tubes, stopped by butyl rubber septa, for sampling SF6 in the ppb range. The procedure is to take a tracer sample from the indoor air with a 60 ml plastic syringe and transferring 40 ml of its contents to the tube by inserting the needle of the syringe into the septum. The tube will then be about one atmosphere above ambient pressure. A syringe needle attached to the inlet port of a gas chromatograph allows the transfer the of the sample gas under pressure in the glass tube to the sampling loop of the instrument. An EC detector is used to measure the concentrations.

A large number of samples can be collected if decay curves are to be plotted, but if this is not possible and reduced accuracy is acceptable, it is suggested that an initial and a final sample container may be enough provided the space is well mixed. Time intervals must, however, be known. The number of samples taken will affect the standard error of estimate of any 'best-fit' to the exponential decay.

Harrje et al [22] notes that in houses with good internal circulation, sampling at one central location is adequate. In larger buildings, or buildings where internal mixing is limited, multi-point sampling should be carried out as airchange rates will vary from one zone to another [24].

5.3. Long-term averaged sampling

Sherman et al [28] describes an inexpensive system which is designed to determine long-term airchange rates in dwellings. It consists of two small suitcases with each containing a solenoid pump pulsed by an interval timer. One system is set up to empty a bag containing tracer gas and the other is used to inflate, with room air, an initially empty bag. The equipment can be left unattended on site for the duration of the experiment and then brought back to the laboratory for analysis. As Chapter 2 shows, the average air change rate can then be calculated by measuring the concentration of the tracer in the sample bag, the volume of gas injected and the time period over which the experiment was carried out.

The perfluorocarbon tracer technique developed by Dietz et al [37] is also suitable for long term measurements of the average air change rate in a space. The tracer source is a diffusion tube consisting of a fluoroelastomer plug impregnated with a known mass of the perfluorocarbon and crimped within a metal shell. The perfluorocarbon tracer diffuses from the tube at a known rate. According to Dietz et al, these sources have useful lifetimes of about five to ten years. A battery operated pump is then used to draw air through an adsorption tube, placed at any location, over the required period. If an EC detector is used for subsequent analysis of the sample, Dietz et al claim that the wide dynamic range of the detector would allow an effective sample period from one to hundred of days.

6. AUTOMATED SYSTEMS

Any part or all of the injection, sampling and analysis procedures carried out in ventilation measurements can be automated. This has become easier with the recent developments in microprocessor technology. Automated systems can carry out complicated tasks which are beyond the scope of manual control and allow additional information to be obtained.

As Chapter 2 describes, two such techniques which require automated systems are those of 'constant concentration' so as to determine infiltration and, multiple tracer measurements so as to determine internal air movement as well as the infiltration rates.

In this Section, automated systems that have been built elsewhere are discussed. Most of these are concerned with systems using single tracers. They have been subdivided into those designed to measure fresh air infiltration using the 'constant concentration' or 'constant flow' technique and those systems built to measure decay rates.

The final subsection looks at various attempts to determine interzonal air movements using multiple tracer gases. The systems used in those measurements, which were not necessarily fully automated, are also discussed.

6.1. Infiltration rate

The 'Autovent' system [25] designed by British Gas uses the 'constant concentration' technique, described in Chapter 2, to determine infiltration into any cell of a multicelled building.

In the Autovent system, a microcomputer controls two sets of solenoid valves. One set controls sample lines whilst the other controls the injection of the tracer gas. Each line is sampled in turn and the amount of tracer needed to maintain concentration to a preset value is calculated. This is then converted into a time interval during which the relevant preset injection valve is opened to deliver the required amount of tracer. Mixing between the tracer and the room air is allowed for by,

- ceasing to inject tracer into the room for six seconds before it is scheduled to be sampled,
- using a purge pump on the sample line,and
- terminating the injection lines in areas where air movement is being generated, for instance near radiators or small mixing fans.

Collet [26] describes a similar system. This differs in the use of fixed jets in the injection lines rather than the stable pressure regulators used in the Autovent system. These jets uses a 'choked' nozzle to maintain a constant flow rate.

Condon et al [27] have developed a system which uses two calibrated dump volumes to deliver a known amount of tracer gas to the test space. The filling of these volumes and the consequent injection is carried out by energising and de-energising solenoids under the control of a microcomputer.

In contrast to these 'constant concentration' systems, Sherman et al [28] describe a 'continuous injection' system. In this, a microcomputer in the system controls the injection of the tracer and a mass flow controller holds the flow rate constant. The gas is injected in 30 minute cycles and the tracer flow rate for any cycle is set equal to the target concentration times the calculated ventilation rate from the previous cycle. Within a cycle, the computer selects the sampling port used during that cycle and concentration data is collected at regular intervals from the gas analyser and retained by the computer so that, at the end of a cycle, the airchange rate can be calculated and stored on computer discs.

The systems so far reviewed have used infrared detectors to measure concentration levels. Other systems have been developed with electron-capture (EC) detectors coupled to gas chromatographs.

Of these, Kumar et al [29] describe an automated system which could be used either for decay or constant concentration experiments. This system uses a Hewlott Packard 9815A programmable desk-top calculator which through a specially designed interface can handle one injection and one sample line.

Under control of the computer, the tracer gas (in this case, SF6) is discharged by trapping a volume of the tracer between two solenoid-operated gas valves and then releasing one of the valves. An interval timer in the interface unit can then be triggered to sample the gas concentration. The EC detector, modified by the replacement of the manually operated sampling valve with an electro-pneumatically operated valve, is triggered from the calculator. The signal from the analyser is digitised and the SF6 peak isolated and retained for subsequent analysis.

6.2. Decay rates

Hartmann and Muhlebach [17] describe a simpler automated system for measuring ventilation rates using the tracer decay technique. In this system, a purpose-built controller is used to inject and then to sample nitrous oxide which is then measured with an infrared analyser.

The application of the systems described above has been confined to small, residential buildings. In the USA, however, studies have been carried out on the seven-storey (37,000 m^3) Norris Cotton building in New Hampshire [30], the 11-storey (28,000 m^3) Administration building at the National Bureau of Standards, Washington [31] and the seven-storey Administration building at Princeton University [24].

In each of these large building investigations, the systems used were semi-automated and the tracer was injected manually into the ventilation systems. The ventilation fans were then used to mix the tracer gas with th internal air. To determine tracer concentrations, samples from various locations were automatically accessed in sequence at regular intervals so that the corresponding decay curves could be determined. The samples were analysed with EC detectors and the resulting data stored on magnetic tapes for subsequent off-line computation.

Grot et al [32] describe a fully automated and sophisticated system for measuring airchange rates, using the decay technique, in two large buildings; the four-storey (68,000 m^3) Collins building near Glasgow, UK and the 26-storey (450,000 m^3) Park Plaza Building in Newark, USA. The key components of the system include a microcomputer, an EC detector/GC, a ten-port sampling manifold and five injection units.

6.3. Internal air movement

Foord and Lidwell [33] carried out some of the early work on measuring interzone air movement using multiple tracer gases. Following on from this work, I'Anson et al [34] used three tracers, Freon 12, Freon 114 and BCF to determine internal air movement in a small house. The concentrations were determined using an EC detector coupled to a GC. The whole process was labour intensive and took about two to three hours to complete. The variability of weather conditions over this long time period added uncertainity to the determination of these interzone air exchange rates and the authors quoted an accuracy of 20%. Recent improvements to the method of tracer gas analysis have been reported [35] thus allowing the time for carrying out a test to be reduced.

Prior et al [36] describe a multiple tracer technique using perfluorcarbons to detect air movement in buildings. Their work, which derives from the earlier work of Dietz et al [37], involves releasing up to four of the tracer gases within the building by flash heating the perfluorocarbons. The mixture of gases is then sampled at various positions in the building as a function of time by using adsorbent tubes. These are then thermally desorbed and analysed using flame ionisation detector coupled to a gas chromatograph. Though the movement of air between spaces could (in principle) be detected, no magnitudes have yet been determined.

7. DISCUSSION

This Chapter reviewed existing experimental techniques that could be usefully considered in our programme of work.

In Section 2, various properties of tracer gases which are required for ventilation measurements were discussed. This was followed in Section 3 by a discussion on two of the methods of analysis, namely infrared (IR) and electron capture (EC), and the tracer gases which are relevant to the present context. The following points emerged from this:

- Parts per million (ppm) detection is well carried out with IR analysers whilst EC detection is required for parts per billion (ppb) measurements.
- IR measurements can be continuous whilst those from EC analysis are discrete. This is because EC detection requires gas chromatography to separate the tracer from other 'electron capturing' gases, like oxygen, which are commonly found in air.
- Even though both N2O and SF6 can be detected using IR analysers, possible health hazaards from N2O precludes its use in occupied spaces.
- SF6 is safe and can be detected both at ppm and ppb levels using IR and EC detection respectively.

- The Freon gases, which can be detected with IR analysers, can also be 'separated' using gas chromatography and dectected at ppb levels with EC detection.

- The perfluorocarbon form a group of very sensitive tracers which are detectable at concentrations of parts per trillion with EC analysers. These tracers are, unfortunately, liquid at room temperature and requires conversions to the vapour phase when used for ventilation measurements.

Some of the characteristics of these gases which may affect ventilation measurements were considered in Section 4. It was shown that there was no direct evidence to suggest that ventilation measurements would be affected by the choice of tracer gases with different molecular weights.

It was also shown that there was no direct evidence to suggest that either N20 or SF6 would suffer from absorption by their surroundings. There is some evidence, however, which says that polyethylene sampling bottles and nylon 'sampling' tubes can adsorb SF6. 'Customised' sampling bag, however, such as those made from Mylar, Teflon or Saran, do not appear to adsorb significantly either SF6 or halocarbons such as Freons.

Experimental procedures which do not require complex, automated systems were discussed in Section 5. The discussion centered on manual methods for dispersing and sampling the tracer gas. Inexpensive systems, designed to determine long-term air change rates, were also considered.

The studies discussed in Section 4 were mainly carried out in dwellings. From the point of our work on large, multicelled buildings the following points are of interest:

- Tracer could be distributed manually by using syringes or flexible, polyethylene bottles filled with the gas.

- There are many containers which are suitable for taking and holding tracer samples for subsequent 'off line' analysis. These containers range from inexpensive polyethylene bottles and 'vacutainers' to the more specialised 'sampling' bags.

- An 'active' or 'passive' approach, utilising the 'constant flow' technique, was possible for determining long-term averaged airchange rate.

  In the active method, sampling bags and pumps would be used whilst the passive method would be based on diffusion tubes.

Finally, in Section 6, the discussion was centred on automated systems. These were subdivided into those designed to measure:

- fresh air infiltration rates in multicelled buildings using the 'constant concentration' technique,
- decay rates from tracer 'decay' concentration profiles, and
- interzone air movement using multiple tracer gases.

The review showed that all these three methods could be used in small buildings. Extension to large, multicelled buildings had only been carried out with single tracer 'decay' measurements and, even then, only in those buildings which were mechanically ventilated.

In addition, the multiple tracer work had concentrated on analytical techniques involving gas chromatography. This was a consequence of not being able to decode 'cross absorption' information which would have come out from infrared analysis.

The 'discrete' nature of gas chromatography thus limited the amount of measurement points possible in any test, and thereby, the validity of the interzone air flows deciphered from the measurements.

8. CONCLUSIONS

From the foregoing review, the following points were noted, and implemented, in our programme of work:

- The best available tracer to use would be SF6 since it could be measured over a wide dynamic range.
- Appropriate Freon gases should be coupled with SF6 for multiple tracer measurements.
- N2O could be used but only for those tests involving ppm measurements and unoccupied premises.
- Containers such as polyethylene bottles, 'vacutainers' and 'sampling' bags should be tested, and if appropriate, used in 'grab' sampling.
- A 'constant concentration' automated system should be developed to determine fresh air infiltration into rooms of a multicelled building.

- Finally, effort should be expended to develop a 'multiple tracer' automated system using infrared analysers so as to determine interzone air movement.

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TABLES

Table 1 ----- reactivity of halogenated compounds to e.c.

Table 2 ------ list of tracers/ comparative costs/ manufacturers/ background levels/ mol wt/ b pt/

10^4 → 10^3	10^3 → 10^2	10^2 → 10	10 → 10^0	10^0 → 10^{-1}	10^{-1} → 10^{-2}	10^{-2} → 10^{-3}	10^{-3} → 10^{-4}
-	CCl_4	$(CF_3)_2C{=}CF_2$	-	-	-	CH_3CHF_2	-
-	SF_6 (Sulphur hexafluoride)	$(CF_3)_2CCF_2CF_2CF_2$	CF_2Cl_2 (Freon-12)	-	-	-	-
-	$SF_5(CF_2)_2Cl$	-	-	$F_2C{=}CCl_2$	-	-	-
-	CF_2Br_2	ClF_2CCFCl_2	-	-	-	-	-
-	$SF_5(CF_2)_6Cl$	$CF_3CF{=}CFCF_3$	-	-	CF_3CF_2Cl	-	$CF_3CF_2CF_3$
-	$SF_5(CF_2)_4Cl$	-	SOF_2	-	$CHFCl_2$ (Freon-21)	-	CF_4 (Freon-14)
-	$CFCl_3$ (Freon-11)	CF_3Br (Freon-13B1)	-	SOFCl	$CF_2{=}CFCl$	CHF_2Cl	-
-	CH_2Br_2	$CF_2CF_2CF_2CF_2$ (Freon-C318)	-	-	-	-	-
-	$Br_2F_2CCF_2Br_2$	-	ClF_2CCF_2Cl (Freon-114)	-	-	-	-
IF_2CCF_2I	$CF_3CF_2CF_2I$	$ClHC{=}CCl_2$	-	-	-	-	-
C_6F_6	$F_3CCHClBr$	$CHCl_3$	-	-	-	-	-

Table 1 Range of reactivity of halogenated compounds to electron-capture detection

Common name	Chemical name	Chemical formula	Molecular weight	Boiling point (°C)	Background level (parts per vol.)	Suppliers	Codes	Sp.Vol. (m^3/Kg)	Cylinder size	Cylinder cost (£)	Total weight (Kg)	weight of gas (Kg)	Volume of gas (m^3)	Cost per litre of gas (p)
Carbon dioxide		CO_2	44	-56.6	350×10^{-6}	**Distillers**		0.547	1	15.0	92.6	22.6	12.36	0.1
Nitrous oxide		N_2O	44	-88.5	$0.2-0.6\times10^{-6}$	**B.O.C. Special Gases**	003560 001560	0.543	3AL 1	19.5 44.5	16.5 92.5	6.5 22.5	3.53 12.22	0.5 0.4
Sulphur hexafluoride		SF_6	146	-50.8	0.5×10^{-12}	**B.O.C. Special Gases**	001122 003122	0.156	1 3	346.0 98.0	113.0 26.5	43.0 9.5	6.71 1.48	5.2 6.6
Freon-12		CF_2Cl_2	121	-29.8	0.13×10^{-9}	**B.O.C. General Gases**		0.195	3P	34.0	15.0	5.0	0.98	3.5
Freon-13		$CClF_3$	104.5	-81.4		**B.O.C. General Gases**	P40403	0.218	40P 3P	436.0 65.0	68.5 15.0	36.5 5.0	7.94 1.09	5.5 6.0
Freon-1361		CF_3Br	149	-57.8	$< 10^{-13}$	**B.O.C. General Gases**	P03404 P40404	0.160	40P 3P	408.0 35.0	68.0 15.0	 5.0	10.93 0.80	3.7 4.4
Freon-114		$ClF_2C.CF_2Cl$	171	3.8		**B.O.C. General Gases**	P40408 P03408	0.140	40P 3P	156.0 32.5	110.0 13.0	78.0 5.0	10.92 0.70	1.4 4.6
BCF		$CBrClF_2$				**Fluorochem Ltd.**			250g	36.0				
PP1	perfluoro n-hexane		338	57.0	$< 10^{-14}$	**Air Products Ltd.**			1Kg	48.0				
PP2	perfluoromethyl cyclohexane		350	76.0		**Air Products Ltd.**			1Kg	49.5				
PP3	perfluorodimethyl cyclohexane		400	102.0		**Air Products Ltd.**			1Kg	46.5				
PP5	perfluoro decalin		462	142.0		**Air Products Ltd.**			1Kg	62.5				
PP9	perfluoromethyl decalin		512	160.0		**Air Products Ltd.**			1Kg	57.5				

Table 2 Details of tracer gases suitable for use in ventilation measurements

CHAPTER 4

DEVELOPMENT OF AUTOMATED SYSTEMS TO MEASURE AIRFLOWS

1. INTRODUCTION

One of the main conclusions from the previous Chapter was that two automated systems should be developed. One system would be dedicated to measuring fresh air infiltration in a multicellular building using the 'constant concentration' technique. The other would use multiple tracer gases to determine interzonal air movement in complex buildings. The multiple tracers would be detected with infrared analysis.

In practice, however, four systems were developed and built. Two were built for use with multiple tracers, one was built to be used with the 'constant concentration' approach and the fourth was constructed to carry out the 'constant injection' technique for use in very specific circumstances. This Chapter describes all these systems. The field measurements in which these were used are described later in Chapter 5.

Once it was decided that a multiple tracer system using infrared analysis was necessary, many options of how best to develop such a system were considered.

The obvious choice was to use a novel multicomponent infrared gas analyser which had just come onto the market. This Miran 980 analyser had, however, to be imported from the USA and delays regarding shipment and USA trade clearance were expected to be considerable. The analyser was a 'stand alone' instrument and since it was 'new', there was no previous experience available to us on how this instrument could be incorporated into a computer-automated system. We therefore assumed (correctly as subsequent events showed) that it would take considerable time and effort to integrate and interface this unit to a multiple tracer system that we would design.

It was thus decided that, as an interim measure, a simpler Mark I system should be designed and built using readily available equipment. Though the performance of such a system would be circumscribed by the limitation of the equipment used, it was considered that it would still provide information regarding the validity of the multiple tracer approach and the problems which may arise. Experience gained and lessons learnt from this system was therefore expected to benefit the development and construction of the more powerful and sophisticated Mark II system incorporating the Miran 980 analyser.

The first system, denoted as Mk I, used dedicated and separate infrared (IR) analysers to discriminate between chosen gases. The Mk II system, however, incorporated the novel multicomponent IR analyser which was capable of determining the individual concentration from a mixture of upto ten gases.

In this Chapter, the two Sections on the multiple tracer systems are followed by a Section on the 'constant concentration' system. The final system, designed to make use of the 'constant injection' technique, is then presented in another Section.

The reason for developing this final system was that it was not going to be as sophisticated nor complex as the others and that, in certain circumstances, such a 'simple' system would prove useful. A full justification, and a discussion on situations where this system would prove useful, is given in the appropriate Section.

2. STRUCTURE OF AN AUTOMATED SYSTEM

The advent of relatively cheap microprocessor controllers has opened up new possibilities for developing and extending techniques of ventilation measurement. Automated systems based on microprocessors provide the ability to control accurately a complicated sequence involving injection of tracer and extraction of air samples from several locations. They also allow the resulting large quantity of raw data to be recorded in an ordered and structured form during the experiment. These tasks would generally be too difficult, or even impossible, to perform manually. It is also often possible, just by changing the control algorithm, to use just one system to cover a wide range of measurement tasks.

The main components common to most automated systems are:

- A microprocessor which controls an arrangement of solenoid valves so as to inject tracer gas and to direct air samples to a gas analyser.
- An analyser which gives a continuous output or makes discrete measurements through commands from the microprocessor.
- A data logging device which may be either;
  - controllable by the microprocessor, e.g. a discdrive, or
  - passive, e.g. a self-triggering cassette-based digital data recorder, or
  - recording directly from the analyser, e.g. a chart recorder.

In addition, it is desirable to have available a computer system to read, process and plot the resulting data.

3. MK. I MULTIPLE TRACER SYSTEM

3.1. Outline of system and hardware

Figure 1 shows the various elements of the system. At the heart of it is an ITT Director microprocessor controller. This monitors signals from Leybold-Heraeus infrared gas analysers and controls an arrangement of solenoid valves and a Microdata data logger. For this particular application, analysers capable of detecting SF6, N2O and CO2 were used. A photograph of the complete system is shown in Figure 2.

The solenoid valves are used both to automatically inject tracer gas (if so desired) for a measured time into test spaces and/or to direct air samples from the test spaces to the analysers. The valves can also be used to periodically direct calibration gases to the analysers.

During the experiment, the analogue signals from the analysers are digitised and recorded on tape cassettes. These tapes are eventually transcribed and stored in a mainframe computer for subsequent analyses.

3.2. Tracer sampling

The system is capable of taking samples from upto six points using 6.4 mm (outside diameter) nylon tubing. Six solenoid valves, one to each line, are connected to the sample lines at the exit points. Under command from the ITT, each line is switched in turn to the Leybold Heraeus infrared analysers. To minimise the delay in obtaining a fresh sample at the analyser each time, a pump 'pre-purges' continuously all sample lines except the one currently being used.

The internal pumps of the analysers draws on the currently open sample line. To flush the previous sample from the cells of the analysers and replace it with the new sample, approximately 12 seconds is allowed during operation of any sampling cycle.

3.3. Automated operating sequence

The sample time on each line and the number of cycles through the six lines are set at the start of the measurement period by altering the program 'code' within the ITT.

At an appropriate point in the sample sequence, and on command from the ITT, the analogue signals from each analyser is separately digitised by the Microdata logger. The digitised values are then written onto cassette tapes.

3.4. Data transcription

The data cassettes are read on a Microdata reader device connected to an LSI microcomputer. The computer communications network, NAARC, at BRE can then be used to send the data to any selected mainframe computer from which subsequent processing and analysis can be carried out.

3.5. System advantages

The system offers the following advantages:

- It is robust, modular and uses easily available components.
- Hardware faults can be identified easily.
- Once programed, the system can be used in a 'turn key' mode.
- Provided the analogue signal level is within the range of the A to D converter, the system is not specific to any particular analyser.

3.6. System disadvantages

The system suffers from the following disadvantages:

- Each tracer requires a separate analyser.
- The A to D conversion resolution is limited to + 5 mV.
- The ITT Director is programmed in an unsophisticated and inflexible numeric 'code' rather than in a high-level language like BASIC.

4. MK. II MULTIPLE TRACER SYSTEM

4.1. Introduction

The Mk II system (Fig 3) was built around three main units:

- A gas line sampler (GLS) unit to draw samples from selected zones and present them to an analyser.
- A Miran 980 multicomponent infrared analyser to form the heart of the system.
- A microcomputer to be in overall control of both the GLS and the Miran 980.

The system was expected to carry out the following sequence of operations:

- Draw a fresh gas/air sample from a given zone to the analyser.
- Activate the Miran 980 analysis cycle.
- Store resulting concentrations of the component tracer gases in computer 'store' files for subsequent analyses.

This process must then be repeated for the duration of the monitoring period and, during this period, each zone should be sequentially scanned.

4.2. Miran 980 multicomponent infrared analyser

With the exception of inert gases and symmetrical diatomics (e.g. N_2, O_2, Cl_2), all gases absorb infrared (IR) radiation at specific characteristic wavelengths. A wavelength which gives the strongest absorption is usually chosen as the 'analytical' wavelength for that substance.

Although IR absorption spectra are quite characteristic, two components of an air sample will often have some contribution to the observed absorbance at one or both of their analytical wavelengths. This 'cross absorption' interference might be avoided by choosing different analytical wavelengths. Failing this, it may be necessary to treat the interfering absorber as a component and compensate for its presence.

This is the approach which is used by the Miran 980. This analyser is a single beam infrared spectrometer with a 20 m path length gas cell of 5.64 litre volume. The whole instrument is controlled by an INTEL 8085 microprocessor. The Miran 980 determines the concentration of each constituent of a multicomponent gas mixture in the following manner:

- The analytical wavelengths of all components are first determined by observing their infrared signatures.
- The cross absorptions at these analytical wavelength are measured for each individual component. These values are then stored within the microprocessor.
- When the concentration of each constituent is required from a mixture of these gases, the absorption at each analytical wavelength is first determined. Then, using the 'calibrated' data stored within it, the INTEL 8085 decodes the absorption information to give concentration values of the components.

The analyser is capable of determining concentrations in a mixture of upto ten substances. The manufacturer, Foxboro Analytical, claim that the instrument typically takes 15 seconds to analyse and print concentrations for a one-component analysis, 40 seconds for five components and 70 seconds for ten components.

4.3. Sampling and Gas Line Sampler

Air samples are brought into the Miran using 10 mm inner diameter polyethylene tubing. This large diameter was necessary in order to ensure an adequate volume flow rate to the cell of the Miran analyser.

The tubing terminates in the Gas Line Sampler (GLS). This consists of two trays of instrumentation with one containing 16 three-way M.A.C. solenoids. Figure 4 shows a schematic diagram of the pneumatic connections between these valves. Two versions of this tray has been built. One contains 6.4 mm inlet valves, whilst the other uses 12.7 mm valves for the occasions when greater throughflow is required.

The second tray contains relay control units required to operate the valves. The relays are in turn controlled by a CBM 4032 microcomputer. Both this tray and the 'valve' tray when mechanically connected make electrical contact though a plug and socket assembly.

4.4. 'Interfacing' the system

The computer, its peripherals (e.g. disc drives) and the GLS all communicate through an IEEE 488 standard interface bus. The Miran, however, uses an RS232C interface. Since these interface standards are incompatible, both physically and conceptually, an IEEE/RS232C converter was used to link up the Miran to the rest of the system. The electronics was configured so that for most of the time the RS232C was acting as a 'listener' whilst awaiting instructions from the computer. On command from the computer, the RS232C configured Miran becomes a 'talker' and after analysing a sample sends a report of the data back to the computer. The data are then archived on computer disc.

4.5. Operating the system

In general, the system uses BASIC as its high level operating program with additional assembly routines to operate the standard peripherals. The CBM contains a somewhat non-standard character code set. This presents a difficulty when operating with the Miran which uses a different standard character set. For example. the Miran recognises 'ESCAPE' as a task terminator but this key is not included on the CBM. To overcome this problem, the character key '!' was used to terminate the task and the 'bit' pattern for 'ESCAPE' transmitted to the Miran when the character key was pressed. These, and other anomalies, were resolved within the software.

The software program not only controls the devices in the system but also provides essential timing delays and Figure 5 shows the sequence of operation. When the program is running, the operator is initially prompted by the program to insert some essential information , e.g. time delays, zones requiring sampling.

During operation, the analysis of a gas/air sample from a particular zone is initiated by operating the zone valve, V(n). Using a vacuum pump, the analysis line is evacuated for a period of t1 seconds before the sample is exposed to the analyser. The sample is then flushed through the cell of the analyser for a further period t2. Valve V(15) is then closed and a brief delay of t3 is imposed during which the pressures on the line are allowed to equilibriate. Valve V(13) is then closed so as to hold the sample within the cell of the analyser.

A command to commence analysis is then issued by the computer. At the end of the analysis period, which lasts for about 30 seconds for a three-component mixture, the concentration readings are output through the RS232C to the computer and archived on disc files.

Valve V(n) is then opened and the sample lines thoroughly purged before selection of the next valve, V(n+1). The procedure detailed above is then repeated for this (n+1) sample zone. After all zones are sampled, the whole cycle is continuously repeated for the desired number of cycles.

4.6. Necessary precautions

The system, has obviously, to be used with some care since all units within it interact considerably with each other. There are, however, two necessary precautions that must be taken:

- The two trays of the GLS should never be physically disconnected from one another when the GLS is switched on. Any such disconnection will result in the complete electronic breakdown of the GLS.

- There is a design fault within the analyser which allows part of the IR beam to be exposed to the air within the analyser enclosure. This is a source of potential error when analysing sample components since they may be present in the air local to the analyser as the enclosure housing is not airtight. Extensive tests showed that the influence of this leakiness on measured values was significant. To negate this, it was shown that, in such instances, the housing requires to be purged with compressed air throughout the measuring period.

4.7. Advantages of the system

The main advantages of this system are;

- Up to ten tracers, in any combination, can in principle be used. In comparison with the simpler Mk I system, only one analyser is required and errors due to cross absorption can be eliminated much more easily.

- The mode of operation is very flexible since control is carried out by software written in the high-level language BASIC.

- Once programed and calibrated, the system can be used in a 'turn key' mode.

4.8. Disadvantages of the system

The main disadvantages are;

- The analyser has to be calibrated for each combination of tracers and for the required measuring ranges.

- Each time the analyser is moved to a different location, a new calibration is required. This is because the 'optics' within the analyser are sensitive to movement.

- Hardware circuit faults are less easy to detect.
- Since it cannot be fully sealed, the analyser housing needs to be continuously purged if the analyser is located within an area containing the tracers.
- The vacuum pump is noisy and cannot be used in an occupied room (other than by the operators of the system).

5. 'CONSTANT CONCENTRATION' SYSTEM

5.1. Overview of the system

Figure 6 shows a block diagram of the system instrumentation. A microcomputer controls a tracer sampling and injection device through an interface unit. Analysers connected to the sampling device transmit analogue signals, corresponding to the trace concentration, through to the interface unit where the signals are digitised. The resulting data is then sent to the computer where the are archived in disc store. Figure 7 shows the system as set up. The following subsections give a brief description of the system and the way in which it functions.

5.2. Computer and peripherals

A CBM 4032 microcomputer is used as the controlling computer because it is easy to use, relatively inexpensive and uses BASIC as its high-level language. CBM Model 4040 'twin disc' drive units are used for program and data storage. A CBM 4022 printer is used to obtain printed output.

5.3. Interface unit

An interface unit was 'custom' built, to BRE specifications, by 3D Digital Design Inlab. This unit is linked to the microcomputer through an IEEE bus. The unit consists of the following rack mounted cards:

- IEEE interfacing card

  The function of this was to configure the IEEE bus of the computer to the internal bus structure of the 3D unit.

- An analogue to digital (A to D) converter

  This card integrates a 0 to 1 V analogue signal over many milliseconds to improve the signal to noise ratio. A 12-bit digitisation is then carried out at a rate of about 5 samples per second.

- Multiplexer card

  The multiplexer allows upto four signals to be digitised by the one A to D converter.

- Thermocouple conditioning card

  This is a Signatrol TC 5021 therocouple input conditioning card consisting of a 16-channel multiplexed thermocouple amplifier. Though hardwired linearisation has been added as an optional extra this is not used because of poor accuracy. The thermocouple output are therefore linearised (over the -10 to 40 degC range) in software.

- Relay cards

  There are two relay cards with each card containing eight separately latched single-pole single-throw reed relays. The relays are rated at 100 V, 0.5 A, 10W. The relay contacts are brought out through two 26-way ribbon cables to the inject and sample box. These cables also carry signals for the LEDs indicating relay state (i.e. 'on' or 'off') above each outlet connector on the sample and inject box.

5.4. Sample and inject unit

This unit was built 'in-house' at BRE and contains three detachable modules; namely, a 'sampling' module, a 'control' module and an 'inject' module.

The 'sample' module houses a samplivalve (i.e. a rotary valve) which, when energised, can sequentially connect upto twelve sample lines to a gas analyser. It is controlled through two relays housed in the 'control' unit. These relays are switched on or off by the computer. The samplivalve can also be 'stepped' and 'homed' manually using switches on the front panel of the control unit.

The 'inject' module contains 14 three-way micro-solenoid switches supplied by Lee Products Ltd. These solenoids are small, have a low power consumption (270 mW) and a rapid (3 ms) response time. A short response time is especially important so that a steady flow rate is quickly achieved when short injection times are encountered. The disadvantages arising from their small size are that,

- only a limited flow rate (7 l/s at 100 kPa) is obtained, and
- it is difficult to connect their very small outlets to the 6.35 mm OD tubing used in most of our work.

The relays are operated through the control module. When a relay is closed, the appropriate solenoid is disconnected from the purge pump and the solenoid directs tracer gas to the outlet. When 'off' (relay contacts open), the outlets of the solenoids are connected to a 'purge' pump so as to push any tracer left in the tube to the test space and prevent any tracer remaining within the tubing.

5.5. Operating procedure

The basic procedure when carrying out a 'constant concentration' experiment is as follows:

- Set a target level at which tracer gas concentrations should be maintained within the test spaces.
- Sample one space at a time and determine the concentration within that space.
- If concentration is below 'target', calculate the time period during which the appropriate injection valve should be kept open and open valve.
- Check whether any other injection valves are open. If so, determine how long they have been kept opened. If they have exceeded the calculated injection period, close valve and record time period during which the injection had taken place.
- Step the scanivalve to next space, determine concentration level and carry out procedure as detailed above.
- Continue to carry out this sequence cycle as long as is desired.

The injection time for any zone can be summed over a suitable period (say, one hour) and the fresh air infiltration into that space during that period can then be determined.

5.6. Necessary precautions

The injection flow rates need to be accurately known and maintained during the measuring period. It is therefore essential that,

- suitable gas regulators should be used between the gas supply (usually kept in high pressure cylinders) and the manifold leading to the solenoids and,
- the flow rates through the tubes are measured (perhaps with a 'soap bubble' meter) as often as possible.

It is also necessary to keep the gas supplies as far away from the test area as possible to prevent any leaks contaminating the measurement procedure.

6. 'CONSTANT INJECTION' SYSTEM

The 'constant injection' technique can be used in buildings which have good internal mixing. This is because the method depends on 'continuously injected' tracer mixing rapidly with the internal air to reach an equilibrium steady-state concentration.

In mechanically ventilated buildings, where an air handling unit is available to disperse the tracer throughout the building, this technique provides a simple method by which to measure the overall ventilation rate.

In buildings such as these, it is sometimes useful to obtain an 'averaged' infiltration rate over some appreciable period of time, say over one day. To make such measurements, a simple 'automated' system was built.

This system contains two identical units (Fig 8). Each unit consists of a Watson-Marlowe peristaltic pump connected to a Tedlar 'sampling' bag through some tubing.

Peristaltic pumps were used because the flow rate through them could be set and accurately controlled. Before a test, the bag in the 'supply' unit is filled with the tracer at a known concentration although, in practice, it is usually undiluted neat tracer.

During a test, the peristaltic pump releases, at a known rate, the tracer into the test space. After a suitable time interval, during which the tracer concentration in the space has nominally become constant, the second 'extract' unit is started. The pump in this unit is set to extract the gas/air mixture from the test space at a known rate and fill up an initially empty bag. Subsequently analysing the tracer concentration in the 'extract' bag and by knowing the supply flow rate, the infiltration flow rate (averaged over the period over which the bag was filled) for that space is determined.

When using this system, accurate calibration of the injection flow rate is essential. The concentration of the tracer, both in the supply and extract bags, also requires to be determined to high accuracy.

To minimise potential sample loss or contamination by the peristaltic tubing, care must be taken to site the injection and sample pumps in the environment in which they are to be used. The system is inexpensive, robust, simple to use and reliable.

7. CONCLUSIONS

In this Chapter, four automated systems (built as part of the this present programme of work) were discussed. Of these, two were developed for multiple tracer measurements, one was built to be used for 'constant concentration' work whilst the fourth was set up for the 'constant injection' method.

The Mk I multiple tracer system was built as an interim measure whilst the more powerful and sophisticated Mk II system was being developed and built. An additional factor was the inordinate delay in obtaining, from the USA, the analyser required for the Mk II system.

The simpler system used existing equipment and analysers. This system was limited to the extent that,

- a number of existing single-tracer analysers had to be used,
- the choice and number of tracer gases that could be used were restricted,
- the number of spaces that could be sampled was constrained to a maximum of six, and
- the controlling microprocessor was relatively unsophisticated and inflexible.

On the credit side, however, this system was robust and could be used in a 'turn key' mode. It was also constructed reasonably quickly so that it could be used in the preliminary 'multiple tracer' field measurements that were made (Chapter 5).

Developing the Mk II system was a technical breakthrough. Interfacing the Miran 980 to a microcomputer was a considerable task since it had not been ever done before. To put together the power of the Miran with the flexibility of control of the microcomputer gave a system with the potential to carry out many multiple tracer experiments in the most optimum manner. This includes the use of up to ten tracer gases, and an unlimited choice of tracer gas combinations.

The 'constant concentration' system was designed and built to be compact and modular. Preliminary testing has shown that it works according to specification. Similar comments apply to the 'constant injection' system.

The complexity of the four systems for various characteristics can be classified as follows:

Complexity	Development	Construction	Ease-of-use
Least complex	Constant-injection	Constant-injection	Constant-injection
↓	Mk I multiple-tracer	Mk I	Mk I
↓	Constant-concentration	Mk II	Constant-concentration
Most complex	Mk II multiple tracer	Constant-concentration	Mk II

The hardware costs for each system can be itemised as follows:

System	Solenoid-valve unit (£)	Analyser(s) (£)	Computer and peripherals (£)	Total (£)
Mk I	600	16,000	5,000	21,600
Mk II	1,800	15,400	2,200	19,400
Constant-concentration	2,800	8,200	2,200	13,200
Constant-injection	1,300	N/A	N/A	1,300

The analyser cost of £16,000 for the Mk I system reflects the cost of two double-component analysers used. It should also be noted that the Mk I system was built from equipment already available within BRE.

It should be once again emphasised that the Mk II is more powerful and has a greater potential for multiple tracer ventilation measurements than the Mk I system.

FIGURES

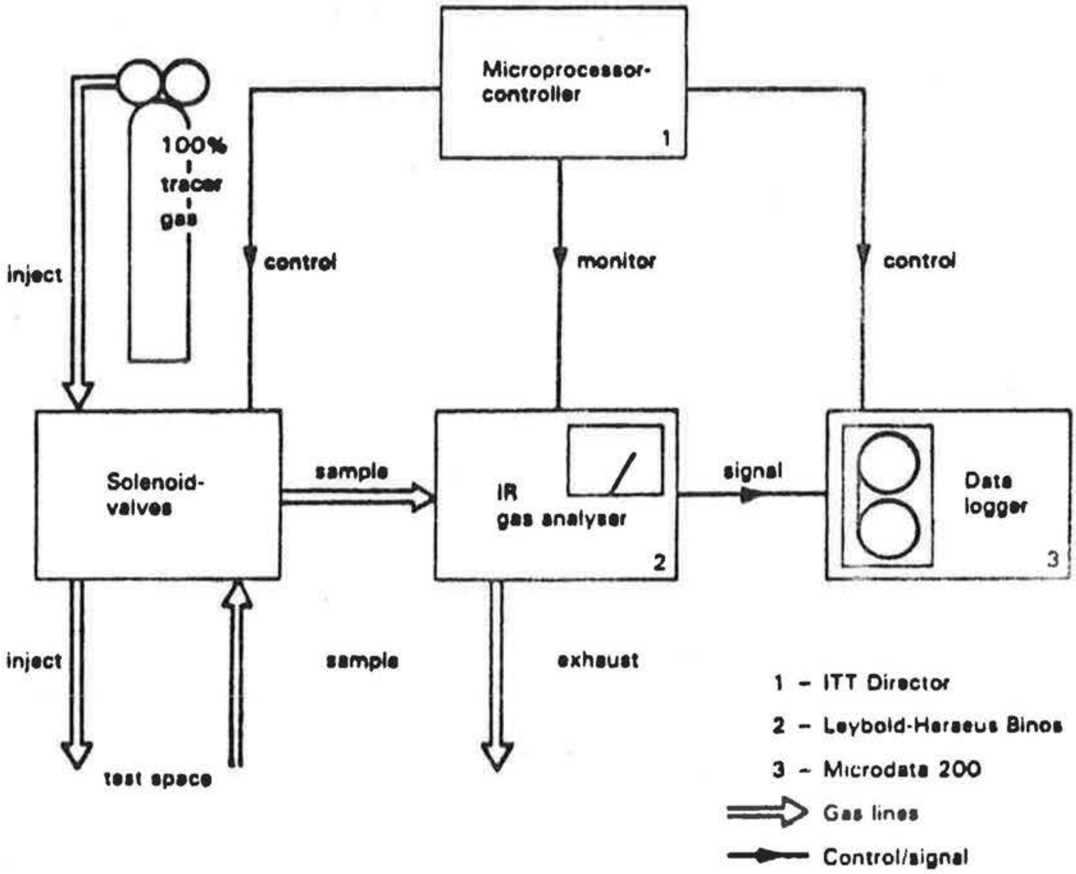


Figure 1 Block diagram of the Mk I automated system

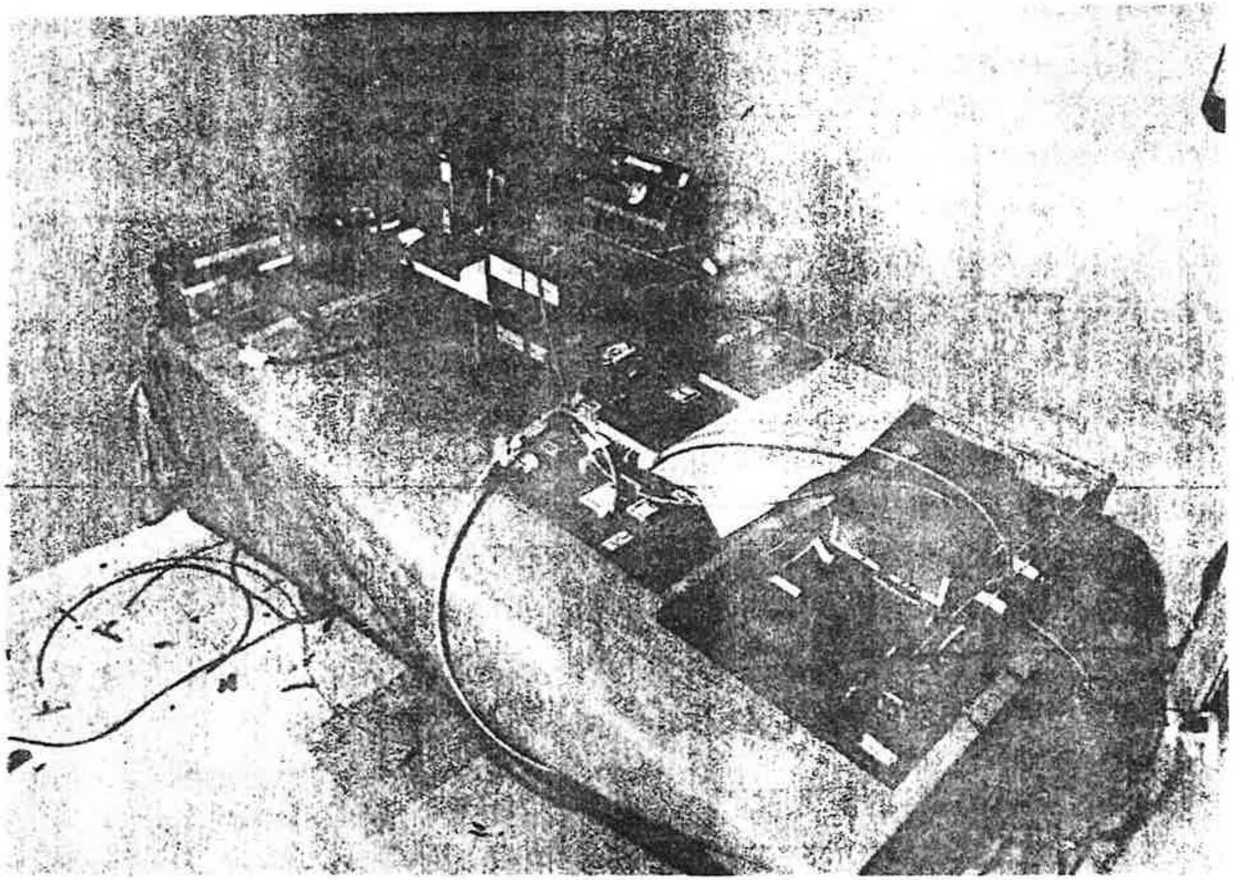
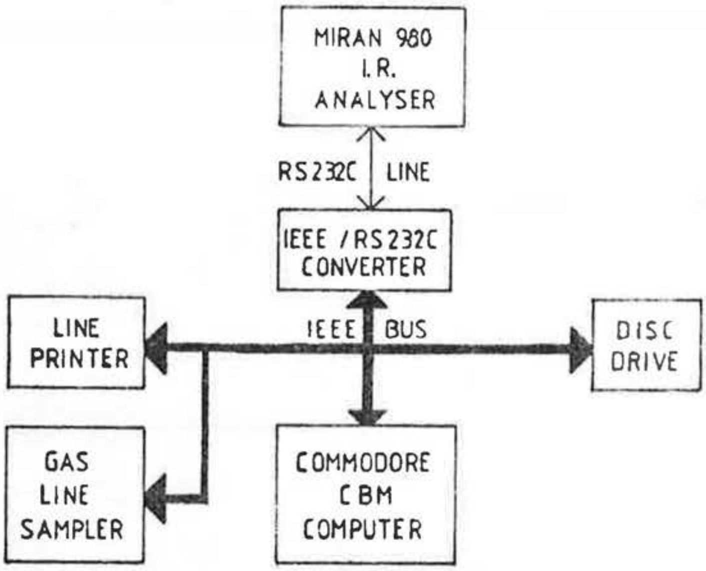


Figure 2 Mk I automated system



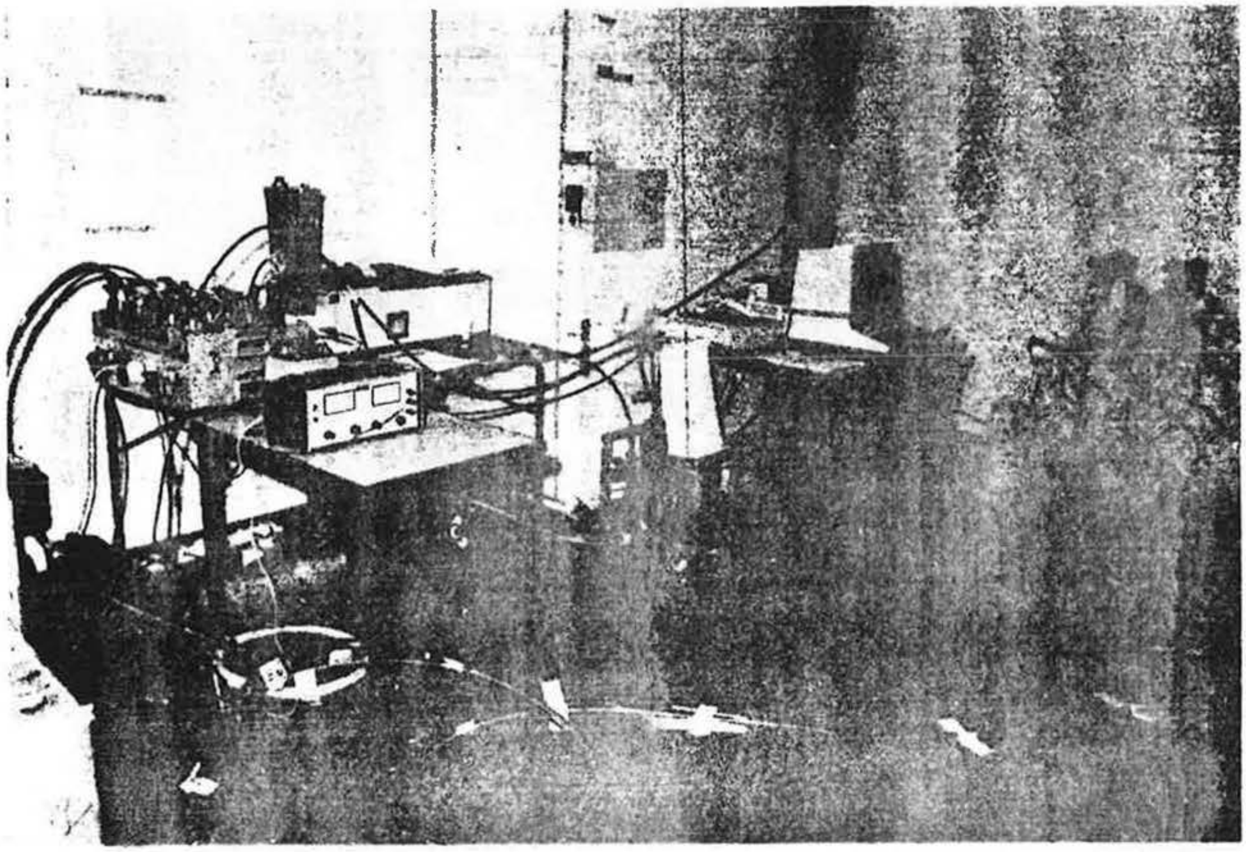


Figure 3 Block diagram of the Mk II system and a photograph of the system in use

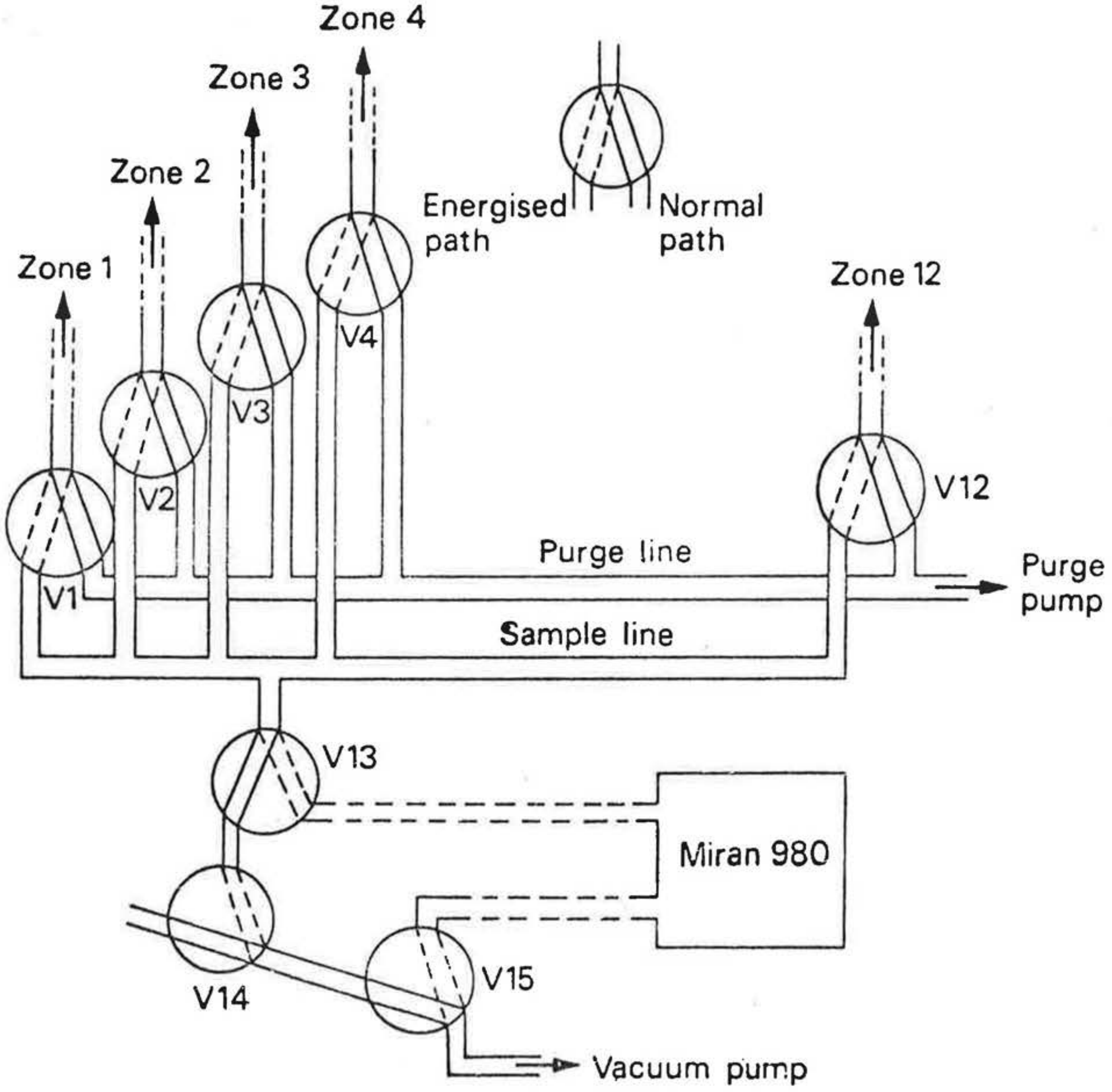


Figure 4 Pneumatic connections of the solenoid valve unit

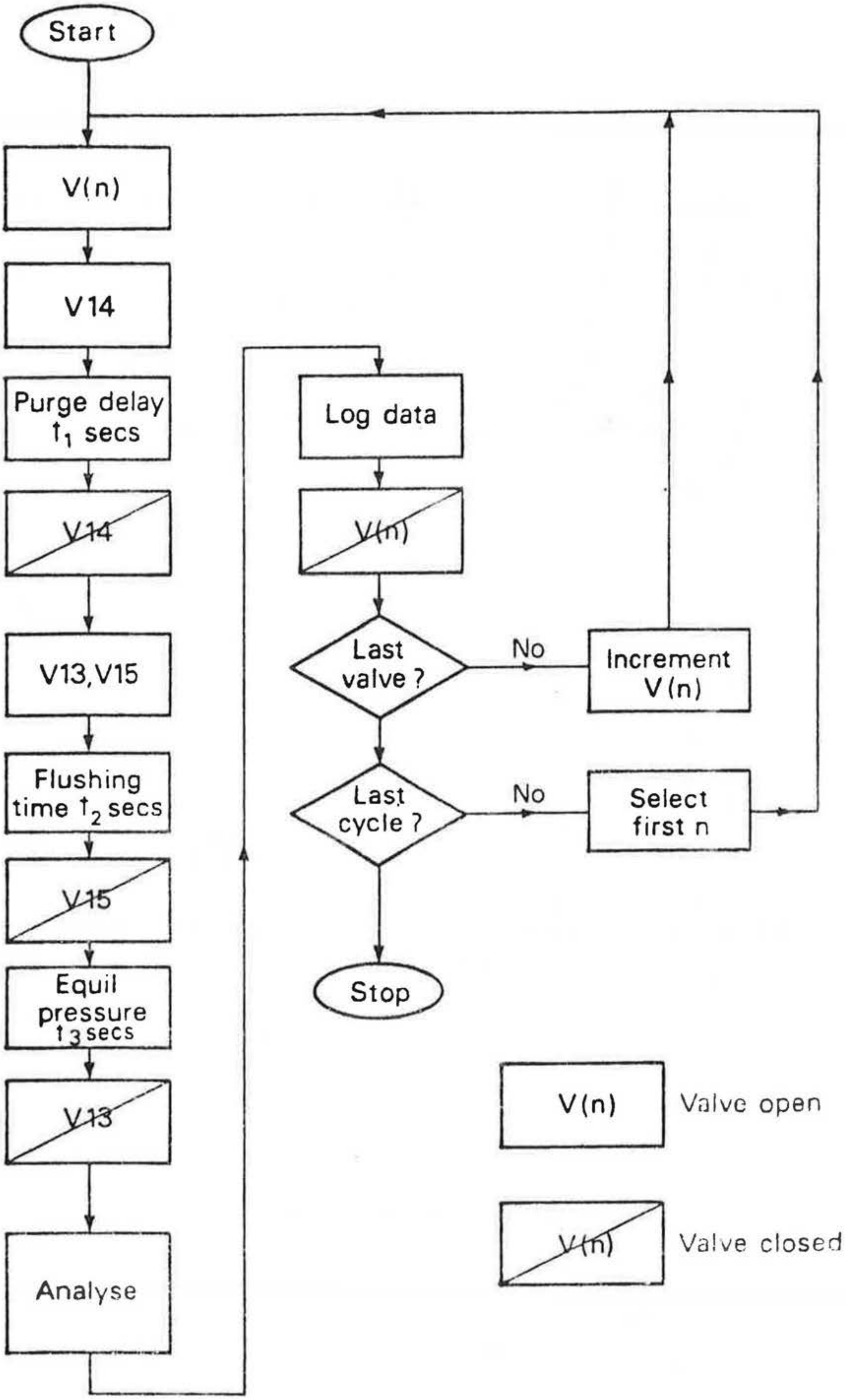


Figure 5. Operating sequence of the Mk II system

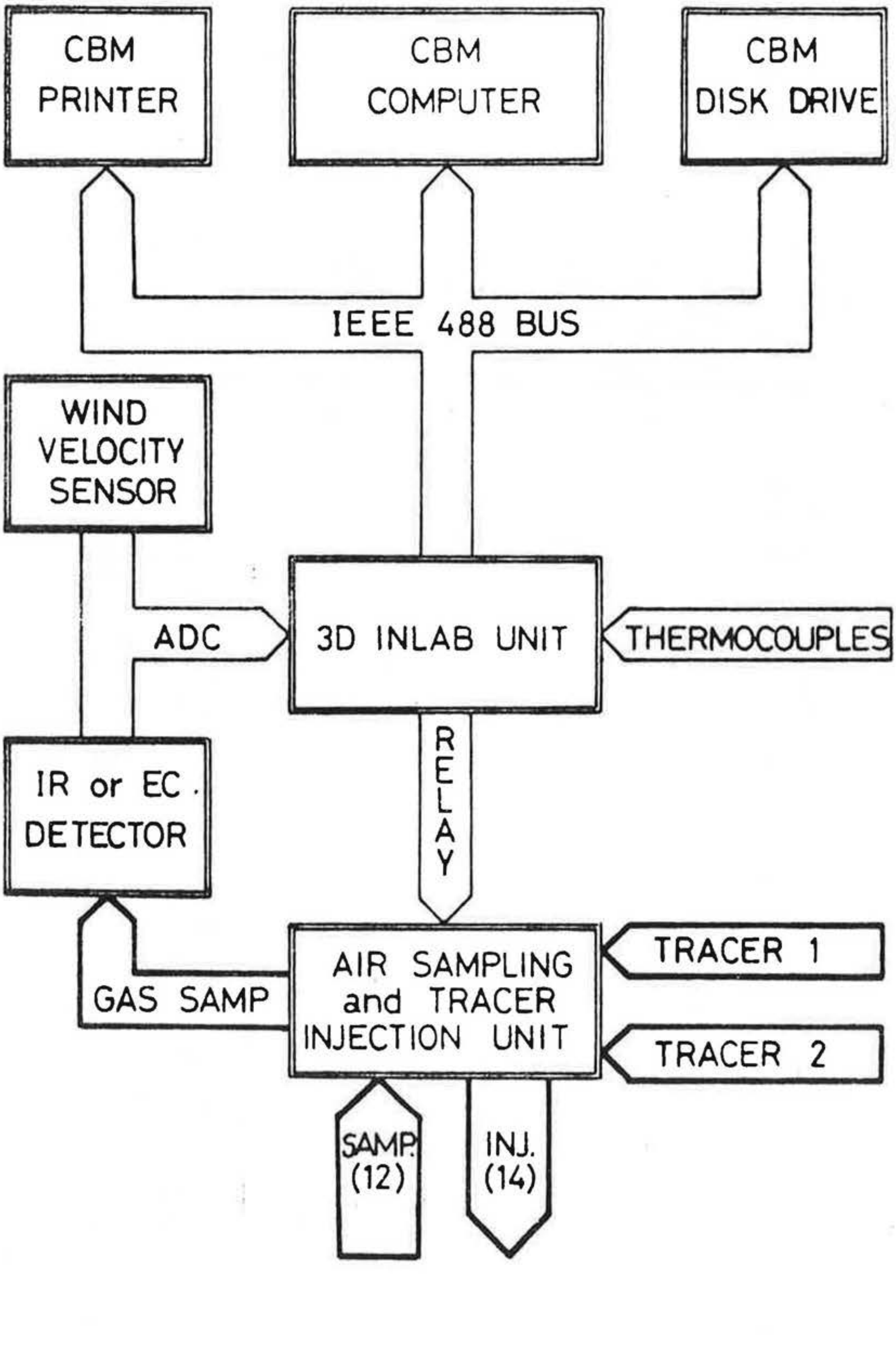


Figure 6 Block diagram of the 'constant concentration' system

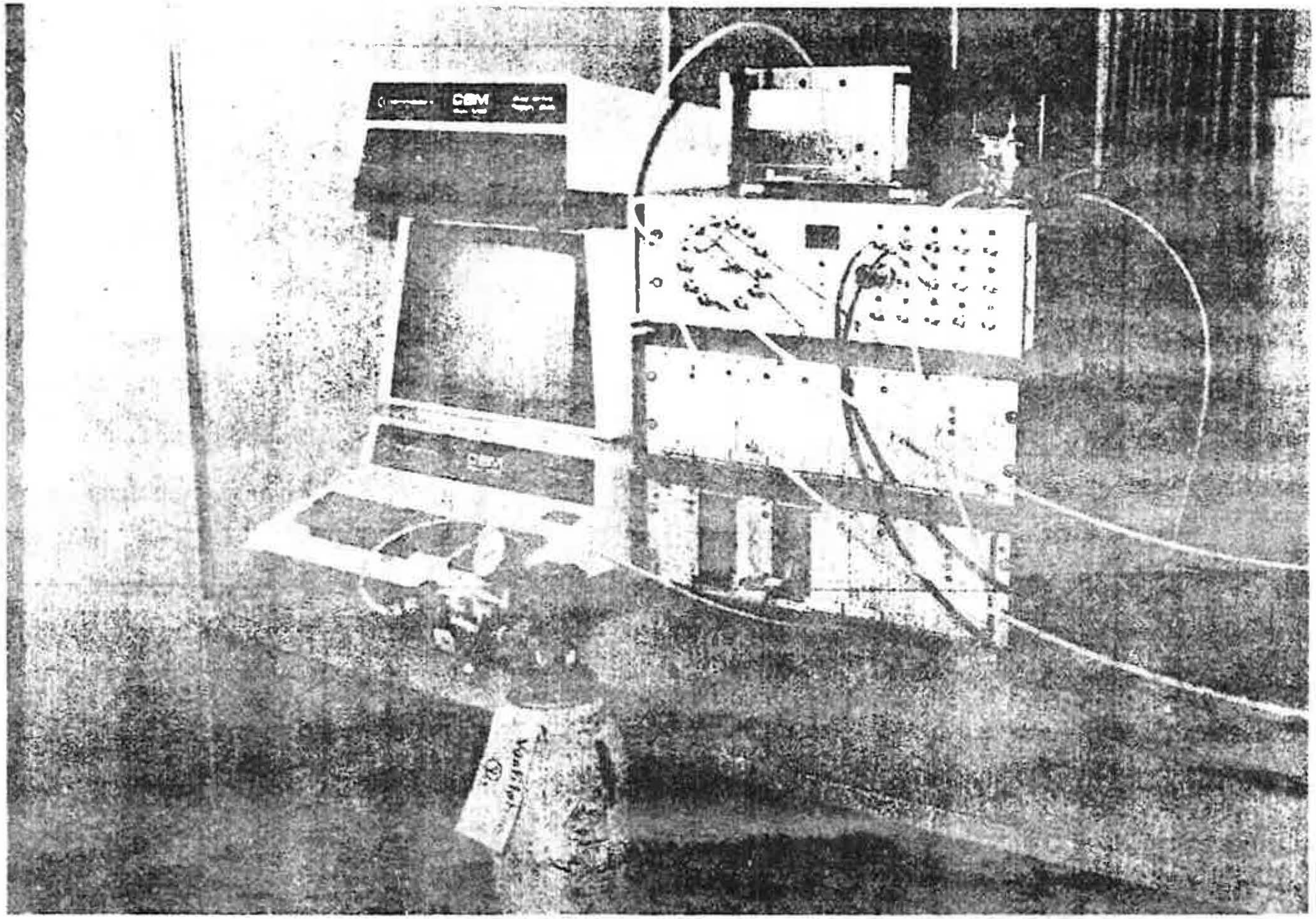


Figure 7   The 'constant concentration' system

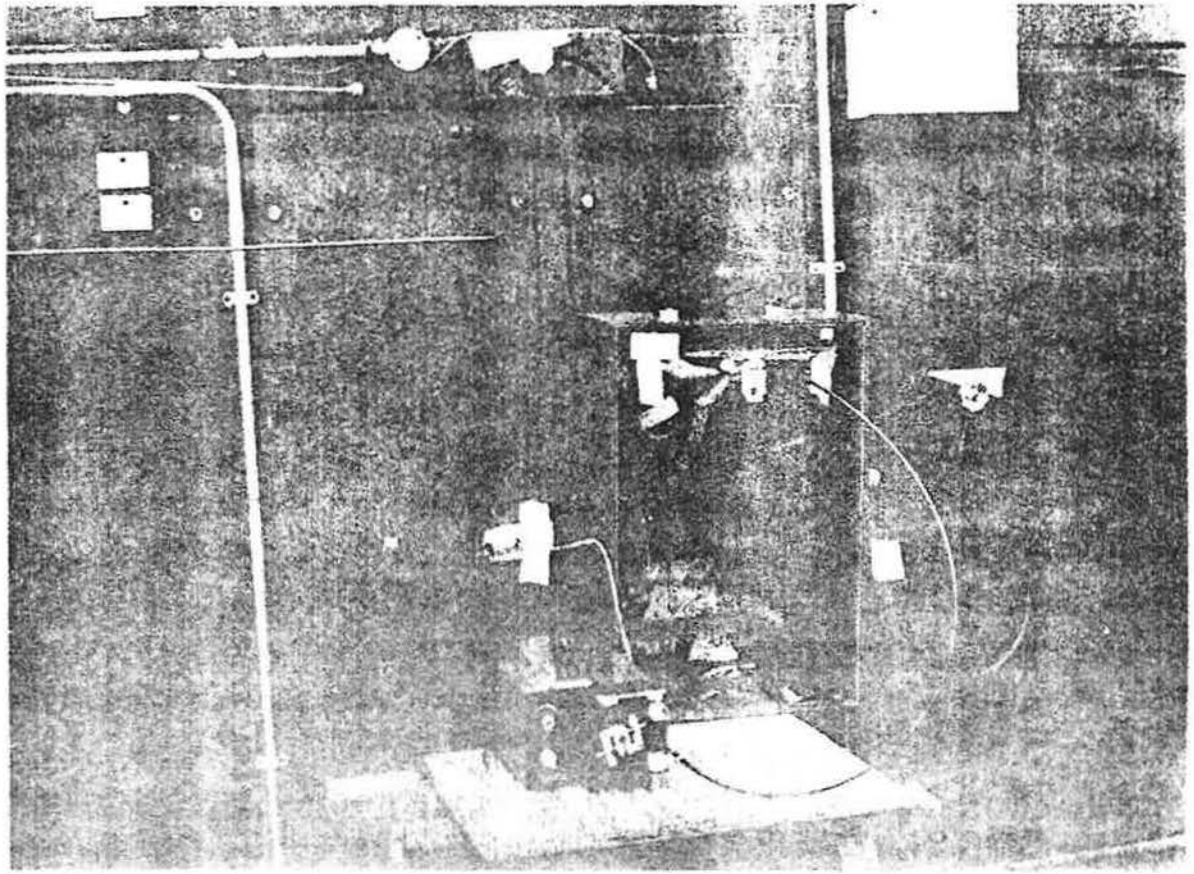


Figure 8 The 'constant injection' system in use

CHAPTER 5

FIELD MEASUREMENTS USING AUTOMATED SYSTEMS

1. INTRODUCTION

This Chapter describes field measurements carried out using the automated systems outlined in the previous Chapter. Three buildings, designated B10, B18 and B9 on-site at BRE were used. A full description of each building is given in Appendix I. The numerical coding for these buildings reflects the designation used at BRE.

Building B10 is a naturally ventilated, two storey office block. Section 2 describes measurements of interzone airflows within this building using the Mk I multiple tracer system. Nitrous oxide (N20), sulphur hexafluoride (SF6) and carbon dioxide (CO2) were used as the tracers.

The Mk II system, incorporating the Miran 980 multicomponent analyser, was used to carry out a series of interzone airflow measurements in building B18. This is a three storey office and incorporates an air handling unit which allows a variable amount of fresh air to be drawn into the building. Measurements, described in Section 3, were carried out using sulphur hexafluoride, Freon 13B1 and Freon 114 as the tracer gases.

Section 4 describes the use of the 'constant concentration' system to measure the changes in infiltration rate over a period of time in a single room in building B9 using sulphur hexafluoride as the tracer gas. The 'constant injection' system was used (Section 5) in building B18 to obtain an overall ventilation rate for the building.

2. INTERZONE AIRFLOWS IN BUILDING B10 USING THE MK I SYSTEM

2.1. Introduction

The objective of the measurements described here were to determine the interzone airflows in building B10, and to assess the effectiveness of the theoretical approach to decoding multiple tracer measurements.

2.2. Zoning the building

For the purposes of this experiment, the building was notionally divided into the following zones:

Zone	Volume (m^3)	Description
G	783	major portion of the ground floor
F	783	major portion of the first floor
S	587	stairwell and southern end of each of the two floors

2.3. Test conditions

During the test, the building was unoccupied and all internal doors were kept open. The wind (monitored at a height of 10 m at a nearby open site) and temperature parameters were,

Internal temperature = 16° C
External temperature = -1° C
Wind speed = 2 m/s
Wind direction = 225°N

2.4. Tracer gases and injection levels

Three Leybold Heraeus infrared gas analysers, dedicated respectively to measuring sulphur hexafluoride (SF6), nitrous oxide (N2O) and carbon dioxide (CO2) were used.

The three tracer gases were injected manually, one to each zone, in sufficient quantity to give (as near as possible) the following target concentrations:

Zone	Tracer	Concentration (ppm)
G	N2O	200
F	SF6	200
S	CO2	2000

During injection, desk-top fans were used to provide mixing.

2.5. Tracer sampling and analysis

Single-point and blended multi-point samples were taken from each zone using equal-length 6 mm ID polyethylene tubes. A sample line was also placed outside the test building in order to provide reference ambient concentrations of the test gases. All tubes were then brought back to individual solenoid valves on the Mk I system.

Air samples were taken sequentially from each zone. The concentration of each tracer in these samples was then determined by the infrared analysers, and the values obtained were then logged onto cassette for subsequent retrieval and analysis.

2.6. Data processing and results

Figure 1 shows N2O concentration as a function of time for each of the three zones. Similar results were obtained for the other two gases giving in all a total of nine concentration profiles. In the case of CO2, the outside background concentration has been subtracted from the raw data.

The mathematical technique described in Section 4 of Chapter 2 was used to derive the interzonal airflows from the tracer gas concentrations. For each of the nine concentration profiles, a smoothed curve was drawn over a small portion of the experimental points. These smoothed curves were centred at time t = 7.5 minutes and were drawn to cover a time range of about five minutes. Tangents were drawn at t = 7.5 minutes and the gradients determined. Using the values of the gradients and the concentrations at these points, the interzone airflows were determined. These are shown in Figure 2.a.

It will be noticed that some of the airflows are negative. Original definitions of these airflows, as derived in Chapter 2, preclude any physical meaning for negative airflows. The results therefore indicate that experimental errors, possibly arising from imperfect initial mixing, have contributed to these negative values.

To avoid these negative quantities, a method of analysis advocated by Penman and Rashid [1] has been used. Since the airflows are calculated from a set of simultaneous linear equations, the solution can be constrained in the least-squares sense to have positive values. Using a computer program given by Lawson and Hanson [2], the constrained solutions were evaluated and are shown in Figure 2.b.

2.7. Discussion

As a check on the validity of these results, a computer program utilising the Runge-Kutta-Merson routine from the NAG library [7] was written. Knowing the interzone airflow quantities and initial concentrations, the time-histories of tracer concentrations in a multizone environment can be predicted.

The calculated airflows were used to obtain predicted concentration profiles. As an example, Figure 1 shows the predicted curves superimposed over the experimental data points obtained for the N20 tracer. The matching between the data points and predictions is seen to be good.

To ensure that no drastic change had occurred in constraining the airflows to be positive, predicted curves with and without constraints were evaluated and are shown in Figure 3. This shows there is only a marginal difference between the two concentration profiles.

With regard to the performance of the building for this test, the following results were obtained:

1. The total fresh air infiltration rate was 0.76 ach.
2. The infiltration rate to the first floor zone was only 0.46 ach compared to 0.99 and 0.84 ach for the ground floor and stairwell zones respectively.
3. Air movement from the stairwell to the first floor dominated interzonal air movement.
4. There was negligible direct interchange of air between the ground and first floor zones.
5. Only 15% of the fresh air entering the ground floor zone entered the other two zones.

3. INTERZONE AIRFLOWS IN BUILDING B18 USING THE MK II SYSTEM

3.1. Introduction

As before, the main objective of the field measurement described here was to determine the interzone airflows in building B18. A set of three tests were designed for three different settings of the air handling unit. The Mk II system was available to carry these measurements and preliminary laboratory tests showed that, with this system, sulphur hexafluoride, Freon 13B1 and Freon 114 could be used as the tracers in three-zone experiments.

3.2. Office building

The 'low energy' office building B18 (Appendix I) incorporates a number of energy saving features. Amongst these is a mechanical ventilation system which allows a variable amount of fresh air to be taken into the building. This value can be varied from nominally zero (complete recirculation) to full (no recirculation) fresh air intake depending upon the setting of the mechanical dampers at its air handling unit (AHU). During the heating season, it is set to about 30% fresh air.

3.3. Injection and sampling points

The design of the air distribution ducting allowed each floor to be individually seeded with a tracer gas. Polyethylene tubing (6 mm ID) was laid between a central 'control' room and various strategic points in the supply side of the ducting.

Samples were taken from suitable points in the extract ducting using 10 mm ID polyethylene tubing. These larger tubes were necessary to ensure an adequate volume flow rate to the cell of the Miran analyser. In each zone, several sampling tubes from that zone were brought together to a common junction and manifolded together. A single tube from each junction then carried the blended samples into the automated system for analysis.

3.4. Test conditions

Three tests are reported here. These were made with all windows and doors, both internal and external, closed. The building was unoccupied during the tests and the heating system was not in operation. The test conditions were as follows:

Test	Mech. vent.	Temperatures (^{o}C)		Wind	
	setting	Internal	External	Speed (m/s)	Direction (degN)
1	Full recirculation	23.	19.	0.8	47
2	No recirculation	23.	18.	1.1	85
3	30% fresh air	23.	17.	0.3	43

3.5. Tracer gases and injection levels

Each of the three floors of the building was seeded with a different tracer gas using the installed tubing. The gases used and the target concentrations were;

Zone	Tracer	Concentration (ppm)
Ground floor (G)	SF6	17
First floor (F)	Freon-114	124
Second floor (S)	Freon-13B1	53

This combination of gases was chosen because of their low values of cross absorption during infrared (IR) analysis. The target concentrations were set by the linearity and the strengths of the signals from the Miran 980 analyser for these concentration ranges. The accuracy of the concentration measurement of any one gas in the mixture was better than 1% of the upper value of its linearised range.

3.6. Data processing and results

Figure 4 shows the concentrations of the tracers as a function of time in the three zones for the experiment carried out with full recirculation (Test 1). Similar results were derived for the other two tests.

The interzone and infiltration airflows were derived as described earlier. Figure 5 is a schematic drawing of the results from all these tests. Unlike the results obtained from the naturally ventilated building, the calculated airflows were always positive. No least-squares constraint was therefore imposed on the calculations. The lack of negative airflow values can be regarded as a consequence of the better mixing imposed by the mechanical ventilation system.

In each zone, the fresh air infiltration rate as well as the total ventilation rate was calculated. The total ventilation rates were calculated by summing either the airflows into or out of these zones.

The calculated whole building ventilation rates were compared with the 'design' values. This comparison, together with individual zonal rates, are as follows:

Ventilation rates (ach)

Test	Ground-floor		First-floor		Second-floor		Whole-building	
	Fresh	Total	Fresh	Total	Fresh	Total	Measured	Design
1	1.05	3.10	1.02	3.38	0.55	3.70	0.87	0.0
2	2.33	3.22	2.00	3.22	1.95	2.64	2.09	4.0
3	1.81	4.57	1.35	3.00	1.15	3.19	1.44	1.5

3.7. Discussion

Interzonal airflow information, as supplied by Figure 5, allows the fresh air contribution to any zone to be separated from the total ventilation rate into that zone or to the building as a whole. The difference between the rates can be seen in the above table.

For this series of measurements, the results tabulated above can be compared with 'design' values which are given in the same table. There are marked discrepancies. One striking feature is the amount of fresh air entering the building when the mechanical system is on full recirculation (Test 1) when there should nominally be no such inflow. It is suggested that this inflow of fresh air is partly due to infiltration through the external fabric of the building and partly due to leakiness in the dampers and ductwork housing the air handling unit.

4. FRESH AIR INFILTRATION INTO A ROOM IN BUILDING B9 USING THE 'CONSTANT CONCENTRATION' SYSTEM

4.1. Introduction

The main purpose of the measurements described here were to determine the fresh air entering a room of a multicelled building using the 'constant concentration' system. The tests were carried out in a first floor room of building B10.

4.2. Test room

The test room (Figure 6) is located on the first floor of the four-storey block which is aligned approximately east-west, facing south. In the test office, there is a 'false' ceiling which extends over the whole of that storey. The height from floor to false ceiling is 3.02 m. Above this is a void which also extends throughout the zone.

There are no direct openings between this room and the rooms on either side of it. The test room, measuring 4.30 x 2.97 m, has a well-fitting door which opens onto a common corridor which is 1.77 m wide and 13.34 m long and terminated by fire-doors.

It was considered impractical to maintain a constant concentration in the extensive void above the false ceiling in the room. For this reason, all possible airflow routes to the room except those allowing direct exchange of air with the outside and with the corridor were sealed. As a result it was necessary only to maintain a constant concentration in the room and the corridor immediately outside the door.

4.3. Injection and sampling locations

The locations of injection and sample points are indicated in Figure 6. In the room these are both at a height of two metres. A small fan was placed in front of the injection line to aid mixing. In the corridor, the sampling point is at a height of one metre, and the injection point is at a height of 2.5 metres, immediately in front of a desk top fan. A second fan was placed at the same height further down the corridor, again to induce mixing.

4.4. Injecting tracer and monitoring concentrations

Throughout the tests, sulphur hexafluoride was injected into the room and the corridor at the appropriate times to maintain both zones at a target concentration of 20 ppm. The injection flow rates were set by needle valves attached to the ends of the nylon tubes. The rates were checked using a soap-film flow meter and were adjusted daily to maintain injection rates of 1000 cc/min in the corridor and 50 cc/min in the room.

The 'constant concentration' equipment was installed in an adjacent laboratory. The system controlled the full operation of injection and sampling. Each injection through a line was followed by a short flushing with outside air. Also, preceding each analysis, a short purge drew a fresh sample from the appropriate sample line. Samples were analysed using a 50 ppm full-scale Leybold-Heraeus IR gas analyser. The analyser was calibrated daily.

4.5. Monitoring temperature and wind data

Inside and outside air temperatures and wind velocity were monitored and recorded. The wind speed and direction were measured at a height of 10 m at a nearby open area. All information was recorded in cassette form on a Solartron Orion A data logger. These were later transcribed to give half-hourly averages.

4.6. Results

Detailed results are presented for two 24-hour periods when the building was 'lightly occupied' (i.e. non-working day) and when it was 'heavily occupied' (i.e. working day). These two sets are only a small sample of the total data set but they are typical and illustrate the major features of the results.

Figure 7 shows the computed airflow rates, into the room and the corridor, over a period when the building was only very lightly occupied. During this period, the concentrations generally were accurately maintained at the set level, except for disturbances around 8.00 hr and 16.00 hr. The wind speed, wind direction and the temperature difference between inside and outside are shown in Figure 8.

Figure 9 shows the computed airflow rates into the room and corridor during a working day when the building was heavily occupied. In this case, the concentrations were maintained at night but deviated significantly from the set level during working hours. The wind speed, wind direction and temperature differentials are shown in Figure 10.

4.7. Discussion of results

Taking the caso of heavy occupation first, the wind velocity remained essentially constant throughout the test and can therefore be ruled out as the cause of a daytime peak in infiltration rate. In addition, the temperature differences were also small at this time which would tend to reduce any temperature-induced infiltration.

The apparent rise in infiltration correspond in time to the arrival of occupants at 8.30 hr, peaking at 14.00 hrs, followed by a return to night-time levels after 18.00 hr when the occupants have left. The calculated infiltration in the rooms follow a pattern similar to that in the corridor, which increase by an order of magnitude.

It is therefore concluded that an increase in the total ventilation rate in the corridor is caused by occupants opening the corridor doors.

During this period of heavy occupancy, the increase in airflow rate was too great for a constant tracer concentration to be maintained by the system. In this situation, air exchanges between room and corridor caused a net loss of tracer from the room thereby precipitating an increase in injection rates into the room. Thus the increase of infiltration in the room may be largely caused by the loss of control in the adjacent corridor.

When the building was lightly occupied, similar but relatively smaller changes in infiltration in the corridor were observed between 8.00 hr and 16.00 hr. But there is only a very small corresponding disturbance in the room infiltration. In this case, there was better control of concentration in the corridor.

Results from the 'light occupancy' period show that the room, with its windows closed, was very airtight. The infiltration averages at about 75 litres per hour which is very low.

5. OVERALL VENTILATION RATE IN BUILDING B18 USING THE 'CONSTANT INJECTION' SYSTEM

5.1. Introduction

The 'constant injection' system can most usefully be used in buildings having good internal mixing (Section 6 of Chapter 4). In view of this, it was decided that this system could be used in building B18 to determine the overall ventilation rate when the AHU was in normal use.

5.2. Experimental arrangement

The equipment was installed on the roof of the building and next to the AHU (Figure 8 of Chapter 4). The 'supply' unit was set up to inject directly into the intake fan in the main duct which was just downstream of the air intake grille. A 10-litre Tedlar bag, filled with neat SF6, was used as the reservoir for the supply unit. The injection rate was set to 132 ml/hr. Assuming a ventilation rate of 1 ach, and taking the volume of the building as 5280 m^3, this injection rate would ensure a steady target concentration of 25 ppb.

5.3. Results

After a suitable time was allowed for the concentration to stabilise, 'spot' measurements were taken at various points in the building. The samples were taken in 100 ml glass syringes and analysed using a gas chromatograph fitted with an electron-capture detector. Details of this method of sampling and of the gas chromatograph equipment are given in Chapter 8.

The resulting concentrations and calculated air change rates were as follows:

Sample location	Sample concentration (ppb)	Air change rate (per hour)
Corridors:		
Ground floor	30	0.83
First floor	29	0.86
Second floor	30	0.83
Rooms:		
Ground floor (south facing)	30	0.83
Second floor (north facing)	28	0.90

5.4. Additional measurements

Subsequent measurements were carried out to determine the overall ventilation rate averaged over various time intervals.

These were made by use the 'sampling' unit with a sample tube inserted into the main return duct on the upstream side of the extract fan. Samples were collected in a five-litre Tedlar bag. The injection flow rate was increased to 2.2 ml/min.

During the course of the experiment, 100 ml samples were extracted from the 'sampling' bag at various time points. At these times, 'spot' syringe samples were also taken at various locations in the building. The concentrations of all these samples are tabulated as follows:

Time into test (hours)	Averaged concentration in bag (ppb)	Spot concentration at other locations
20	24.7	29.4 ppb in 2nd floor corridor
40	28.3	30.7 ppb in 2nd floor corridor
96	26.0	23.4 ppb in 1st floor corridor

23.0 ppb in north facing room (2nd floor

Unfortunately, the gas chromatograph was not kept calibrated during these measurements. Since the absolute values for these concentrations were suspect, no attempt was made to derive air change rates from these values.

5.5. Discussion

The results given above showed that, with the AHU turned on, the overall ventilation rate was averaged at 0.85 ach.

It is unfortunate that no time-averaged airchange rates could be derived from the bag samples because of calibration problems. Calibration procedures were subsequently tightened up and similar problems should not occur in future. It was however encouraging to note that the time-averaged concentration in the bag reflected, even over four days, the concentration of the tracer in the building.

6. CONCLUSIONS

Three office buildings were investigated using the four automated systems described in Chapter 4. The air movement within two of these buildings were determined using the multiple tracer systems. The constant-concentration system was used in the third building to determine room fresh air infiltration whilst the constant-injection system was used to determine overall ventilation rates in a building with an AHU.

The Mk I system, built as an interim measure, was used to determine the interzonal airflows in the naturally ventilated office building, B10. The tracer gases that could be used with this system were dependant upon the available analysers. The measurements showed that, for the particular weather conditions, the airchange rate was 0.76 ach. In addition, a knowledge of the movement of air air within the building was gathered.

Interzonal airflows were measured in building B18 using the Mk II system. The building incorporates an AHU which allows a variable amount of fresh air to be drawn into the building. Measurements were made for different settings of this unit. Marked discrepancies were found between measured and design values. The overall ventilation rate of the building, with the AHU set at normal operating condition, was measured as 1.44 ach. This value is in excess of that measured by the constant-injection system. It seems that further work may be necessary to disentangle this discrepancy.

The fresh air infiltration into a rather airtight office room in building B9 was measured using the constant concentration system. The measurements showed that the system works well when the control zones surrounding the test room are not much disturbed. For this particular room, the averaged fresh air infiltration was low at 75 litres per hour.

The overall infiltration rate in building B18, with its AHU operating normally, was measured as 0.85 ach by using the constant injection system.

7. FUTURE WORK AND APPLICATIONS

The multiple tracer systems give information regarding interzonal air movements which no other existing experimental system or prediction technique can do. Such information is invaluable if there is a need,

- to identify the movement of air, and hence contaminants or heat, from one zone to another and,
- to determine the effectiveness of remedial measures or to indicate zones where selected remedial measures will be cost-effective.

It is therefore necessary that a limited amount of further field measurements be carried out using the Mk II system so as to fully sort out the measurement technique. The complexity of these two multiple tracer systems precludes them from being used more widely. Future work should therefore be confined to in-depth monitoring of a few selected office buildings. The same comments apply to the constant-concentration system.

Now that the gas chromatograph can be calibrated in a much more reliable manner, the constant-injection system could be used to give time-averaged ventilation rates. The buildings in which this system could be used will, however, be limited to those with good internal mixing.

This Chapter therefore suggests that the multiple tracer systems or the constant-concentration system should only be used when comprehensive information regarding air movement is required for a building. Otherwise, simpler techniques which will give less comprehensive but nevertheless useful information are required. The manner in which we set out to develop such techniques is set out in the following Chapters.

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2. Lawson, C L and Hanson, R J, Solving Least Squares Problems, Prentice Hall, Englewood Cliffs, New Jersey, (1974).

3. Numerical Algorithm Group, NAG manual (mark 9), (1978).

FIGURES

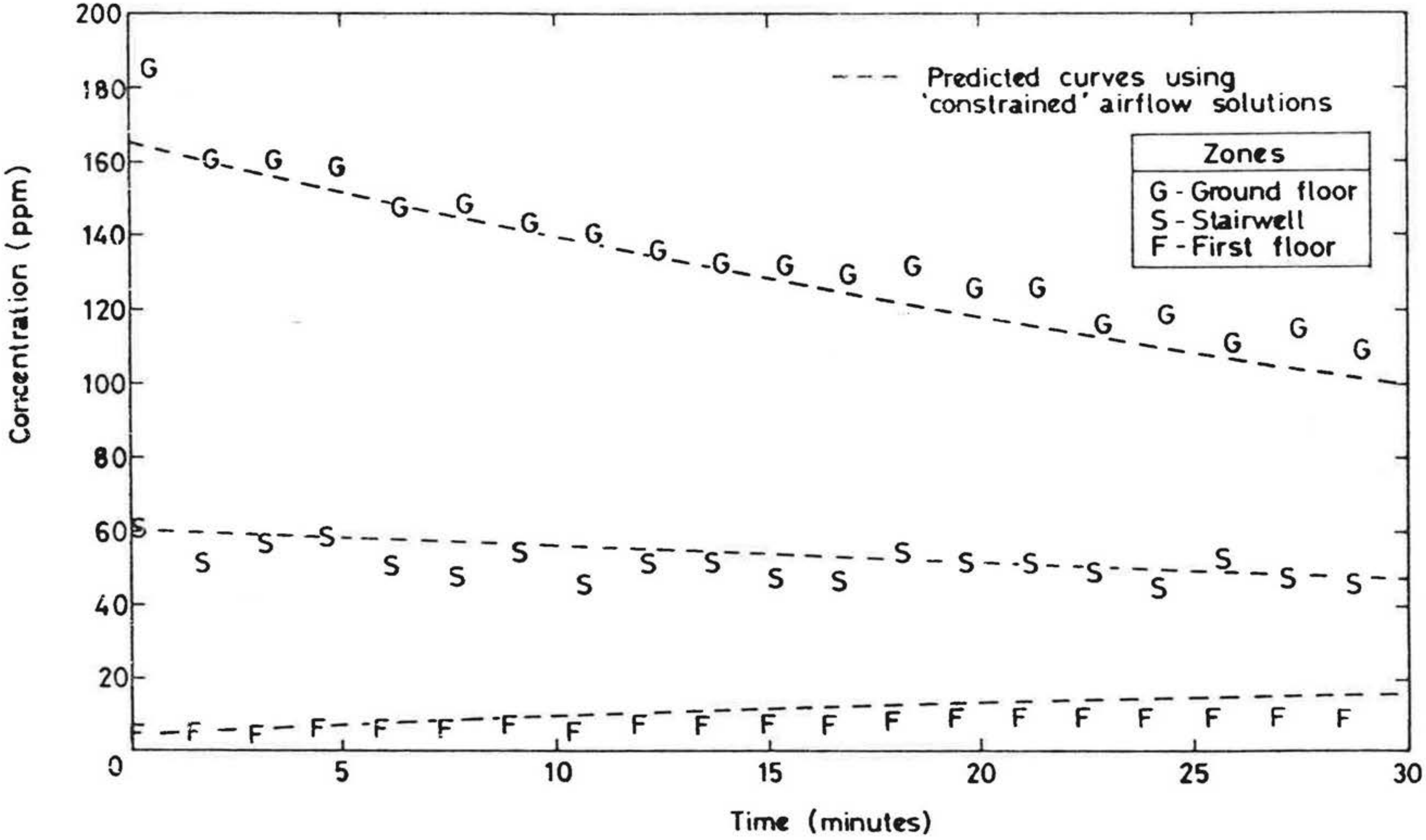
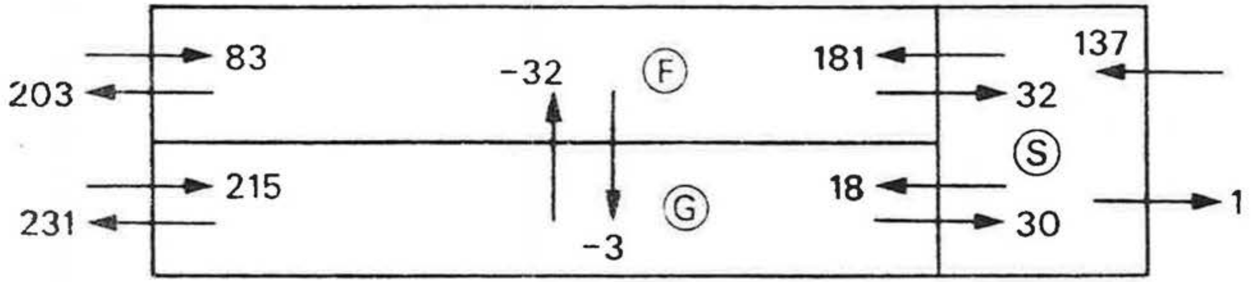
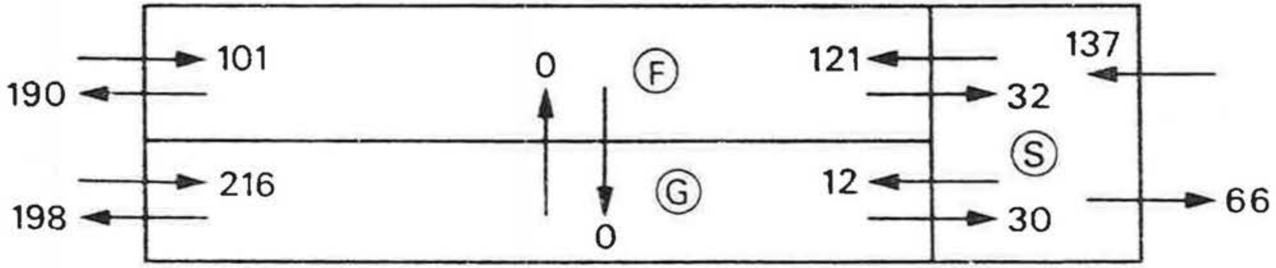


Figure 1 Nitrous oxide concentrations in building B10



'Unconstrained' solution



'Constrained' solution

FIGURE 2 Interzone airflows (litres/sec) in naturally ventilated office

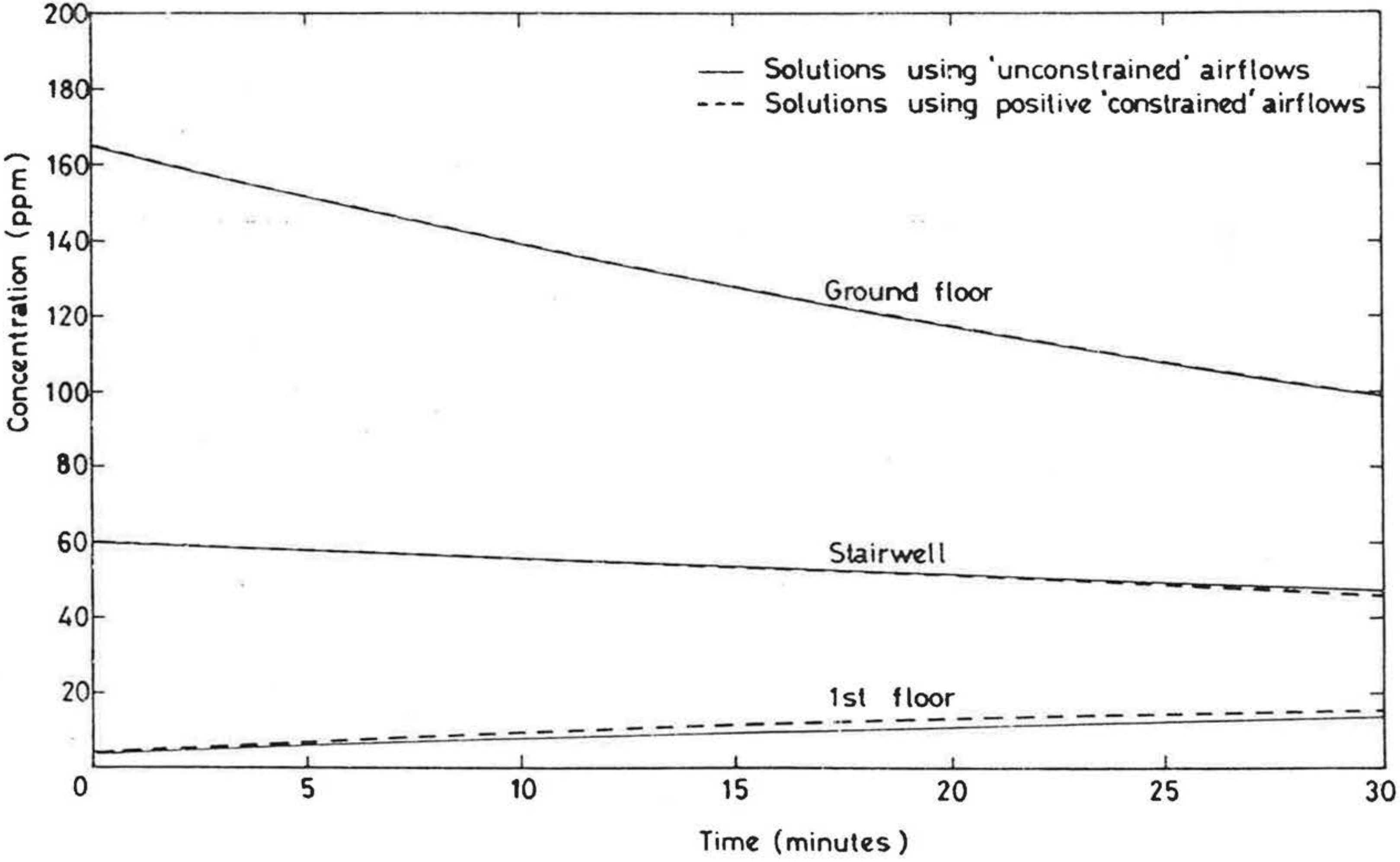


Figure 3 Predicted Nitrous oxide concentrations in building B10

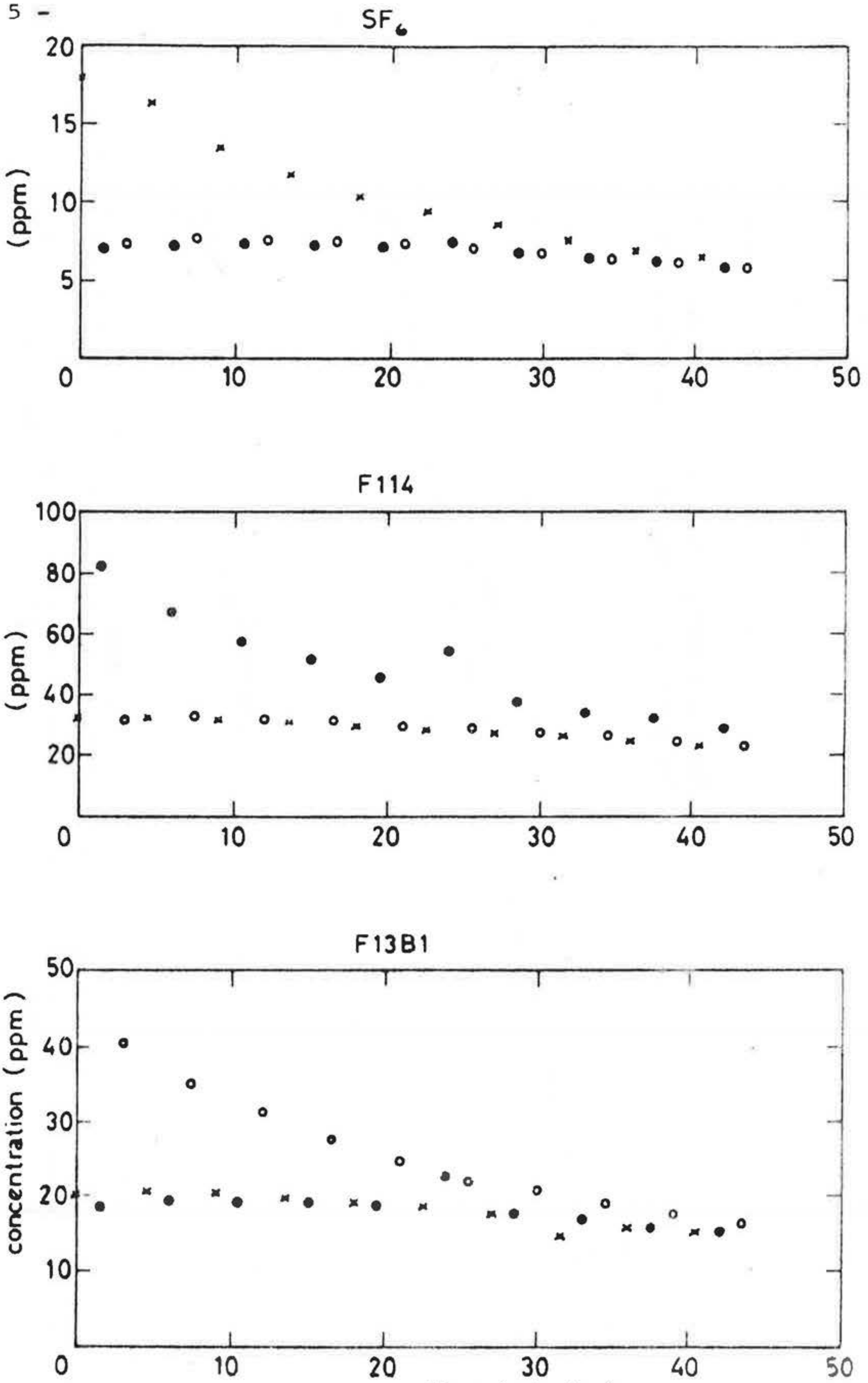


Figure 4a Tracer concentrations in building B18
- Test 1

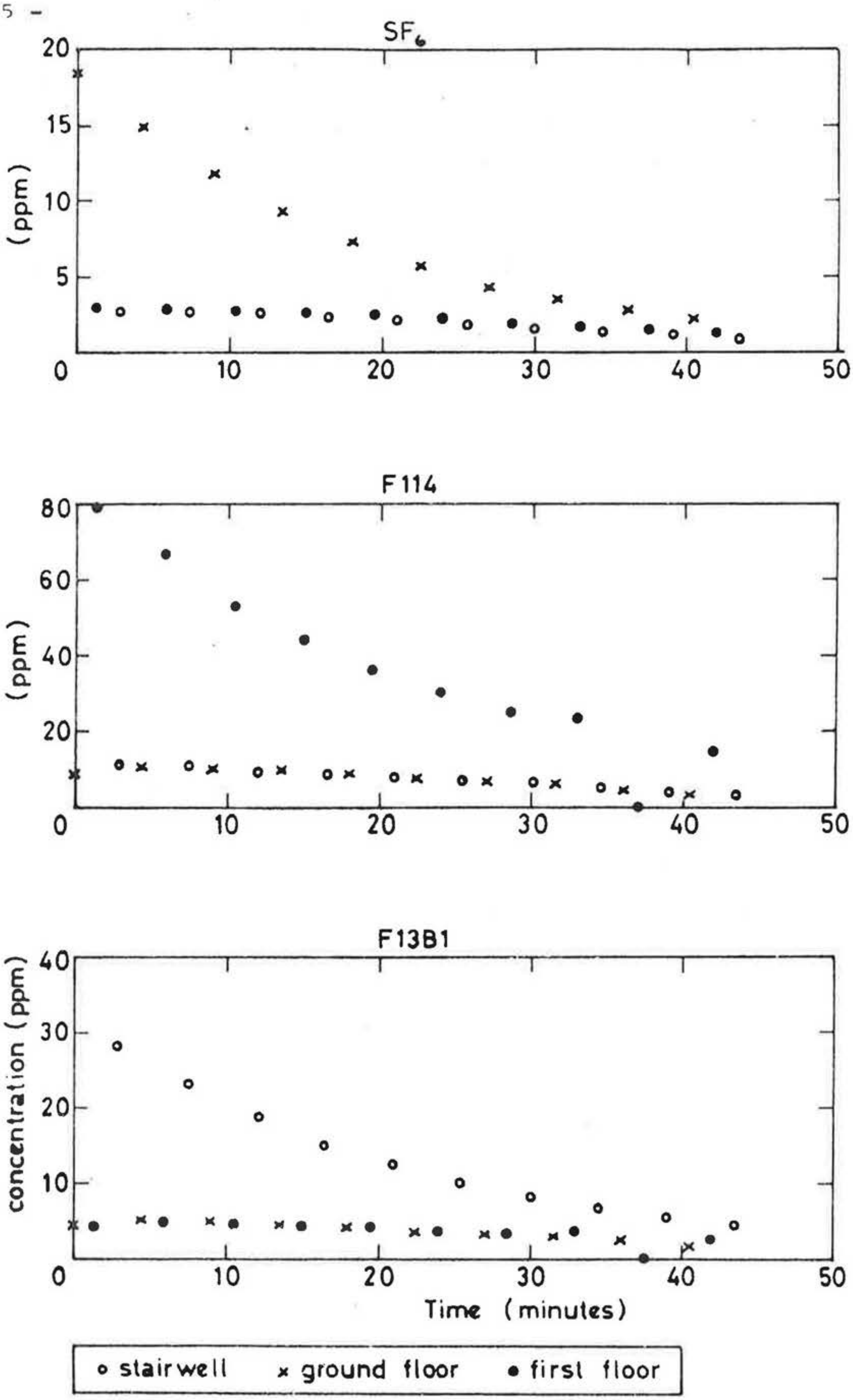


Figure 4b Tracer concentrations in building B18 - Test 2

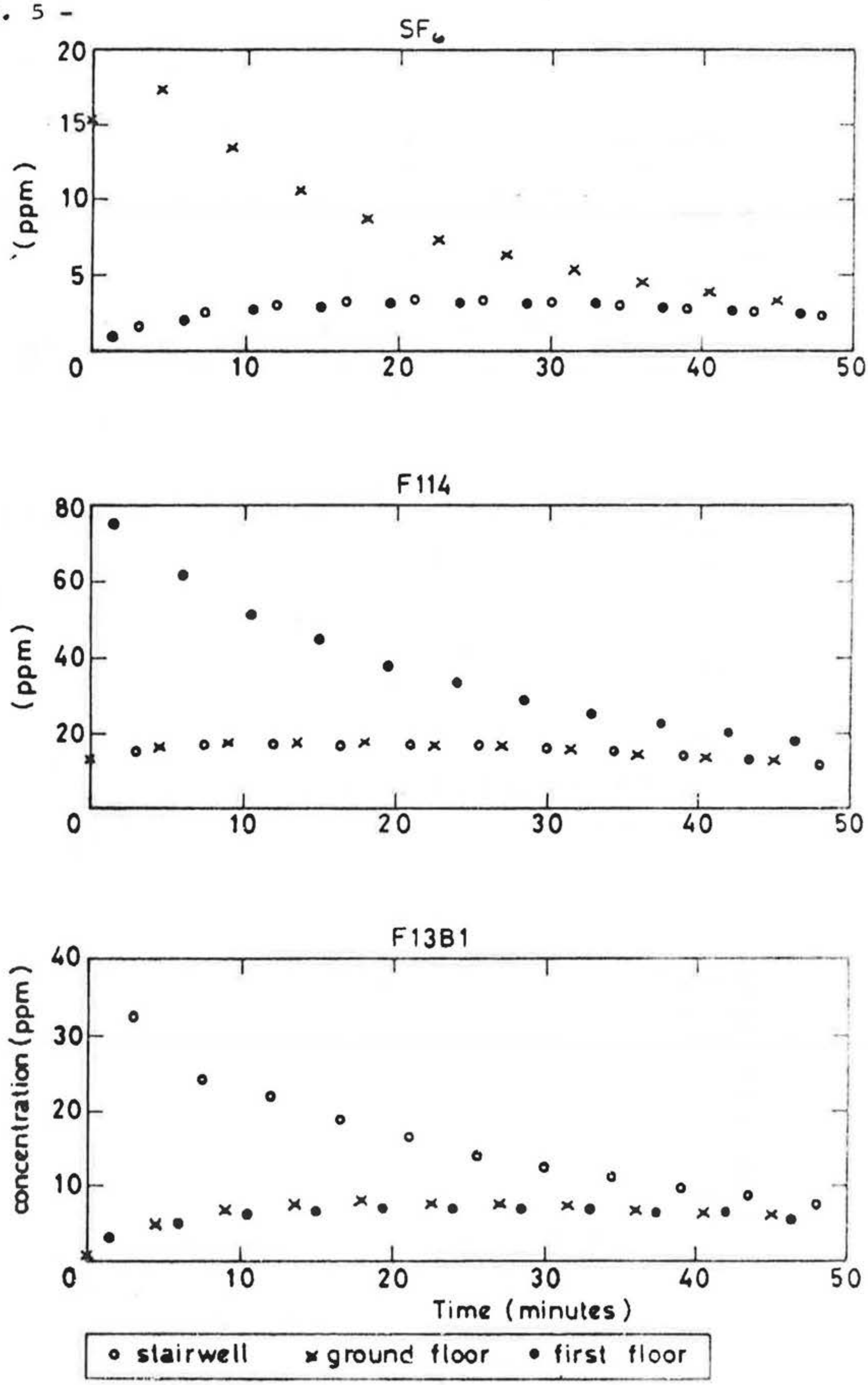
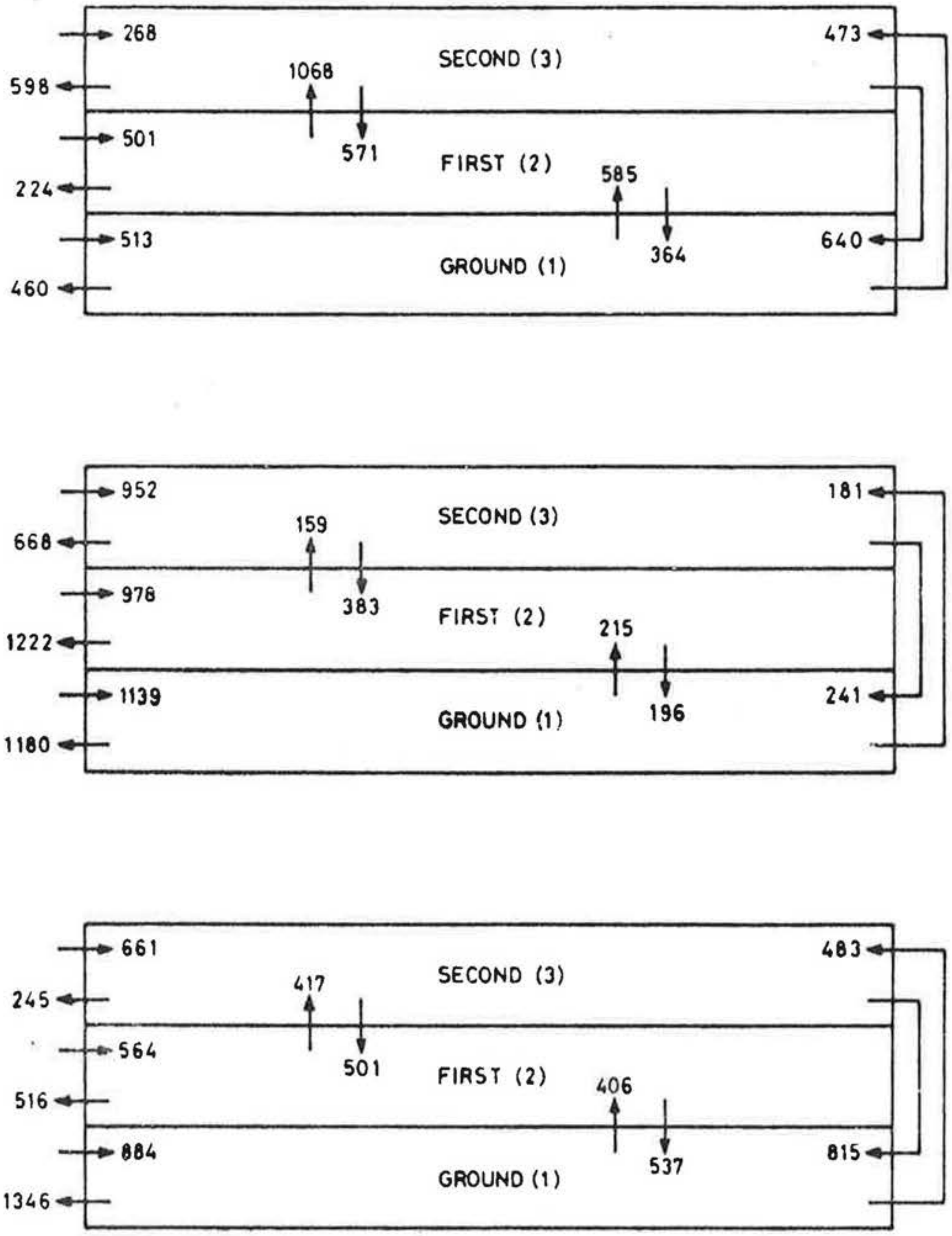


Figure 4c Tracer concentrations in building B18 - Test 3



Full recirculation

Internal temperature = 23 °C
External temperature = 19 °C
Wind speed = 0.8 m/s
Wind direction = 047 deg. N

No recirculation

Internal temperature = 23 °C
External temperature = 18 °C
Wind speed = 1.1 m/s
Wind direction = 085 deg. N

30 % Fresh air

Internal temperature = 23 °C
External temperature = 17 °C
Wind speed = 0.3 m/s
Wind direction = 043 deg. N

Figure 5 Interzonal airflows (l/s) in building B18 for Tests 1, 2 and 3

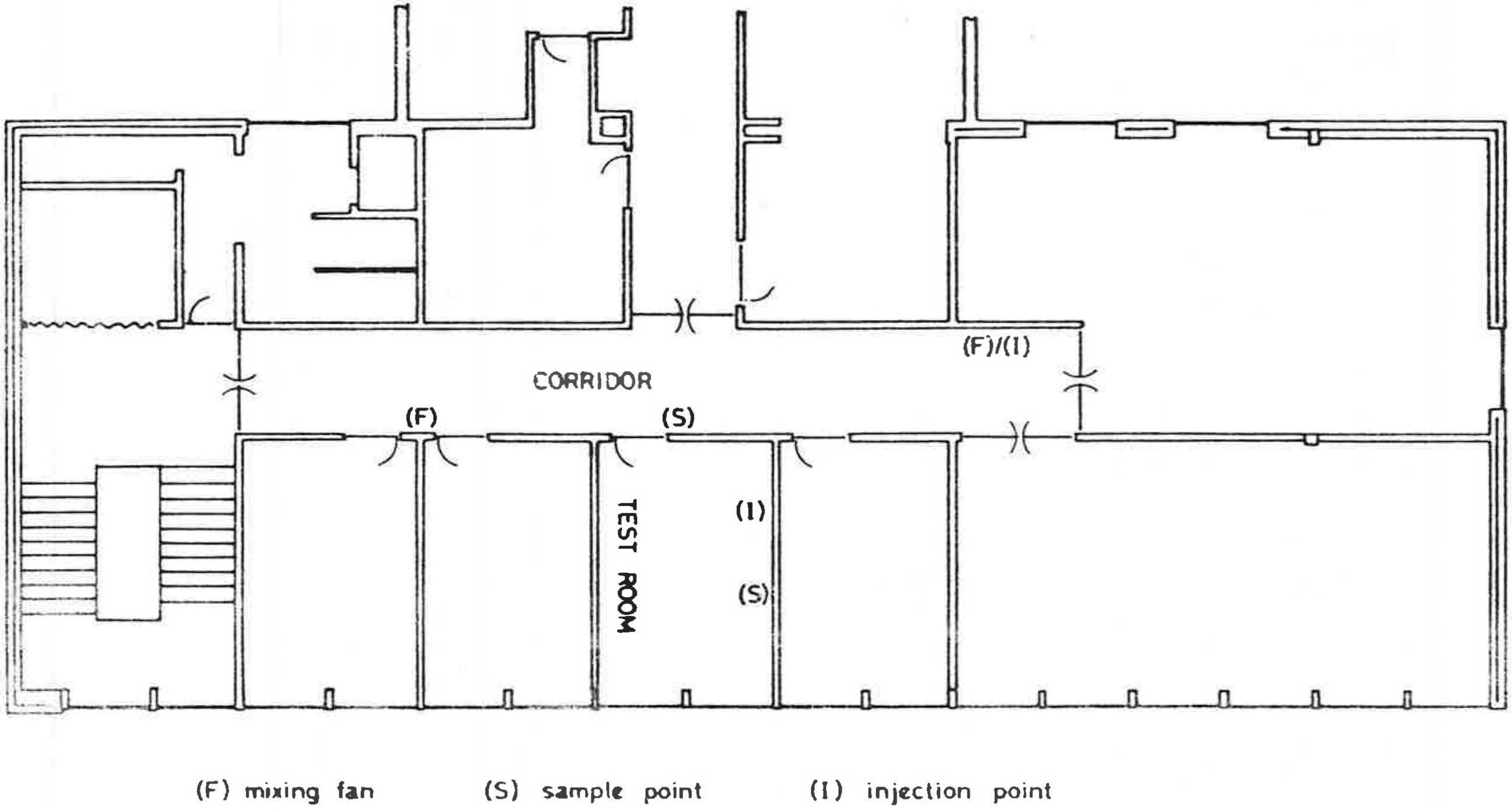


FIGURE 6 Plan of test building showing location of 'test' room

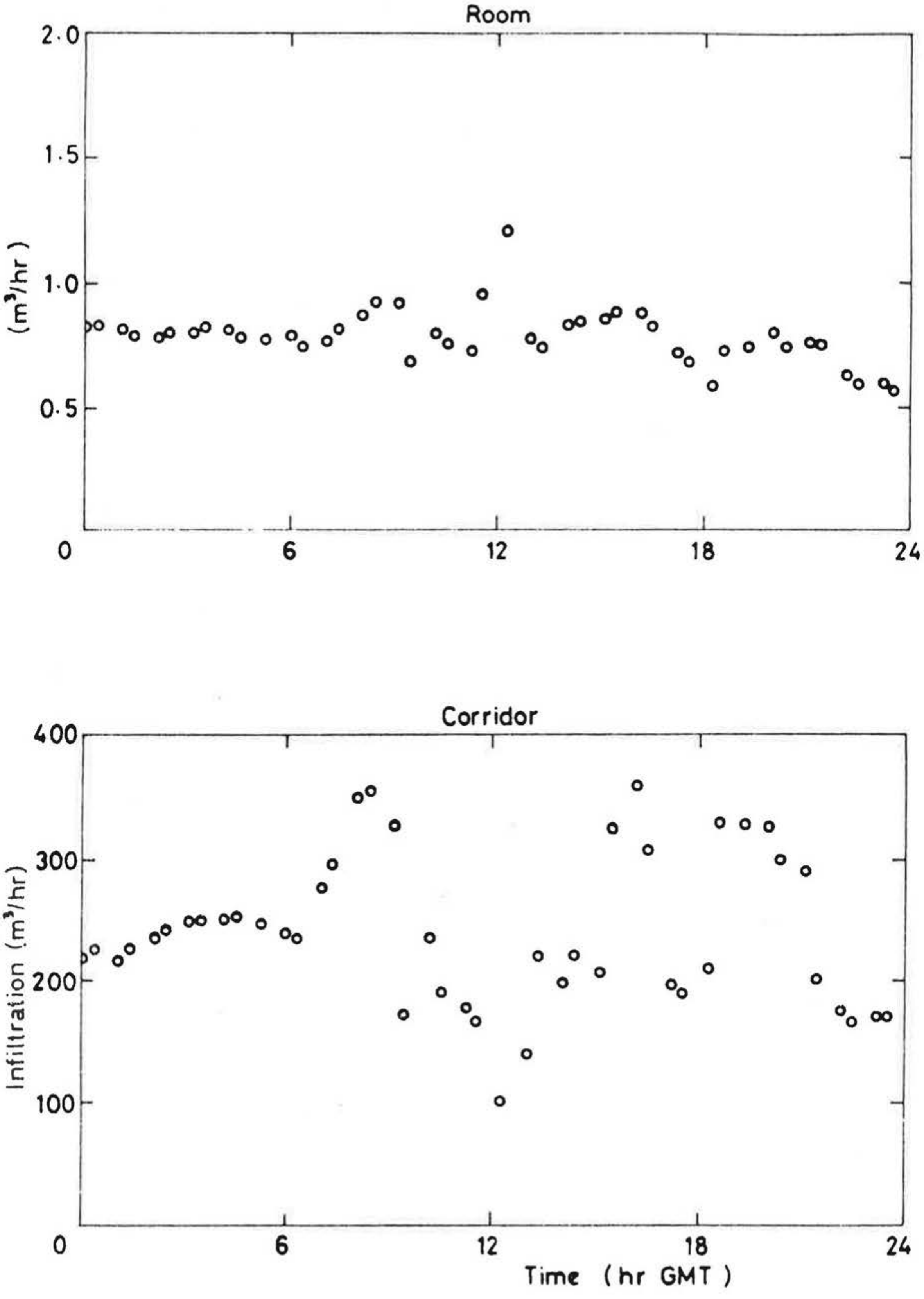


Figure 7 Room infiltration and corridor air exchange rate - (light occupancy)

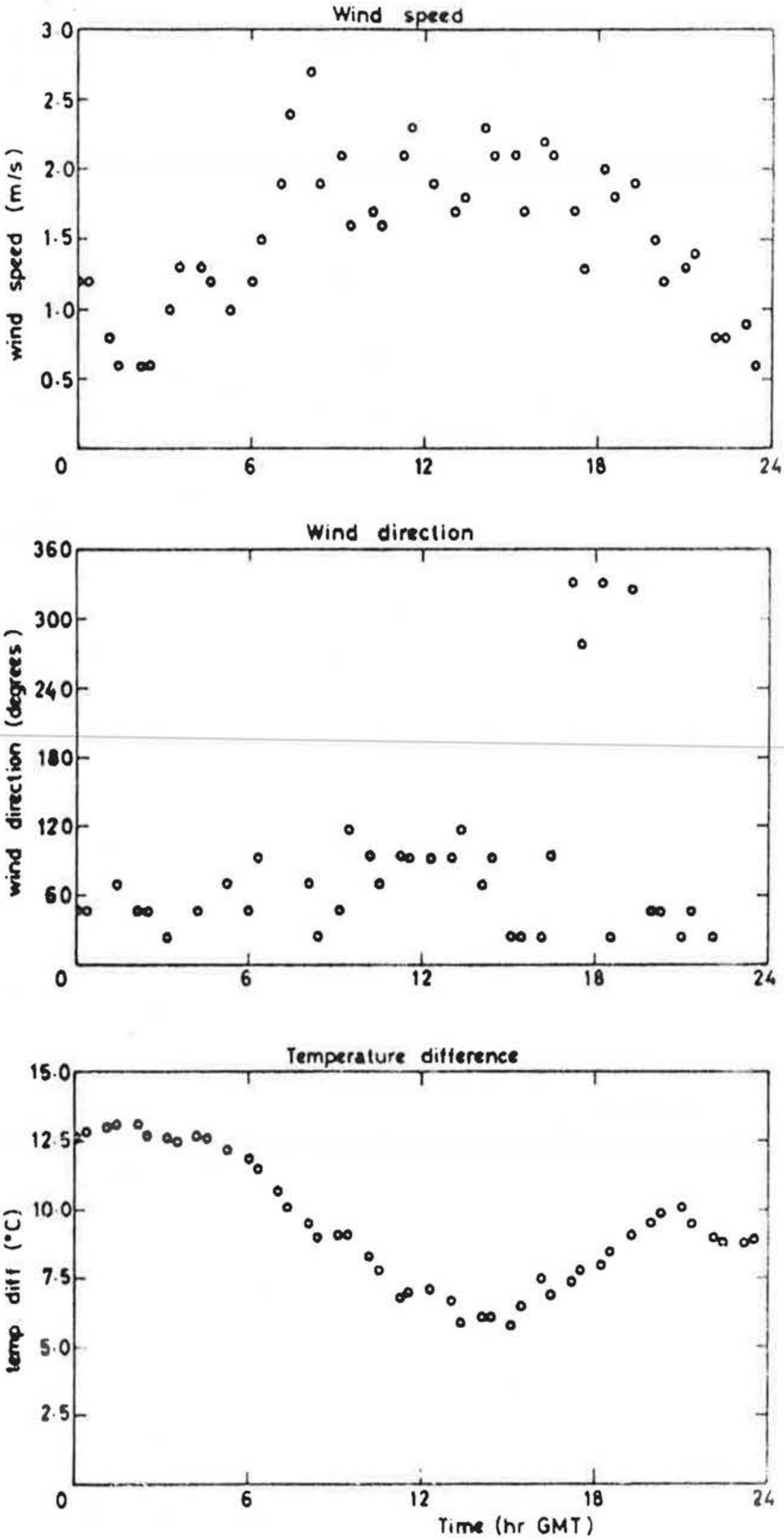


Figure 8 Wind speed, wind direction and temperature differential records - (light occupancy)

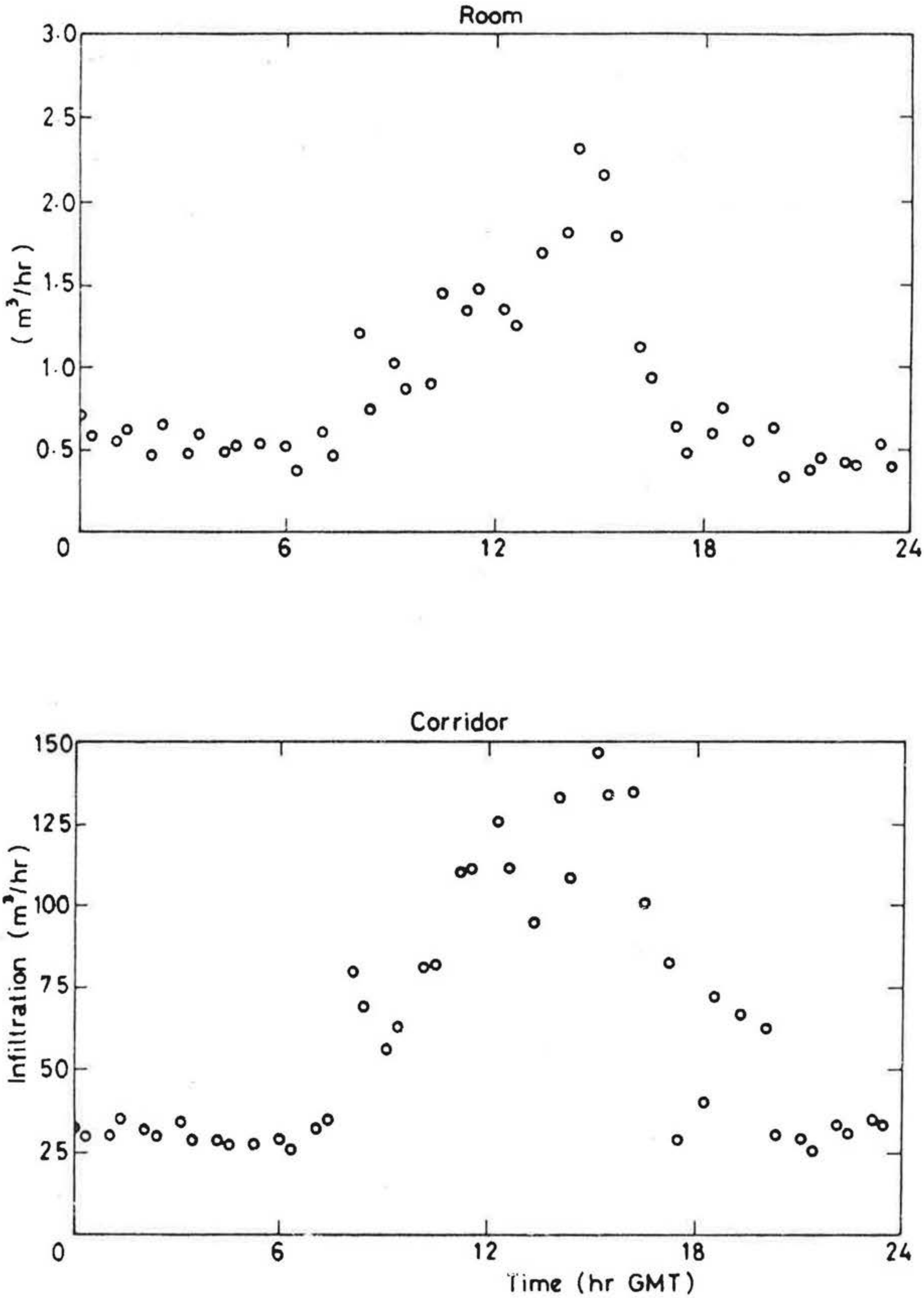


Figure 9 Room infiltration and corridor air exchange rate - (heavy occupancy)

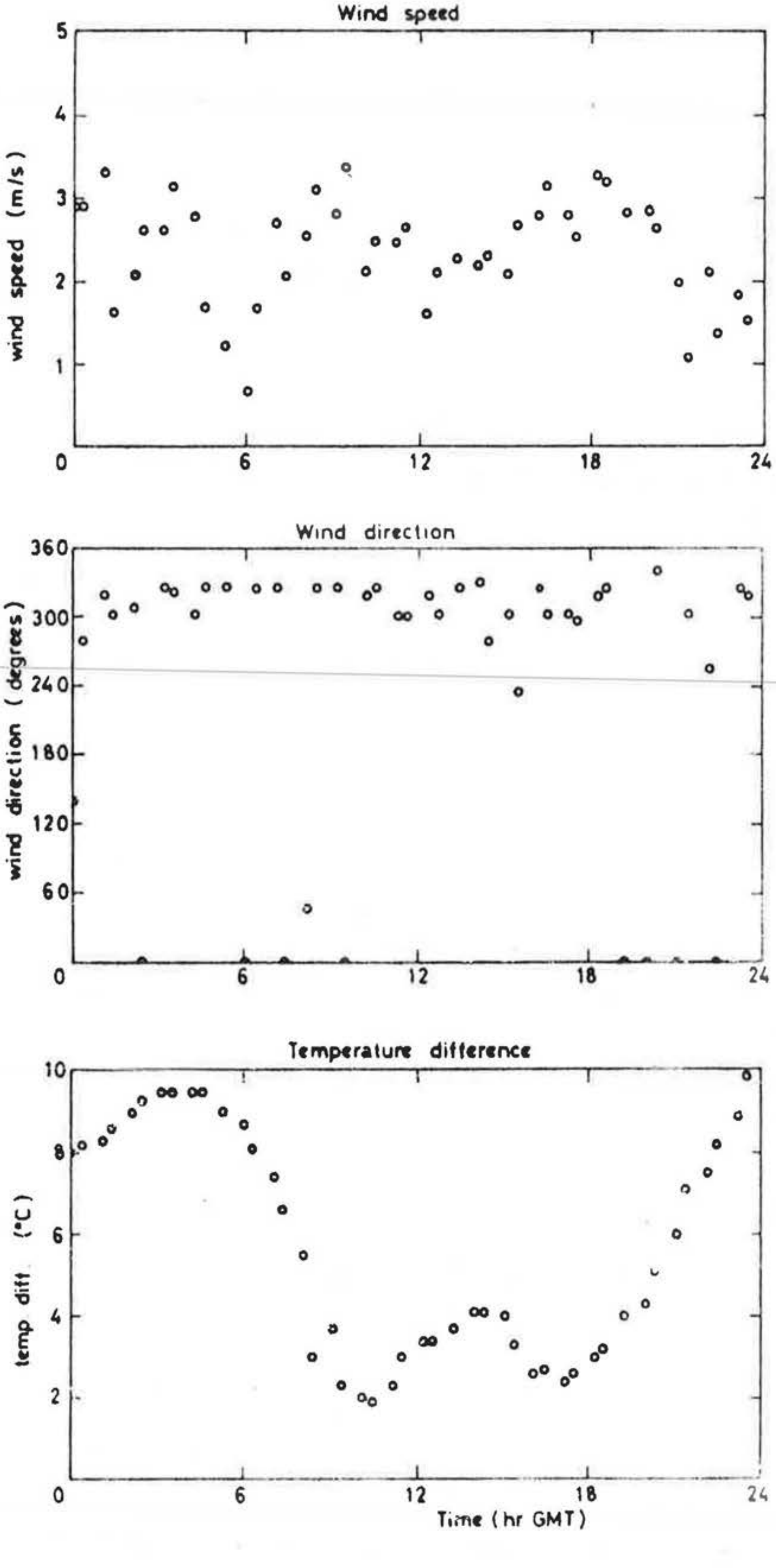


Figure 10 Wind speed, wind direction and temperature differential records - (heavy occupancy)

CHAPTER 6

FIELD DEVELOPMENT OF SIMPLIFIED STRATEGIES FOR VENTILATION MEASUREMENT IN OFFICE BUILDINGS

1. INTRODUCTION

The previous Chapter described possible measurement techniques that could be used to investigate, in detail, the airflows in large, multicelled buildings. Such information was, however, gathered at the expense of using sophisticated and complex automated measuring systems.

The cost and complexity, however, of carrying out such detailed experiments can be prohibitive and in many instances it would be beneficial to obtain less comprehensive, but nevertheless useful information using only a single tracer gas.

Large, multicelled and naturally ventilated buildings pose many inherent difficulties for the measurement of overall infiltration rates using a single tracer gas. The most obvious difficulties are;

- local variations in infiltration,
- imperfect internal mixing of the air, and
- practical difficulties in distributing (i.e. seeding) the tracer gas and subsequently obtaining air samples.

In this Chapter, a relatively simple technique which avoids these problems is proposed and field experiments to test the method are described. The technique is first illustrated in Section 2 by analysing the decay of a tracer initially dispersed in a two-cell model representation of a building.

The eigenvalue solution to this model shows that one of the two eigenvalues will dominate after a long time period. When the influence of the other eigenvalue becomes negligible, the dominant eigenvalue is directly related to the decay rate measured during this period from a semilog plot of the time-history profile of the tracer concentration.

Conditions under which this dominant value approximates to the overall infiltration rate are next discussed. It is then suggested that these conditions, which are rather restrictive, can be relaxed in real multicelled buildings to help towards correspondence between the above two values.

The Sections following this describe field measurements designed to develop an understanding of this proposed new simplified technique. All measurements were carried out in building B18

(Appendix I) and details of the tests are given in Table 1.

Field measurements carried out with the building mechanically ventilated are described in Section 3. In this building, the air handling unit connects directly only to the rooms whereas the corridors and stairwells are not directly ventilated in this way. Therefore, whilst the internal air was expected to exhibit good mixing, perfect mixing was not expected. It was therefore considered justifiable to test the new technique with the building operating under this ventilation mode. Results from these measurements demonstrated the characteristics predicted by the theory in the earlier Section.

Section 4 describes field measurements carried out with the building naturally ventilated. The tests include various tracer seeding strategies ranging from whole building seeding through to seeding of individual zones or cells. A zone in the present context may be a single cell within which mixing is assumed perfect or a collection of such cells which can be taken to act as one aggregate cell. The results, as they reflect on the simplified technique, are then discussed.

In Section 5, the concept of local ventilation rates is introduced. This value, unlike the more often used decay rate, can in certain circumstances be used to predict the steady local concentration of a contaminant which would result from distributed sources. A more detailed explaination of this local rate, together with field measurements, are discussed in that Section.

Finally, in Section 6, conclusions are drawn regarding the work described in this Chapter. The implications from these, as regard to future work, are then discussed.

2. THEORY OF 'SIMPLIFIED' TECHNIQUE

2.1. Introduction

In a well-mixed single cell building, the single eigenvalue solution to the tracer decay equation (Equation 3 given below) represents the air change rate of that building. What is important is, however, whether the eigenvalue solutions obtained by considering a multicelled building can in any way be used as a measure of the air change rate of the whole building.

If a tracer gas, at an initial concentration level of $\{C(0)\}$, is allowed to decay in a multicelled building, then its subsequent behaviour at any later time, t, is governed (Chapter 2) by the system of ordinary differential equations

$$\{\dot{C}\} = [\ V\ ]^{-1} . [\ Q\ ] . \{\ C\ \} \qquad (1)$$

where $[V]$ is the cell-volume matrix and $[Q]$ describes the intercell airflows.

In Chapter 2, the unique solution

$$\{C(t)\} = e^{[V]^{-1}.[Q]\ t} . \{C(0)\} \qquad (2)$$

which satisfies Equation 1 is given.

It was further shown that if the matrix $[V]^{-1}.[Q]$ has distinct eigenvalues λ, then the solution reduces to

$$\{C(t)\} = [A]\ \{e^{\lambda\ t}\} \qquad (3)$$

where $[A]$ is dependent on $\{C(0)\}$ but is independent of time t. It can therefore be seen that each element of $\{C(t)\}$ is a linear combination of exponential functions with no polynomial contributions.

2.2. Two cell model

Let V_1 and V_2 be the volumes of two interconnected cells, 1 and 2 and let Q_{ij} be the airflow from cell i (= 0,1,2) to cell j (= 0,1,2). The two eigenvalues are then given by,

$$-2\lambda - \left(\frac{Q_{01}}{V_1} + \frac{Q_{02}}{V_2}\right) + \left(\frac{m_2 V_2}{V_1} + \frac{m_1 V_1}{V_2}\right) \pm \sqrt{\left[\left(\frac{Q_{01}}{V_1} - \frac{Q_{02}}{V_2}\right) + \left(\frac{m_2 V_2}{V_1} - \frac{m_1 V_1}{V_2}\right)\right]^2 + 4 m_1 m_2} \qquad (4)$$

where $\qquad m_i = Q_{ij} / V_i \quad$ for j=1,2

Taking the negative square root term, the minimum eigenvalue is obtained. The square root term in the resulting equation consists of an infiltration term,

$$X = (Q_{01} / V_1) - (Q_{02} / V_2)$$

and mixing terms. If the infiltration rates in each cell are approximately similar to each other, or if the mixing terms are large in comparison with X, then the square root term can be expanded as a Maclaurin series in X for small X.

Therefore by expressing Equation 4 in terms of a polynomial in X for small X, and then by

- collecting like terms, and
- replacing m_2 by considering the airflows into Cell 1,

Equation 4 can be simplified to,

$$-\lambda_{min} = \frac{\dfrac{m_1 Q_{01}}{V_2} + \left(\dfrac{Q_{10} - Q_{01} + m_1 V_1}{V_2}\right)\dfrac{Q_{02}}{V_1}}{\dfrac{m_1 V_1}{V_2} + \dfrac{Q_{10} - Q_{01} + m_1 V_1}{V_1}} + O(X^2) + \ldots.. \qquad (5)$$

If the following hold true;

- there is enhanced mixing between cells, i.e. m large, or
- infiltration balances exfiltration in each cell,

then Equation 5 can be further reduced to

$$-\lambda_{min} = (Q_{01} + Q_{02}) \,/\, (V_1 + V_2) \qquad (6)$$

$$= R$$

where R is the total infiltration rate.

It might be concluded that the conditions, required for the dominant eigenvalue λ to tend towards the infiltration rate R, are rather restrictive. It is suggested, however, that the two-cell model is an extreme simplification of a multicelled building, and that in a real building two factors help towards correspondence between λ and R; namely

- the influence of any one cell is reduced since there are many cells, and
- there may be a combination of internal mixing, equal local infiltration rates and locally balanced infiltration and exfiltration.

These ideas are investigated further in the following field measurements.

3. FIELD MEASUREMENTS WITH BUILDING MECHANICALLY VENTILATED

3.1. Introduction

In tests A to E (Table 1), the air handling system was used to seed the whole building with a single tracer gas. The decay in concentration in the main exhaust duct (Tests A and B), at the three floor levels (Test C) and at the local levels of rooms and corridors in the centre-zone of the second floor (Tests D and E) were measured.

3.2. Measurements at main air handling duct

The two tests, A and B, were designed to provide a measurement of the overall building ventilation rate and the tracer decay characteristics as seen at the main return duct of the air handling unit. In both tests, SF6 was injected directly into the main supply duct to reach a target concentration of about 200 ppm.

Concentration decay in the main return duct was measured using a Leybold Heraeus Binos 200 ppm (full scale) SF6 analyser. Once the injection was stopped, measurements were made over a period of about 70 minutes.

The concentration decay curve (Fig 1) for the first test shows, on a semilog plot, a continuously changing slope which is tending towards a decay rate of 0.82 per hour. This value can be detected about 30 minutes after tracer injection ceased.

This gradual change in slope suggested that measurements should have continued for a longer time period. This was carried out in Test B when the measurement period was extended to 150 minutes. The second test (Fig 2) reproduced the results of the first with the slope tending towards a value close to 0.80 per hour. Once again, this slope can be observed after about 30 minutes from the end of injection. During both tests, the wind was blowing from the south-west to the north-west sector.

3.3. Measurements at individual floor levels

In Test C, the Mk II system installed during the multiple tracer experiments (Chapter 5) was used to rapidly inject the tracer gas. Freon 13B1, to a target concentration of 50 ppm throughout the building. The gas was injected at strategic points into the ductwork of the air handling system through previously installed nylon tubing. Injection time was approximately two minutes.

Concentration measurements began immediately after the tracer injection was completed. The Mk II system was used to draw and analyse samples from each of the three floors as the concentrations decayed over a period of 75 minutes. During measurement, the Miran analyser enclosure was continuously flushed with outside air using a 30 l/minute Austen pump. No continuous prepurge of the sample line was carried out since similar tests (not reported here) have shown that flushing the line immediately before sampling was adequate.

Figure 3 shows the decay curves measured in each of the three floors. The curves measured on each floor are similar and all show a decay rate tending towards 1.1 per hour in the long term. The wind was blowing from the south-east sector during this test.

3.4. Localised measurements in centre-zone of the second floor

The two tests described in this Section were designed to investigate the local variations in infiltration rate within a single floor level. In particular, ventilation rates obtained in rooms, corridors and stairwells in the centre-zone of the 2nd floor of building B18 were examined and compared.

For both Tests D and E, SF6 was introduced into the building to reach a target concentration of about 200 ppm. As before, injection was through tubing installed into the air handling system.

Once injection had ceased, the Mk I multipoint sampling system was used to draw air samples sequentially from six points as the concentration decayed. The locations at which measurements were made are shown in Figure 4. The Leybold Heraeus Binos 200 ppm SF6 infrared analyser was connected to the Mark I system (Chapter 4) to determine tracer concentrations. Measurements were made over periods of 90 minutes for Test D and over 270 minutes for Test E. During the tests, the wind was blowing from the north-east to the south-east sector.

Figures 5 and 6 show the decay curves obtained at these locations from the two respective tests. The first data points plotted were recorded 10 minutes after the end of injection.

In each test, curves corresponding to Locations 1 to 5 were very similar though trace 1 (room) and trace 2 (extract duct) show concentration levels slightly lower than the others.

In the first test, the initial decay rates all give an approximate rate of 1.05 per hour. Near the end, the decay rates were approximately 0.85 per hour for Locations 1 to 5 and 0.63 per hour for the stairwell (Location 6). It should be noted that the traces flatten out at the end of the test, after 90 minutes, when the air handling unit was switched off.

The initial decay rates for the the second test were not easily visible on the longer timescale plot. For this reason, additional data points on traces 1 and 4 have been plotted in Figure 6.b. The initial decay rates for traces 1 and 2 were near to a value of 1.2 per hour whilst for the remaining locations the rate is nearer 0.9 per hour. The final rates were 0.85 per hour for Locations 1 to 5 and 0.57 per hour for Location 6.

3.5. Discussion

From all these tests, and made at various locations within the building, two interesting features emerge from the decay curves:

- There are two parts to a decay profile; an initial 'transition' region and a final 'dominant' region.
- In the 'dominant' region, the decay rate tends towards a constant value.

It is very encouraging to note the emergence of the dominant region as predicted in Section 2. As stated in that Section, the decay rate measured in this region of the curve is equivalent to the dominant eigenvalue.

It was also said that the dominant decay rate in a multicell building would reflect the overall ventilation rate of the building. The dominant rate measured during Test C was 1.1 per hour whilst for Tests A, B, D and E the rates all lie within 0.80 to 0.85 per hour. These values compare favourably with the rates 0.83 to 0.90 per hour evaluated using the 'constant injection' technique (Section 5.3 of Chapter 5).

4. FIELD MEASUREMENTS WITH BUILDING NATURALLY VENTILATED

4.1. Introduction

The understanding gained in terms of the theoretical two-cell model representation (Section 2), and the general success of the field measurements carried out with the building mechanically ventilated, indicate a favourable basis from which to extend investigations to the case of natural ventilation.

In this Section, two major series of tests involving tracer decay measurements are described. The first series of tests (Table 2) were carried out without draughtstripping the windows in building B18. The second series of measurements (Table 1) were carried out with the windows draughtstripped as were the measurements described in Section 3 above and in Chapter 5 earlier.

The first series (Table 2) of measurements, carried out without draughtstripping the windows, consists of 20 tests designed to measure the overall infiltration rate of the building for a wide range of external weather conditions. Though not directly related to the line of argument pursued in this Chapter, the results reported here have relevance to the later Chapter dealing with the effect of retrofit measures on the energy consumption of this building (Chapter 8). For the sake of completeness, these measurements are discussed in this Chapter in Section 4.2.

The second series (Table 1) of measurements, with the building naturally ventilated and numbering in all seven tests (denoted by the letters F, G, ..., M but excluding the letter I), are described in the remainder of the Section. These tests were carried out with all the windows draughtstripped as were all other measurements (excluding the specific series of tests tabulated in Table 2) relating to building B18 described elsewhere in this Report.

Subsection 4.3. describes Tests F and G carried out with the whole building initially seeded with the tracer with measurement periods of seven and four hours respectively.

In Tests H, J and K (Subsection 4.4.), the seeded region is reduced to the centre-zone of the second floor. Tests H and K are essentially the same but with different tracers and slightly different seeding technique. During these two tests, all internal doors within the seeded region were kept closed. To determine the influence of open doors, and hence localised enhanced mixing, Test J was carried out.

Tests L and M, described in Subsection 4.5., were designed to determine the effect of reducing the seeding region still further down to room level. These two were also dual tracer gas experiments with the second tracer seeded in the corridor area of the second-floor centre-zone region.

In the second series of tests (Table 1) all measurements were localised to the centre-zone of the second floor.

4.2. Overall infiltration rate in building with non-draughtstripped windows.

Twenty overall infiltration tests were carried out over a period of one month during the summer. In all these tests, the following experimental arrangements were maintained:

- All windows and external doors closed.
- All inlet/exhaust openings of the air handling unit blanked off.
- All internal doors, including 'fire' doors, kept opened.
- Air handling unit on full recirculation during the tests.
- Warm air heating system switched off.

Using nylon tubing, the tracer gas, SF6, was injected into the main supply duct of the ventilation system located on the roof of the building. The fans of the AHU, on full recirculation, were used to initially disperse the gas throughout the building and then, subsequently, to keep the tracer well mixed with the internal air.

During the measurement periods, the tracer was sampled through a nylon tube inserted into the main extract duct of the ventilation system. The gas concentration was measured with a portable Analytical Instrument gas chromatograph coupled to an electron-capture detector. Wind speed and direction during the tests were monitored at a height of 10 m in an open, i.e. unsheltered, location within BRE.

The measured overall infiltration rates are tabulated in Table 2 together with weather conditions corresponding to the measurement periods. It can be seen that, during most of the tests, the average hourly wind speed was between 2 to 4 m/s with the winds blowing mainly from the south-west. The majority of the infiltration rates lie within 0.35 to 0.55 air changes per hour.

4.3. Measurements with whole building seeded

With the air handling unit switched on, the SF6 tracer gas was injected directly into the supply duct so as to disperse the tracer throughout the whole building. The mechanical ventilation system was then switched off once the target concentration was reached within the building. This was set at 30 ppm and 150 ppm for the Tests F and G respectively.

For both tests, tracer gas concentration was measured at six locations on the second floor level. Sampling locations for Tests G and F are given in Figures 4 and 7 respectively. Air samples were taken using the Mk I system in conjunction with the Leybold Heraeus infrared analyser. The measurement periods ranged from over seven hours for Test F to over four hours for Test G.

Concentration profiles over the first three hours of Test F shows (Fig 8) two distinct groupings. The room, west corridor and west stairwell form one group and the room ventilation duct together with the two locations (midpoint and outside the room along the corridor form the other. Two decay rates of 0.18 and 0.26 per hour were respectively measured over the linear portion of the semilog plot for these two groups. Also, a manifolded sample of all lines showed a decay rate of 0.18 per hour over this seven hour period.

The semilog plot (Fig 9) for Test G showing the concentration profiles for the first six hours of the test indicates that after about 80 minutes, the decay rates at all locations are close to 0.23 (+ 0.02) per hour with two exceptions. First, the measurements in the west corridor (trace 4) becomes unsettled after 160 minutes. The cause of this is unknown. The second is the slower decay rate of 0.17 per hour observed in room 214 (trace 2) after 200 minutes.

From these tests, two tentative but important observations can be made:

- The steady decay rates, measured over the time constant of the experiment, are similar to each other and suggests a degree of grouping of regions, or cells, which have similar ventilation characteristics. These may be taken together to form a zone which can lead to a simplification of the sampling procedure, and perhaps also, of the seeding procedure.
- The concentration curves tend towards a constant decay rate in the long term as postulated in Section 2.

4.4. Measurements with only the centre-zone of the second floor seeded

The aim of Tests H, J and K, was to determine the influence on tracer gas decay measurements when only a limited region of the building is seeded. The intention was to exploit the possibility that measurements carried out in seeded zones may reflect the overall ventilation characteristics of a partly seeded building. In addition, the effect of open or closed doors within the measuring region on the measured values were also to be assessed.

In all these three tests, only the centre-zone region in the second floor was seeded with the tracer. Seeding was by either of two methods; manually by injecting neat tracer directly from a cylinder or by bursting balloons inflated with the tracer to a calculated diameter. These experimental arrangements as well as the position of internal doors can be summarised as;

Test	Tracer	Target (ppm)	Seeding procedure	Position of internal doors
H	SF6	200	Manual	closed
J	SF6	200	Manual	open
K	N20	200	Balloon	closed

N20 was used in Test K because a parallel test, Test G, using SF6 as the tracer was also being carried out (Section 4.3.). It was intended that the dominant decay rates from these two tests could be compared to determine any variation caused by single zone seeding as opposed to whole building seeding.

During Test K, the east and west zone corridors of the second floor were also, inadvertantly, seeded with the tracer. The seeding strategy of Test K is therefore not exactly similar to that of Test H.

The Mk I system was used to measure the concentration of the tracers, at six points, as it decayed. The locations of the sampling points for Tests H and J are shown in Figure 10. Locations (Fig 7) for Test K were similar except for the substitution of a further 'room' point for a 'corridor' point. Note that in all these tests, Location No. 4 was outside the intended zone of seeding.

Measured concentration profiles for the Tests H and K, carried out with the internal doors closed, are shown in Figures 11 and 12 respectively. All profiles show that a steady decay region has been established.

For Test H, and ignoring Location No. 4, the decay rates range between 0.45 to 0.67 per hour whilst in Test K, the rates ranged from 0.25 to 0.37 per hour. The lower infiltration rates in Test K, compared with those of Test H, is possibly caused by the inadvertant seeding of a larger portion of the building. The rates from Test K compare favourably with the rate of 0.23 per hour obtained from the parallel whole building seeding Test G (Section 4.1.).

The spread of decay rates within a test is reduced when the room doors in the centre-zone were opened. The profiles (Fig 13) for Test J show that the decay rates are now contained within 0.31 and 0.40 per hour. Furthermore, these values dominate well within an hour of the start of the test.

These observations are in contrast to those in Tests H and K and suggest that opening the doors enhances the air movement and, in turn, increases the mixing of air and tracer within the zone.

4.5. Dual tracer measurements with rooms seeded

This Section consists of two tests, L and M, in which individual rooms in the centre-zone of the second floor were seeded with SF6 to target concentrations of 200 ppm. In Test L, only one room was seeded whilst in Test M, six out of the 14 available rooms were seeded. Seeding six rooms instead of one allowed measurable levels of SF6 tracer into the corridor.

In both these tests, the corridor outside all the 14 rooms was seeded with N2O to a target concentration of 200 ppm using balloons (Section 4.4.). All internal doors were kept closed during these tests.

The measuring points for Test L are shown in Figure 10. Sampling point No. 1 was located in the seeded room. Measurement locations for Test M are shown in Figure 7 with sampling points 1, 3 and 5 located within three of the seeded rooms, sampling point No. 2 placed in an unseeded room. Measurements were carried out using the Mk I system coupled to a Leybold Heraeus dual channel (200 ppm SF6/N2O) analyser.

In Test L, with the single seeded room, SF6 concentration in that room show (Fig 14) a steady decay rate of 0.56 per hour throughout the entire three and a half hour measuring period. The SF6 levels in all other locations were too low to be reliably detected. The decay rate of N2O (Fig 15) at the two corridor locations is 0.42 per hour.

With six rooms seeded in Test M, both tracers are measurable at all locations. For SF6, a decay in concentration is observed (Fig 16) in the seeded rooms and a build-up followed by decay in the non-seeded regions. With the exception of the unseeded room (Location No. 2), decay rates between 0.45 and 0.62 per hour are observed after approximately two hours into the test.

The N2O concentration profiles (Fig 17) for Test M show a rapid initial fall in the initially seeded corridor at Location No. 6. This is then followed by a more gradual decay. In the non-seeded regions, however, a gradual build-up followed by decay is observed. It is not possible to explain the rapid exhaustion at Location No. 3.

After approximately two hours, steady decay rates begin to emerge. Excluding the 'anomalous' trace from No. 3, these rates range from 0.41 to 0.57 per hour. The spread and distribution of values is similar to that for the SF6 measurements.

4.6. Discussion

Various conclusions can be arrived at from these measurements carried out with the building naturally ventilated. Of these, one of the most significant is that nearly all concentration profiles show the following characteristics:

- There is an initial transition period which is then followed by a steady period.
- In seeded zones, the concentration decay rate during the transition period is much faster than in the steady period.
- During the steady period, the decay rate gradually approximates to a steady value.

The changeover from the transition regime to the steady period is gradual and not distinct. The point at which this changeover period is arrived at is determined by,

- the extent to which the building has been seeded, and
- the amount of internal mixing present.

It is shown that the decay rate measured after the transition period is not constant but is always approximating towards a steady value. Given the measurement periods of about four hours for the 'part seeding' tests, the evaluated decay rates can be compared with the 'whole building' seeded tests and summarised as follows:

Seeding strategy	Test codes	Decay rates (per hour)
Whole building	F G	0.18 to 0.26 0.23
Centre zone + east and west corridors	K	0.25 to 0.37
Centre zone (doors closed)	H	0.45 to 0.67
" (doors opened)	J	0.30 to 0.40
Corridor (in centre zone)	L M	0.42 0.41 to 0.57
Six rooms (in centre zone)	M	0.45 to 0.62
One room (in centre zone)	L	0.56

These results show that the decay rates, obtained from the best fit to the linear part of the semilog plots, increases as less of the building is seeded.

The most likely explaination could be that, within the time constant of the experiment, the higher decay rates obtained with the building partially seeded have not yet reached the dominant state.

How soon and to how near the decay rate approximates towards the overall infiltration rate seems to thus depend on,

- the extent of seeding, and
- the internal mixing.

Further work is therefore required, either through field measurements or multicell computer simulation, to investigate these questions.

5. LOCAL VENTILATION RATE

5.1. Introduction

Apart from decay rates, there is another useful indicator of ventilation rate which can be computed from local measurements. This is a parameter which is based on the air movements associated with that space. This value is the 'mean residence time' or 'mean age' of a 'parcel' of air at a point. The reciprocal of this time constant is called the 'local ventilation rate'.

Sandberg [1] showed that, if a tracer is initially uniformly distributed throughout a space, the local ventilation rate can be computed from measurements of the dilution (i.e. decay) of the tracer at a point. If the tracer is not initially uniformly distributed, a different local ventilation rate (characterising that particular tracer distribution) is obtained.

The local ventilation rate r can be used directly to predict the steady local concentration of a contaminant which would result from sources distributed throughout the space. This is true provided the production rates from the sources mirror exactly the distribution of initial concentration used in measuring the local rate.

In practical terms, the local ventilation rate can be computed from decay curves by evaluating the time integral A of the curve from an initial concentration C(0) to zero concentration. Since the concentration does not usually fall to zero during the finite measuring time, a truncation error has to be estimated. To evaluate this error, it is necessary to carry on measuring until there is a steady exponential decay. The final concentration, divided by this decay rate, gives the truncation error.

Local ventilation and local infiltration rates were determined for three series of tests:

- Building mechanically ventilated; whole building seeded; localised sampling in second floor centre-zone (Test E).

- Building naturally ventilated; whole building seeded; localised sampling in second-floor centre-zone (Tests F and G).

- Building naturally ventilated; second-floor centre-zone seeded; localised sampling in second-floor centre-zone (Tests H, K and J).

For all these tests, the local infiltration rates were evaluated by integrating the areas underneath the appropriate concentration profiles. As a check on these, the rates were also calculated for all tests, excepting E and F, by measuring tracer samples captured in Tedlar sampling bags (Chapter 8). For each of the relevant tests, two sampling bags were taken. One was filled with a 'spot' sample taken at the beginning of the measurement period whilst the other was slowly but continuously filled throughout the test to give an 'averaged' sample.

5.2. Measurements in mechanically ventilated building

The experimental conditions for Test E have been described in Section 2.3. Table 3 lists the evaluated local ventilation rates together with the decay rates. On the whole they compare within 10% of each other.

An exception is the location on the west stairway which is not directly ventilated by the mechanical ventilation system. At this point (Location No. 6) both rates are consistently lower than those at the other locations.

5.3. Measurements in naturally ventilated building with whole building seeded

The experimental arrangements for Tests F and G are given in Section 4.3. Bag samples, as described earlier, were taken for Test G at four locations.

The local infiltration rates, together with the decay rates, are tabulated in Tables 4 and 5 for Tests F and G respectively. Good correspondence between the decay rates and local rates can be seen.

5.4. Measurements in naturally ventilated building with only the second-floor centre-zone area seeded

Section 4.4. describes the experimental arrangements for Tests H, J and K. In all these tests, 'averaging' bag samples were also taken at various locations (Section 4.4). The evaluated local infiltration rates are tabulated in Tables 6, 7 and 8 for the respective tests.

In Tests H and K, when all doors were kept closed, the decay rates in the rooms are similar to the corresponding local rates. In the corridor, however, the local rates are significantly higher than the decay rates.

When the room doors were opened, as in Test J, there were no significant differences between decay rates and local rates at any of the measuring points.

The results from Test K can be compared with those from the whole building seeding Test G which was carried out in parallel (Section 5.3). Comparing Tables 5 and 8, it can be seen that the local rates are higher when the building was partly seeded. This is as expected since the local rates reflect the dilution of a contaminated region by uncontaminated 'fresh' air.

5.5. Discussion

A consequence of the definition of the local infiltration rates is that these values reflect the rate at which uncontaminated 'fresh' air arrives at sampling locations. The field measurements show that these local rates correspond closely to the decay rates measured provided there is adequate internal mixing.

There was also good comparison between the local rates evaluated from 'averaged' bag samples with those determined by area integration of the concentration profiles. This was taken as a good test of the integrity of 'averaged' bag sampling.

6. GENERAL DISCUSSION AND CONCLUSIONS

In this Chapter, we have considered the possibility of a simplified technique which could enable the infiltration rates of large and complex buildings to be determined. The technique, if successful, would bypass difficulties such as,

- local variations in infiltration,
- imperfect internal mixing of the air, and
- practical difficulties in distributing (i.e. seeding) the tracer gas and subsequently obtaining air samples.

The basis of the technique is to partly seed the building with a single tracer without having to resort to complete and uniform dispersion throughout the building. The tracer is then allowed to decay and concentration measurements taken at suitable locations within the building. The objective of the simplified technique is to determine the whole building infiltration rate from these measurements.

In Section 2, a theoretical foundation was laid by looking at the decay of a tracer initially dispersed within a two-cell model representation of a building. The eigenvalue solution showed that one of the two eigenvalues will dominate after a sufficiently long period of decay. The decay rate then measured would reflect the value of this dominant eigenvalue.

It was then shown that, under certain conditions, the dominant decay rate will correspond closely to the overall infiltration rate. It was stated that the conditions, which were rather restrictive for the two-cell model, would be relaxed in multicelled buildings.

A large number of field measurements were carried out in an office building so to develop an understanding of this technique as applied to complex buildings. Measurements included those with a mechanical ventilation system on and those in which the building was naturally ventilated. Seeding strategies ranged from those where the whole building was seeded to those where only certain localised regions were seeded.

From these field measurements, the following conclusions could be drawn:

- All concentration profiles, in a seeded region, exhibit two distinct regions of decay. The two regions are separated by a transition phase.
- The initial region has a high decay rate. Decay rate measurements, carried out during this period, do not reflect the infiltration rate either at that point or of the whole building.

- As internal mixing is enhanced and more zones of the building are seeded, the transition phase is arrived at sooner and the decay rate tends towards the overall infiltration rate during the measurement period.

As regards the simplified decay technique, these measurements show that, in practical terms, the experimental procedure is helped by

- seeding as much of the building as possible, and

- keeping internal doors open.

Further work, both theoretical as well as experimental, is required before the simplified technique can be used in the most optimum manner. The theoretical aspect is considered in the next Chapter. Further field work has started but cannot be discussed in this Report because this new work extends outside the present period of reporting.

This Chapter also discussed the concept of local infiltration rates and carried out some measurements of these rates. From these, it was concluded that;

- local infiltration rates mirror uncontaminated 'fresh' air arriving at the sampling locations, and

- these values correspond closely to the decay rates provided there is adequate internal mixing.

REFERENCES

1. Sandberg, M, What is ventilation efficiency?, Building and Environment, Vol 16(2), pp 123-135, (1981).

TABLES

FIGURES

Test code	Test date	Tracer	Target conc. (ppm)	Injection method	Sampling method	Duration of test (mins.)	State of internal doors	Temperature (°C) int.	Temperature (°C) ext.	Wind speed (m/s)	Wind dirn. (deg.)
MECHANICAL VENTILATION TESTS											
Whole building seeded - measurements at main 'extract' duct.											
A	06/12/83	SF_6	200	A	A	70	as occupied	20	3.0	1.8	345
B	08/12/83	SF_6	200	A	A	150	as occupied	20	9.3	5.0	220
Whole building seeded - measurements at floor levels.											
C	02/12/83	Freon 1381	50	B	B		as occupied	20	7.0	2.2	130
Whole building seeded - Localised measurements in 2nd floor centre zone.											
D	26/01/84	SF_6	200	A	C	90	2nd floor doors closed	20	7.0	3.5	160
E	27/01/84	SF_6	200	A	C	270	2nd floor doors closed	20	6.0	4.6*	035*
NATURAL VENTILATION TESTS											
Whole building seeded - Localised measurements in 2nd floor - centre zone.											
F	26/01/84	SF_6	31	A	C	420	2nd floor doors closed	18	5.5	3.3 - 4.1	[illegible]
G	29/04/84	SF_6	150	A	C	240	2nd floor doors closed	(18)	9.0*	6.2 - 4.1*	080*
Single zone seeding - Localised measurement.											
H	07/03/84	SF_6	200	C	C	270	2nd floor doors closed	(20)	7.0 - 2.7*	5.6 - 3.0*	030*
J	12/03/84	SF_6	200	C	C	240	2nd floor doors open	20	4.0*	3.3*	040*
K	29/04/84	N_2O	200	D	C	240	2nd floor doors closed	(18)	9.0*	6.2 - 4.1*	080*
Individual cells seeded - Dual tracer gases - Localised measurements											
L	08/03/84	SF_6 N_2O	200 200	C (1 room) D	D	240	all doors closed	(20)	4.0*	3.6*	035*
M	29/04/84	SF_6 N_2O	200 200	C (5 rooms) D	E	240	all doors closed	(18)	13.5*	7.5*	[illegible]

Injection methods

A) Injection into main duct of air handling unit.

B) Injection into ductwork using installed tubing.

C) Manual injection.

D) Injection using balloons.

Sampling methods

A) Leybold Heraeus analyser sampling from main 'return' duct.

B) Mk II System, manifolded samples from each floor level.

C) Mk I System, various locations in 2nd floor.

D) 3 points in seeded room, 2 points in seeded corridor, 1 point in 2nd floor corridor of unseeded West wing.

E) 3 points in 3 of the seeded rooms, one in an unseeded room 2nd floor West wing corridor.

Table 1 Test details with windows draughtstripped.

Test date	Test no.	Duration of test (mins)	R (ach.)	Wind		External temperature (C)	R/U
				speed (m/s)	dirn. (deg.)		
18/05/81	5a	33	0.57	3.3	180	12.1	0.17
18/05/81	5b	51	0.56	2.7	180	12.2	0.21
19/05/81	6a	117	0.32	1.9	180	12.9	0.17
19/05/81	6b	75	0.83	2.5	180	14.8	0.33
19/05/81	7	60	0.40	2.0	220	15.2	0.20
23/05/81	8	60	0.52	3.6	200	11.4	0.14
23/05/81	10	50	0.25	4.3	200	13.3	0.06
24/05/81	11	60	0.36	3.3	220	11.5	0.11
24/05/81	14	60	0.44	3.1	220	13.0	0.14
25/05/81	15	60	0.54	3.2	205	8.4	0.17
25/05/81	18	60	0.42	2.9	230	9.3	0.14
26/05/81	19	60	0.42	2.0	220	11.9	0.21
26/05/81	22	60	0.85	2.6	190	14.3	0.33
02/06/81	25	60	0.42	3.8	240	16.7	0.11
03/06/81	28	60	0.35	3.2	225	16.5	0.11
04/06/81	33	60	0.43	5.6	225	14.3	0.08
05/06/81	34	60	0.39	4.3	260	12.8	0.09
10/06/81	37	60	0.52	3.7	240	12.7	0.14
11/06/81	40	60	0.47	3.3	210	12.8	0.14
12/06/81	43	60	0.41	2.3	050	12.4	0.18

Table 2 Test details with windows not draughtstripped.

			Duct			West	West	
		Rm208 #1	Rm208 #2	c'dor #3	c'dor #4	c'dor #5	stairs #6	units
Final concentration	C_τ	11.2	11.9	13.2	12.7	13.2	16.2	ppm
Decay rate	λ	0.86	0.86	0.86	0.86	0.86	0.57	h^{-1}
Truncation error	$T = 60.C_\tau/\lambda$	781	830	921	886	921	1705	min x ppm
Time integral	$A = \sum_i^\tau \delta A_i$	5872	6009	6449	6477	6572	5957	min x ppm
Initial concentration	C_0	107	120	104	107	110	98.4	ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$	0.96	1.05	0.85	0.87	0.88	0.77	h^{-1}
		Measurement error estimates						
	ΔT	80	80	90	90	90	170	+/- min x ppm
	ΔA	378	388	374	378	381	369	+/- min x ppm
	Δr_j	0.08	0.08	0.05	0.06	0.06	0.06	+/- h^{-1}
		Bag sample analyses						
		Not applicable						
Average concentration	$\bar{C}$							ppm
Time integral	$A = \bar{C}.\tau$							min x ppm
Initial concentration	C_0							ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$							h^{-1}

Table 3 Results from Test E

		duct				west	west	
		rm208	rm208	c'dor	c'dor	c'dor	stairs	
		#1	#2	#3	#4	#5	#6	units
Final concentration	C_τ	22.6	17.5	16.2	17.4	21.3	21.4	ppm
Decay rate	λ	0.18	0.26	0.26	0.26	0.18	0.18	h^{-1}
Truncation error	$T= 60.C_\tau/\lambda$	7533	4038	3738	4015	7100	7133	min x ppm
Time integral	$A=\sum_i^\tau \delta A_i$	4360	3787	3560	3702	4181	4206	min x ppm
Initial concentration	C_0	31.3	31.4	28.6	29.2	30.5	32.9	ppm
Local ventilation rate	$r_j= 60.C_0/(A+T)$	0.15	0.24	0.23	0.22	0.16	0.17	h^{-1}
		Measurement error estimates						
	ΔT	750	400	370	400	710	710	+/- min x ppm
	ΔA	323	329	327	326	323	326	+/- min x ppm
	Δr_j	0.02	0.02	0.03	0.03	0.02	0.02	+/- h^{-1}
		Bag sample analyses						
Average concentration	$\bar{C}$	Not applicable						ppm
Time integral	$A= \bar{C}.\tau$							min x ppm
Initial concentration	C_0							ppm
Local ventilation rate	$r_j= 60.C_0/(A+T)$							h^{-1}

Table 4 Results from Test F

		rm208	rm214	rm213	c'dor west	rm212	c'dor	units
		#1	#2	#3	#4	#5	#6	
Final concentration	C_τ	66.6	85.8	54.4	44.2	67.6	71.8	ppm
Decay rate	λ	0.22	0.17	0.21	0.32	0.23	0.23	h^{-1}
Truncation error	$T = 60.C_\tau/\lambda$	18163	30282	15542	8287	17634	18730	min x ppm
Time integral	$A = \sum_i^\tau \delta A_i$	24155	28956	20511	19062	25695	24692	min x ppm
Initial concentration	C_0	131.6	156.0	131.0	136.0	140.0	130.8	ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$	0.19	0.16	0.22	0.30	0.19	0.18	h^{-1}
		Measurement error estimates						
	ΔT	1816	3028	1554	828	1763	1873	+/- min x ppm
	ΔA	555	559	566	584	563	546	+/- min x ppm
	Δr_j	0.02	0.02	0.02	0.02	0.02	0.02	+/- h^{-1}
		Bag sample analyses			τ_s=240 minutes			
		rm204	east c'dor	rm213	west stairs			
Average concentration	$\bar{C}$	74.2	136.6	89.6	60.0			ppm
Time integral	$A = \bar{C}.\tau_s$	17808	32784	21504	14400			min x ppm
Initial concentration	C_0	(135)	(135)	131	(135)	( ) estimate		ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$	(0.23)	(0.16)	0.21	(0.25)			h^{-1}

Table 5 Results from Test G

		west						
		rm208 #1	rm214 #2	rm213 #3	c'dor #4	c'dor #5	c'dor #6	units
Final concentration	C_τ	24.6	9.6	10.4	13.2	10.0	10.4	ppm
Decay rate	λ	0.45	0.67	0.57	-	0.45	0.45	h^{-1}
Truncation error	$T= 60.C_\tau/\lambda$	3280	859	1084	-	1333	1386	min x ppm
Time integral	$A=\sum_i^\tau \delta A_i$	20440	14982	14620	6863	11384	11837	min x ppm
Initial concentration	C_O	182	176	174	26.4	169	176	ppm
Local ventilation rate	$r_j= 60.C_O/(A+T)$	0.46	0.66	0.66	-	0.79	0.79	h^{-1}
		Measurement error estimates						
	ΔT	330	90	110	-	130	140	+/- min x ppm
	ΔA	819	835	831	588	826	842	+/- min x ppm
	Δr_j	0.03	0.03	0.04	-	0.05	0.05	+/- h^{-1}
		Bag sample analyses			τ_s=286 minutes			
		perist. pump rm208	pulse pump rm208				c'dor	
Average concentration	$\bar{C}$	71.8	88.0				47.2	ppm
Time integral	$A= \bar{C}.\tau_s$	20534	25168				13499	min x ppm
Initial concentration	C_O	187.2	187.2				188.4	ppm
Local ventilation rate	$r_j= 60.C_O/(A+T)$	0.47	(0.39)	( ) approximate - very small bag sample			0.75	h^{-1}

Table 6 Results from Test H

		rm208 #1	rm214 #2	rm213 #3	west c'dor #4	c'dor #5	c'dor #6	units
Final concentration	C_τ	55.8	36.2	41.8	20.6	54.4	46.6	ppm
Decay rate	λ	0.31	0.40	0.38	0.25	0.35	0.36	h^{-1}
Truncation error	$T= 60.C_\tau/\lambda$	10800	5430	6600	-	9325	7766	min x ppm
Time integral	$A=\sum_i^\tau \delta A_i$	26817	21126	23184	9376	28075	24319	min x ppm
Initial concentration	C_0	194.0	185.6	190.0	73.6	214.0	202.0	ppm
Local ventilation rate	$r_j= 60.C_0/(A+T)$	0.30	0.41	0.38	-	0.34	0.37	h^{-1}
		Measurement error estimates						
	ΔT	1080	540	660	-	930	780	+/- min x ppm
	ΔA	726	745	745	569	768	761	+/- min x ppm
	Δr_j	0.01	0.02	0.02	-	0.02	0.01	+/- h^{-1}
		Bag sample analyses			τ_s=271 minutes			
		rm208					c'dor	
Average concentration	$\bar{C}_s$	98.0					94.0	ppm
Time integral	$A= \bar{C}.\tau$	26558					25474	min x ppm
Initial concentration	C_0	190.0			( ) estimate		(172.0)	ppm
Local ventilation rate	$r_j= 60.C_0/(A+T)$	0.30					0.31	h^{-1}

Table 7 Results from Test J

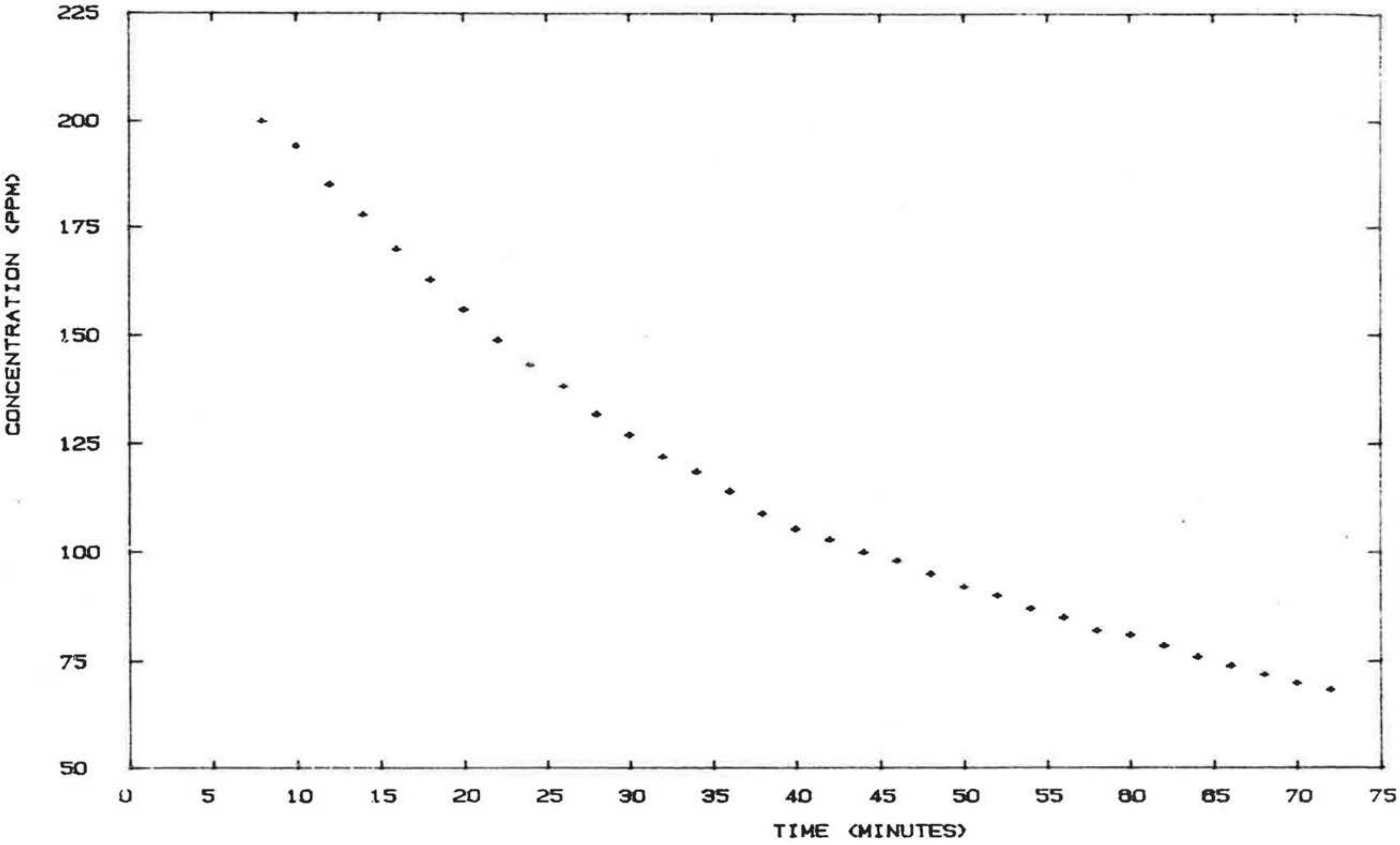


Figure 1 Concentration profile from Test A

					west			
		rm208	rm214	rm213	c'dor	rm212	c'dor	
		#1	#2	#3	#4	#5	#6	units
Final concentration	C_τ	52.6	63.2	50.0	7.8	55.6	30.2	ppm
Decay rate	λ	0.26	0.31	0.25	-	0.34	0.37	h^{-1}
Truncation error	$T= 60.C_\tau/\lambda$	12138	12232	12000	-	9811	4897	min x ppm
Time integral	$A=\sum_i^\tau \delta A_i$	19729	24197	18018	1706	23267	14516	min x ppm
Initial concentration	C_0	136.0	170.0	131.4	9.6	172.0	152.0	ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$	0.26	0.28	0.26	-	0.31	0.47	h^{-1}
		Measurement error estimates						
	ΔT	1213	1223	1200	-	981	489	+/- min x ppm
	ΔA	537	563	531	437	576	584	+/- min x ppm
	Δr_j	0.02	0.02	0.02	-	0.02	0.03	+/- h^{-1}
		Bag sample analyses			τ_B=216.25 minutes			
		rm204	east c'dor	rm213	west stairs			
Average concentration	$\bar{C}$	9.0	15.6	90.0	10.2			ppm
Time integral	$A= \bar{C}.\tau_B$	1946	3373	19462	2205			min x ppm
Initial concentration	C_0	-	-	(131.4)	-	( ) estimate		ppm
Local ventilation rate	$r_j = 60.C_0/(A+T)$	-	-	0.25	-			h^{-1}

Table 8 Results from Test K

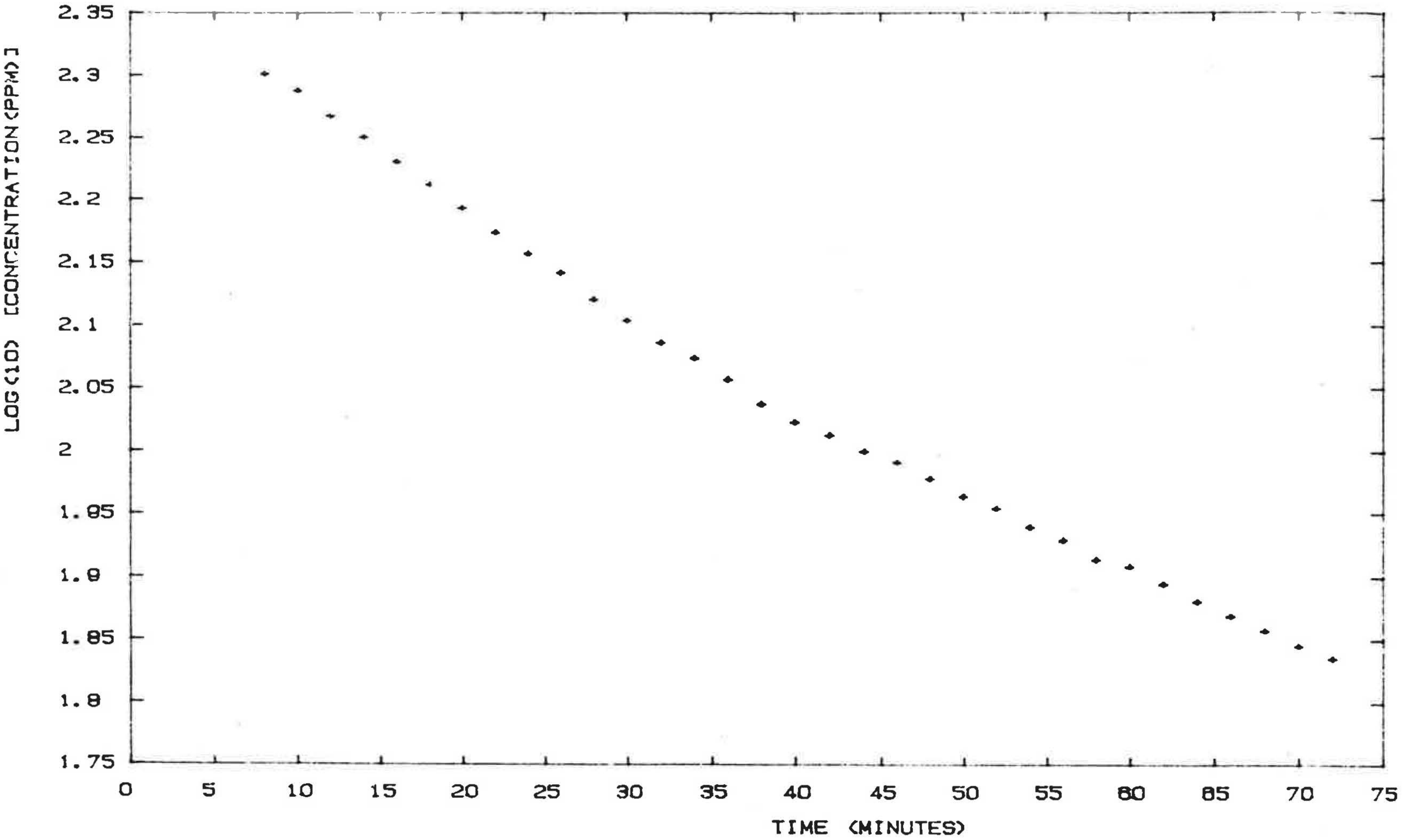


Figure 1 Continuation.

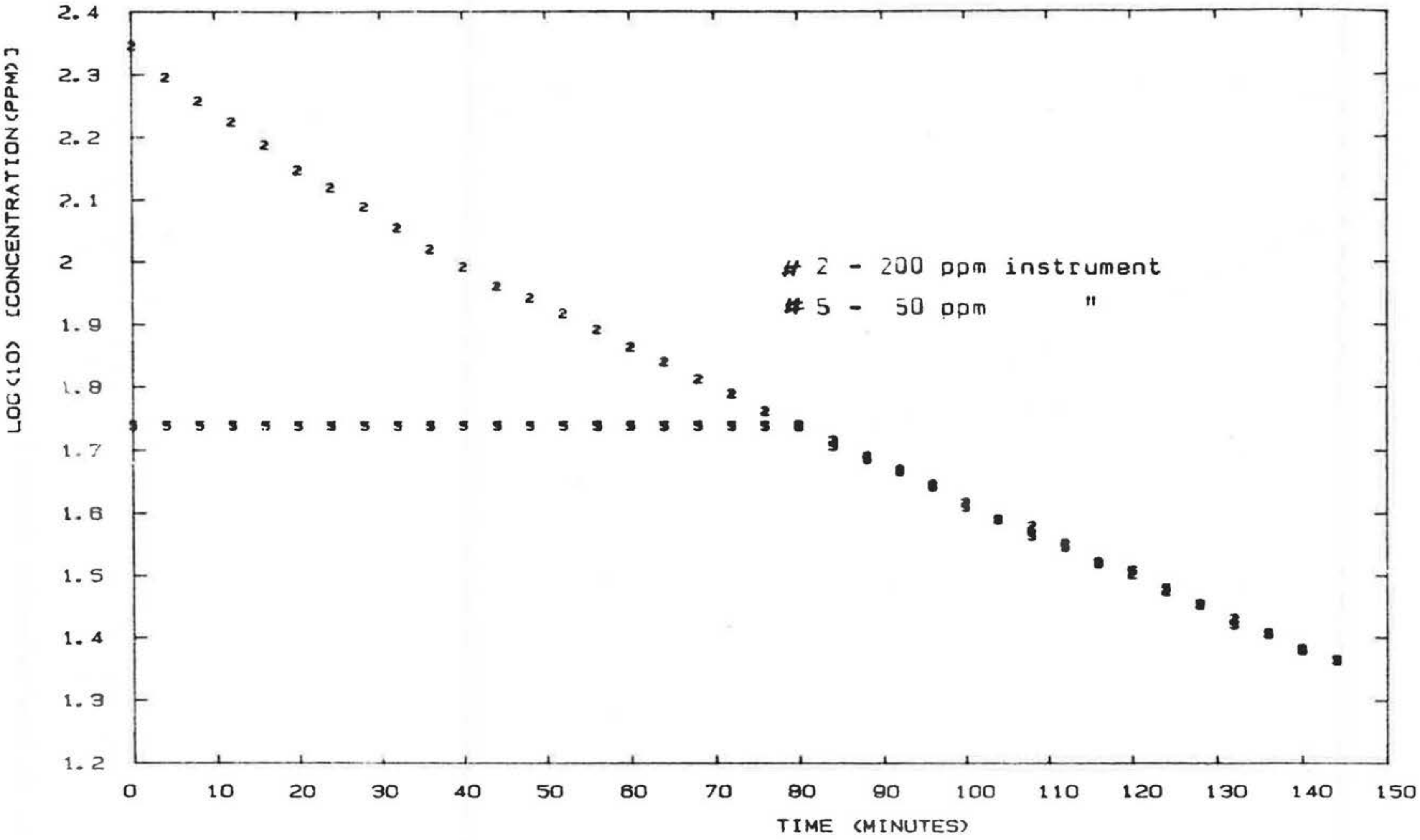


Figure 2 Concentration profiles from Test B

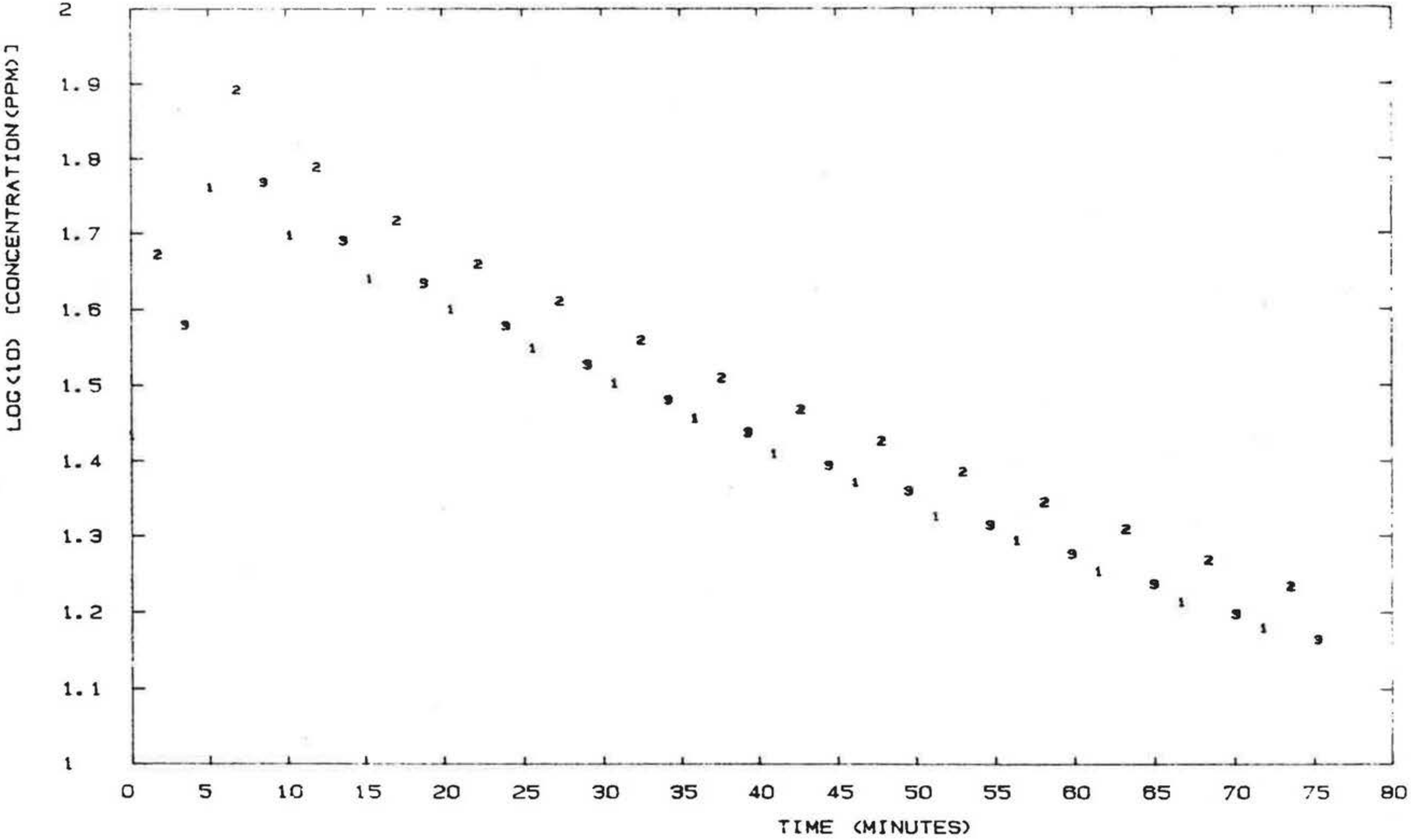


Figure 3 Concentration profiles from Test C

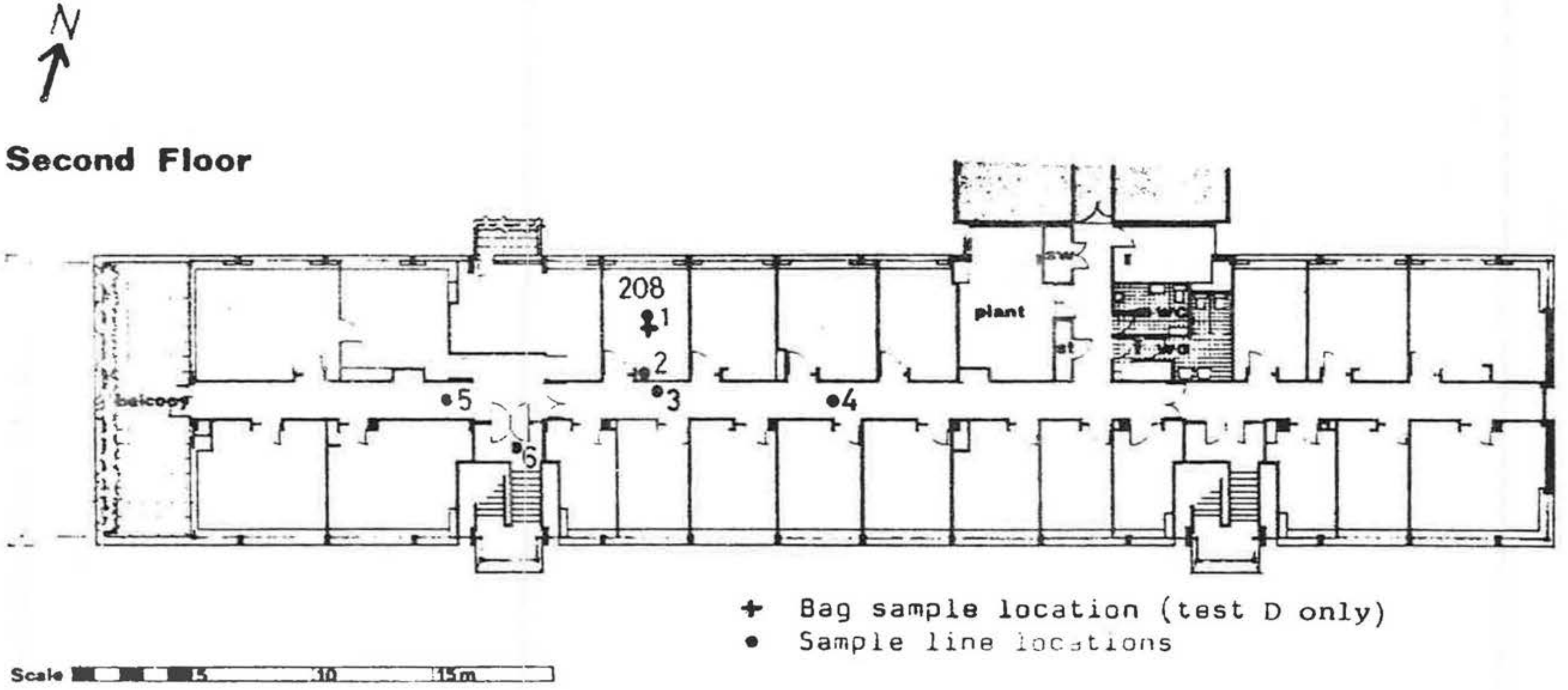


Figure 4 Locations of sampling points for Tests D, E and F

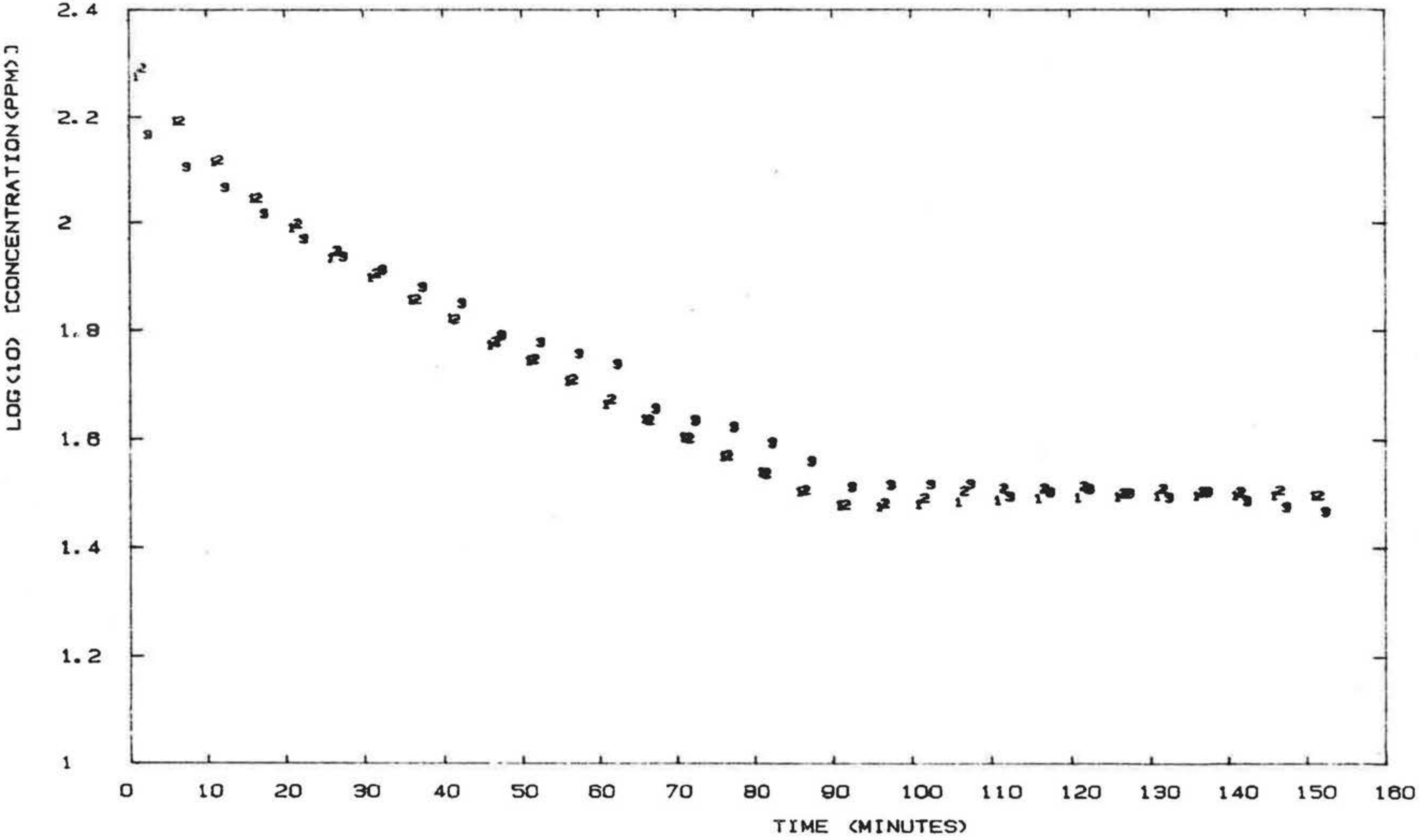


Figure 5 Concentration profiles from Test D

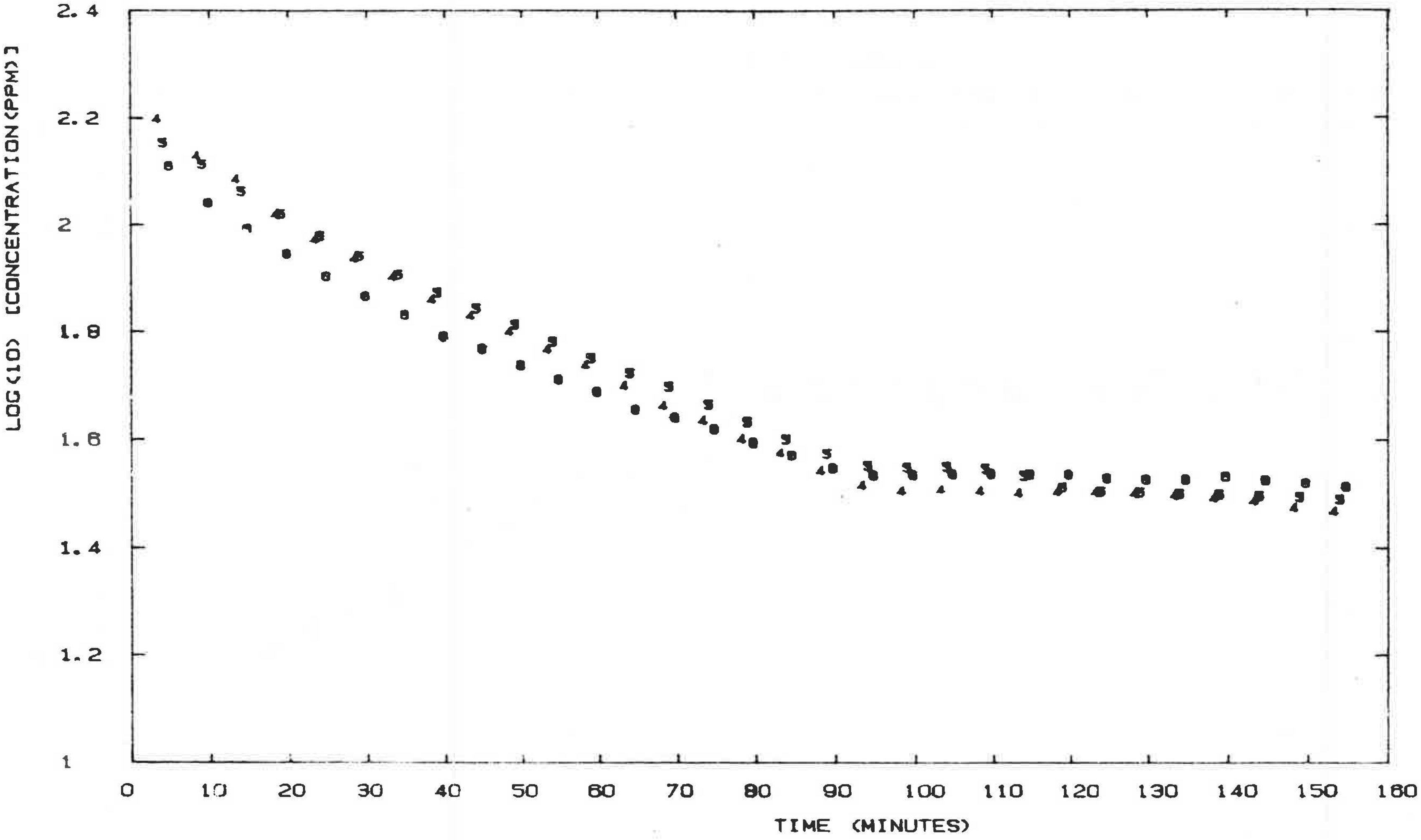


Figure 5 Continuation.

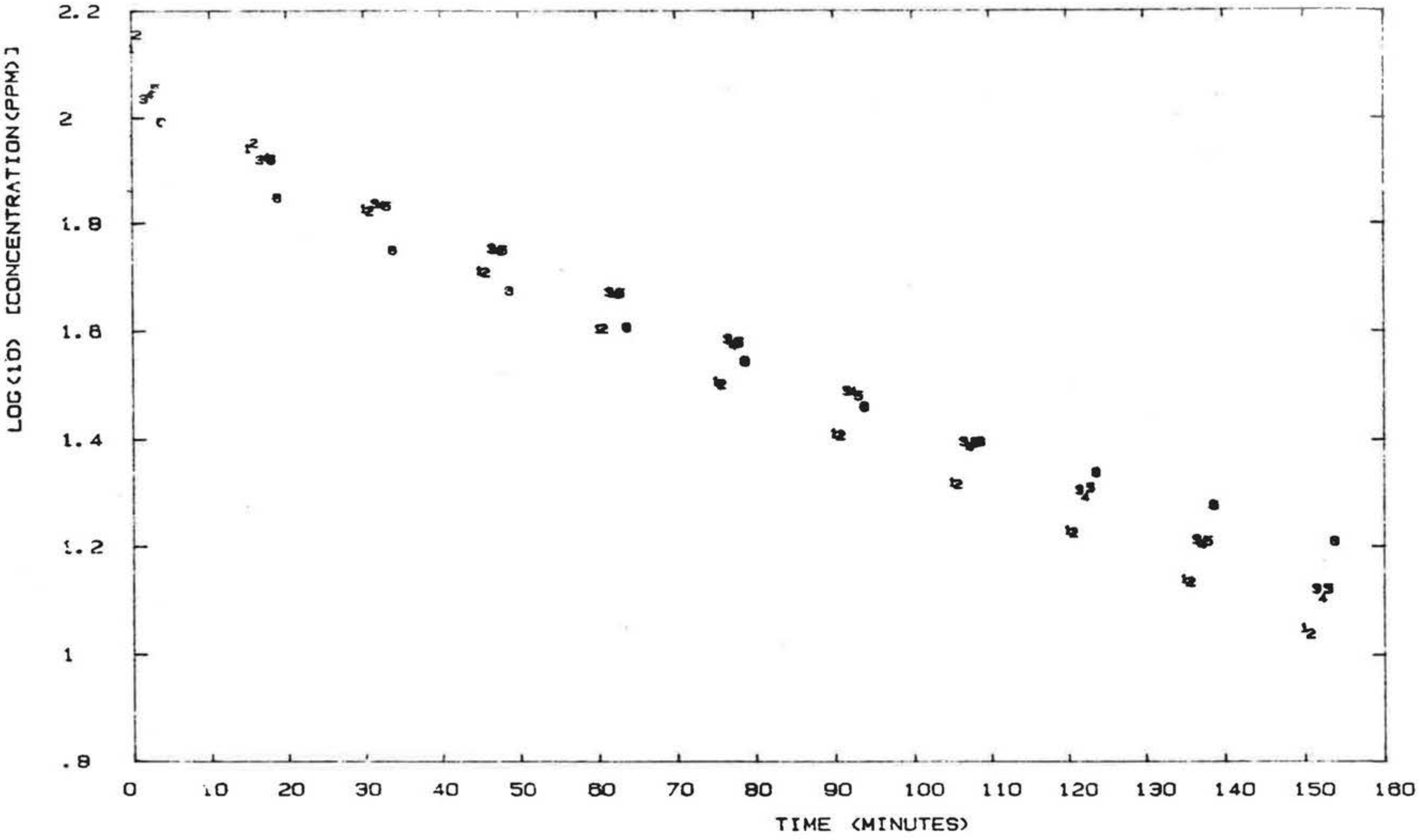


Figure 6 Concentration profiles from Test E

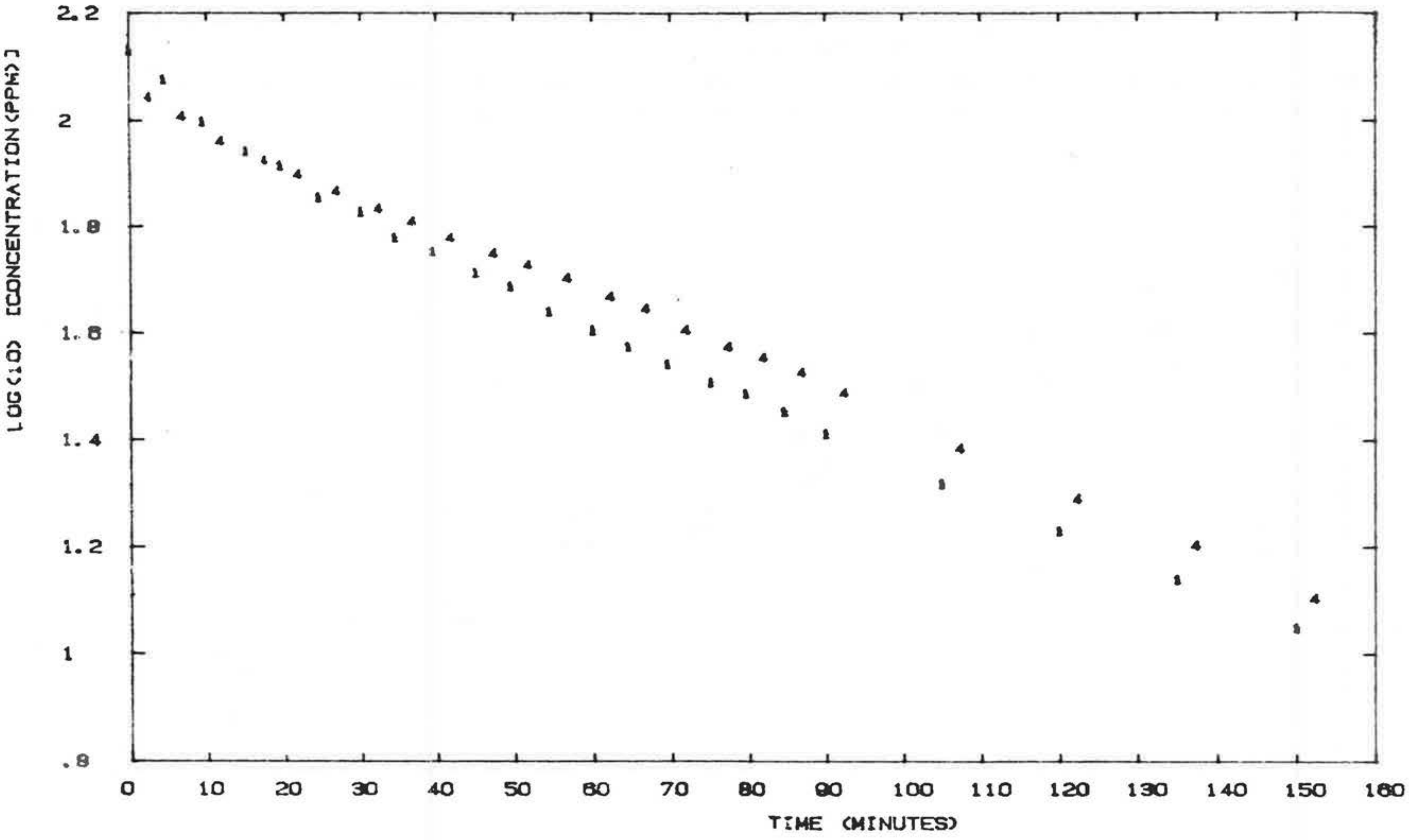
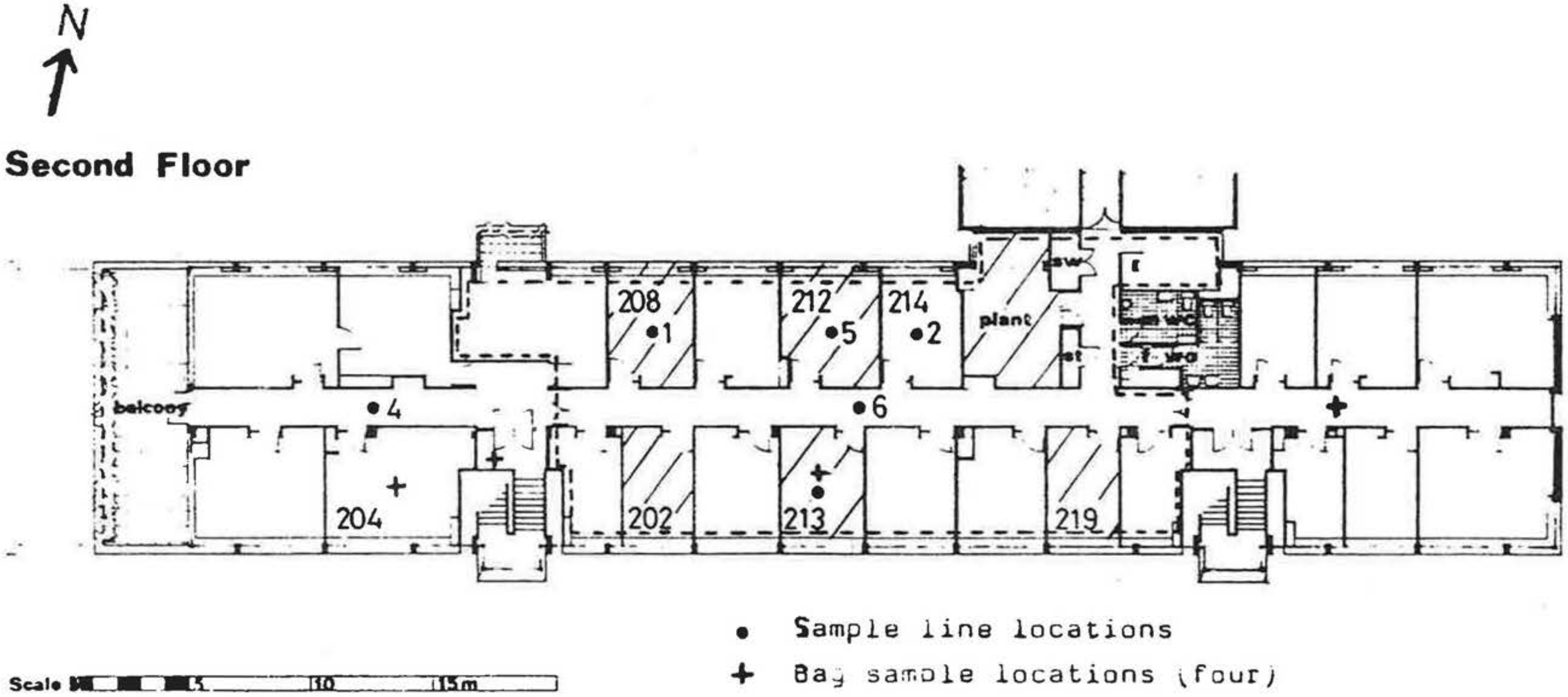


Figure 6 Continuation.



● Sample line locations

+ Bag sample locations (four)

⬚ Zone boundary

▨ Rooms seeded with SF$_6$ - test M

Figure 7 Sampling locations for Tests G, K and M

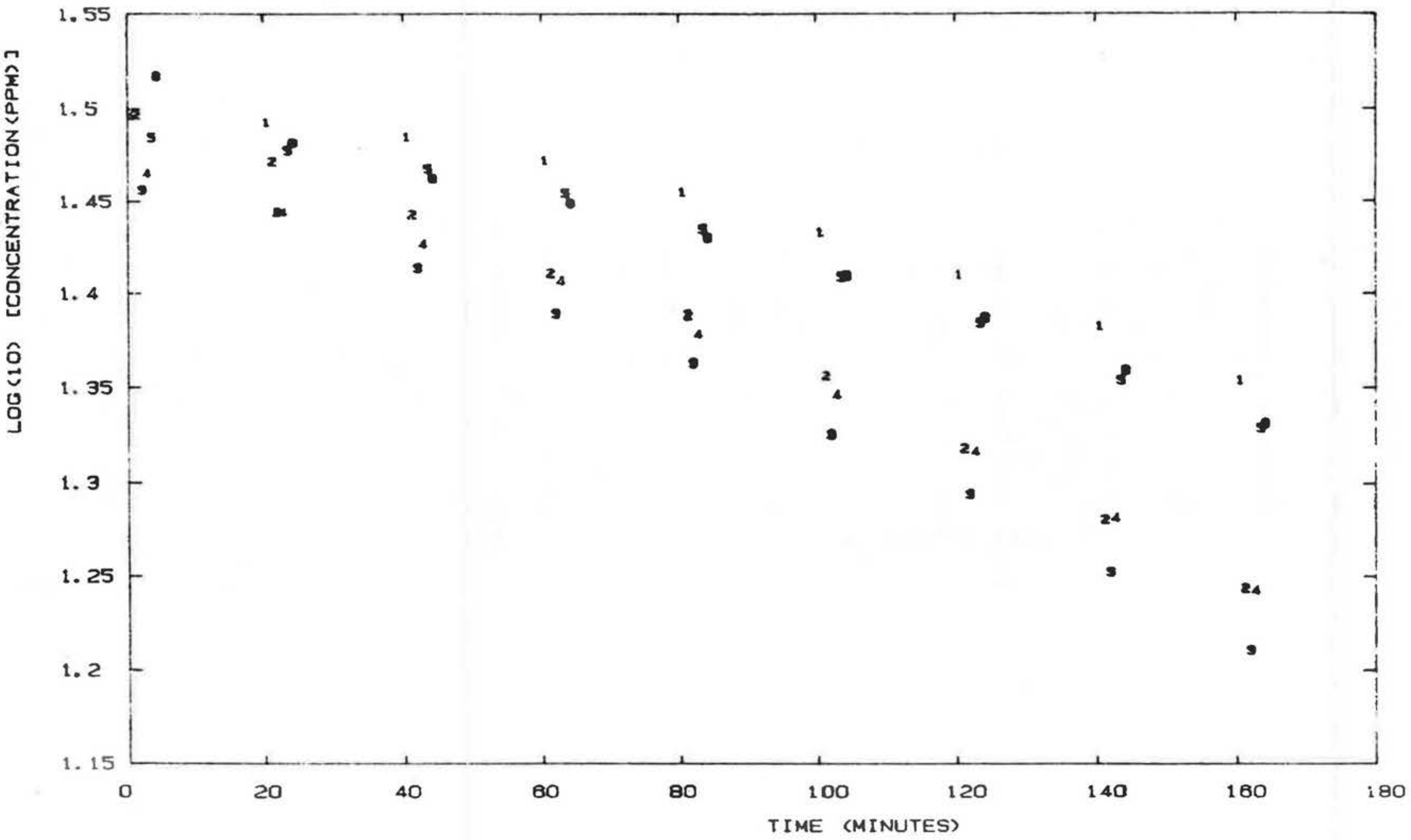


Figure 8 Concentration profiles from Test F

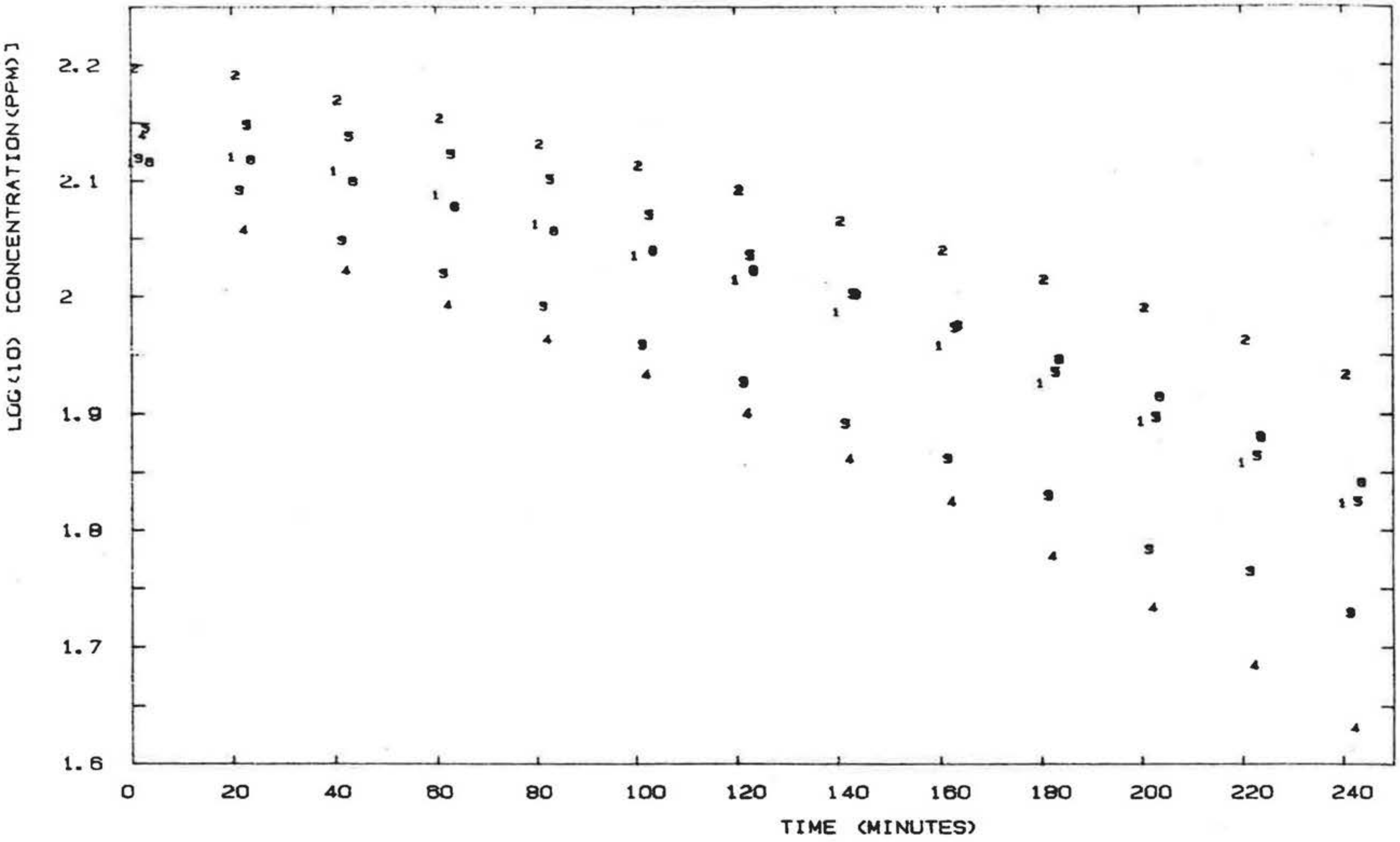


Figure 9 Concentration profiles from Test G

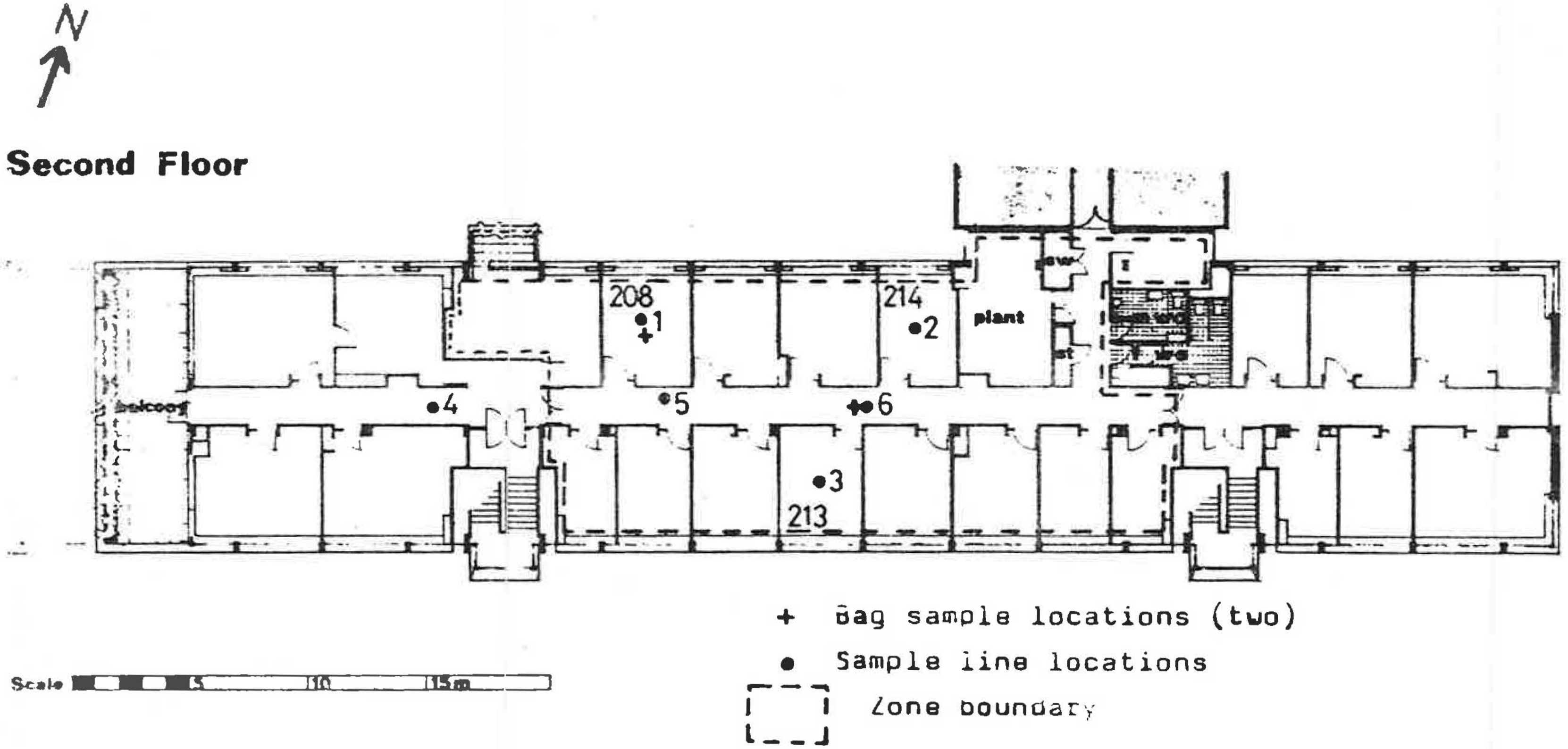


Figure 10 Sampling locations for Tests H, J and L

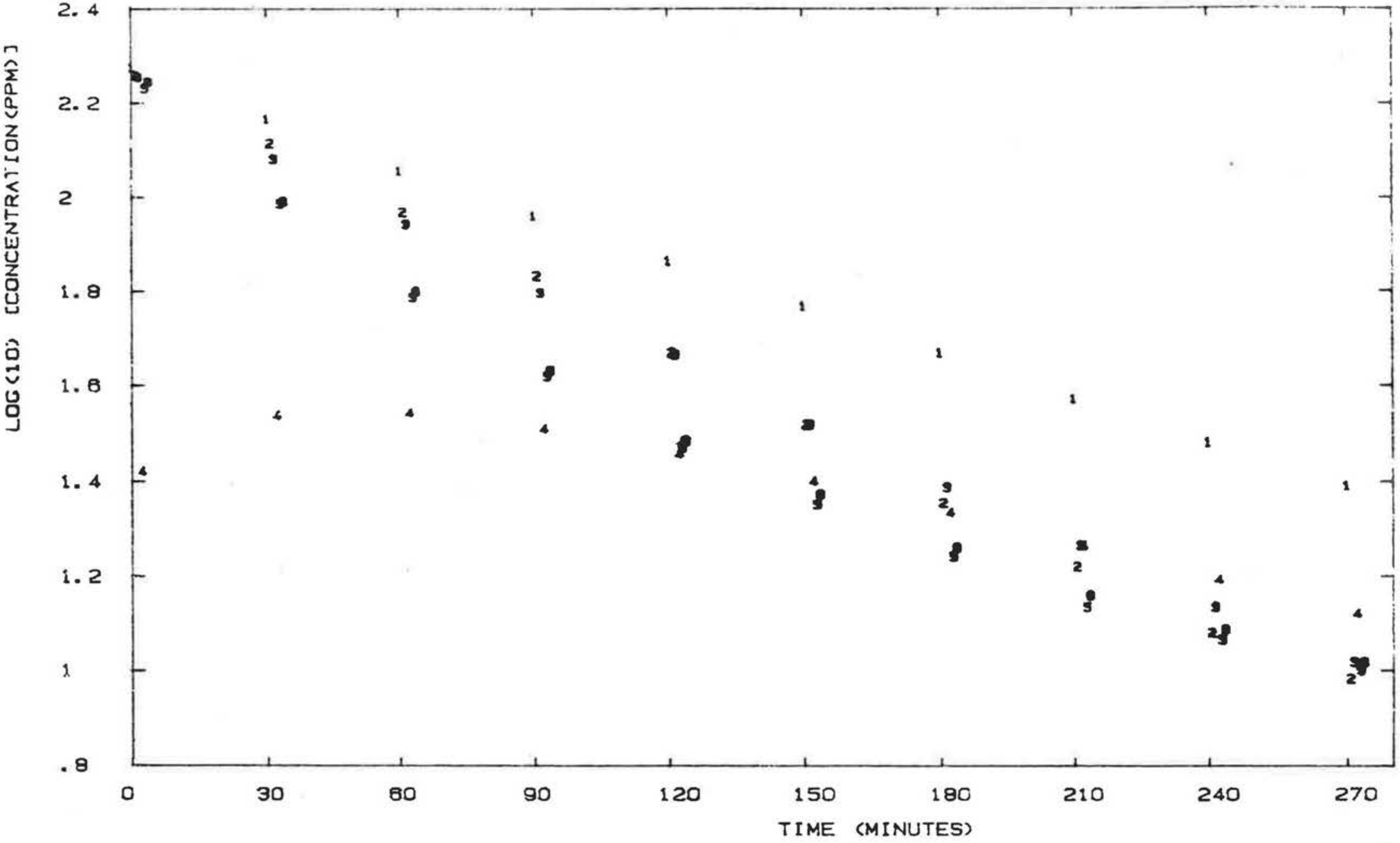


Figure 11 Concentration profiles from Test H

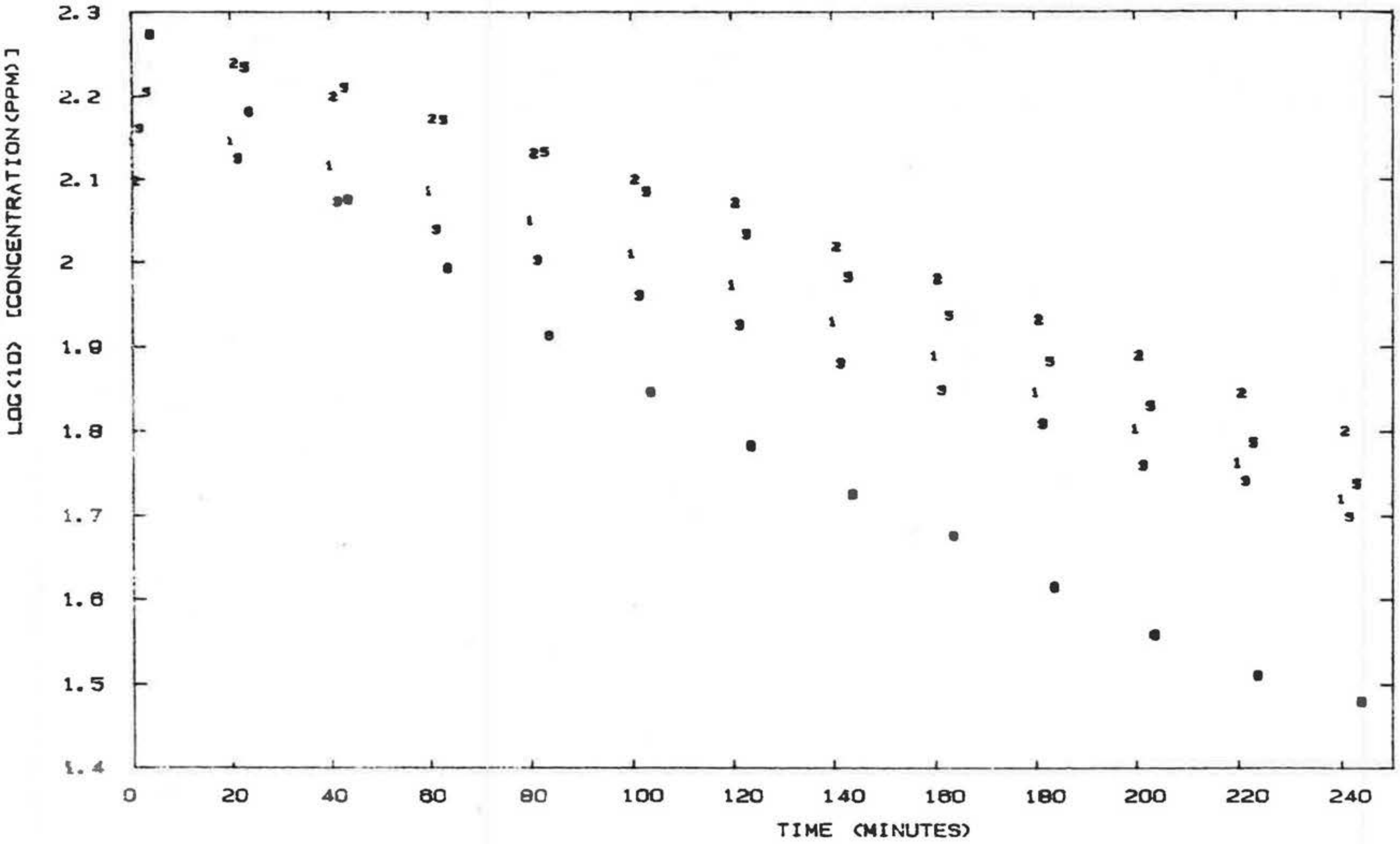


Figure 12 Concentration profiles from Test K

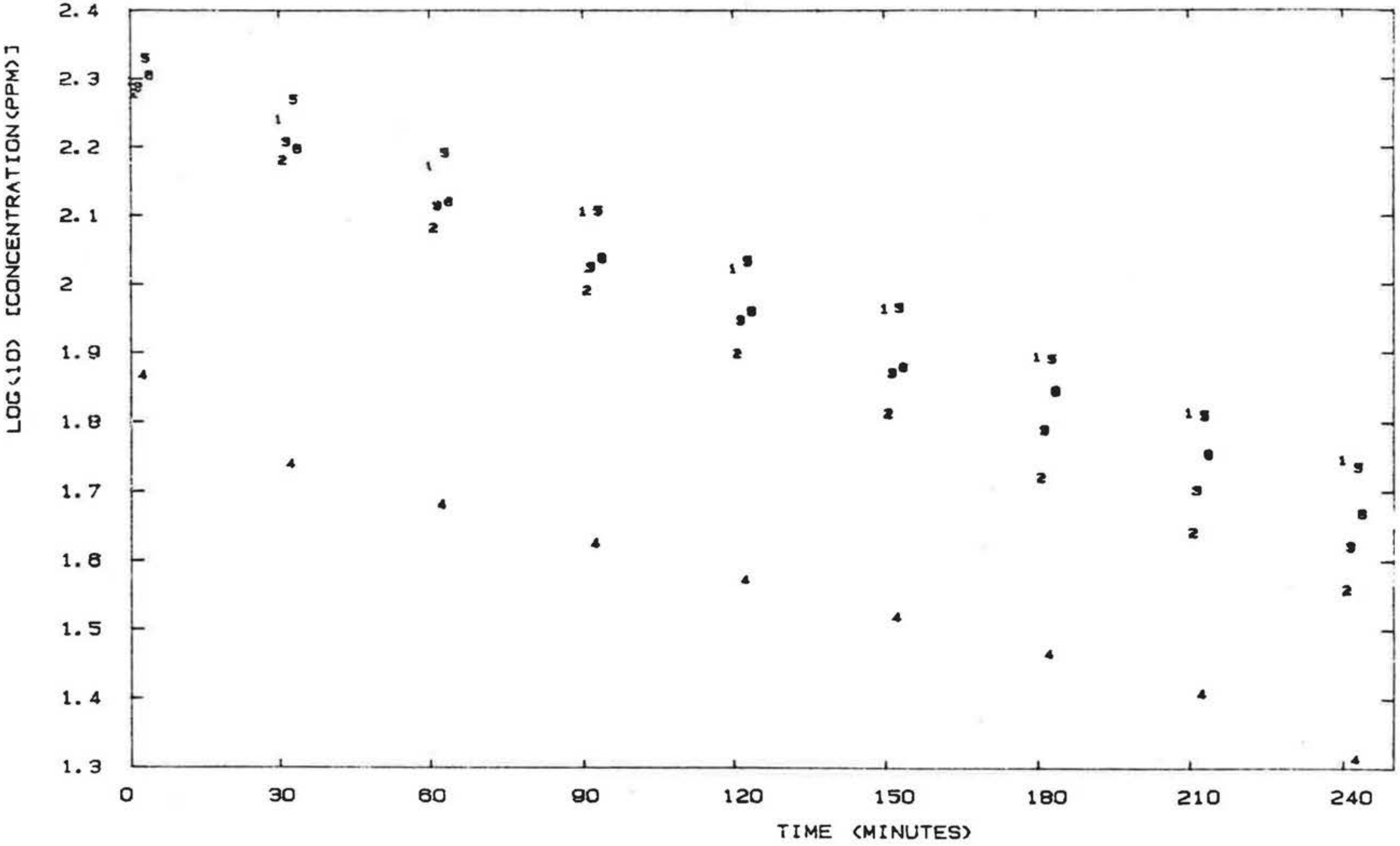


Figure 13 Concentration profiles from Test J

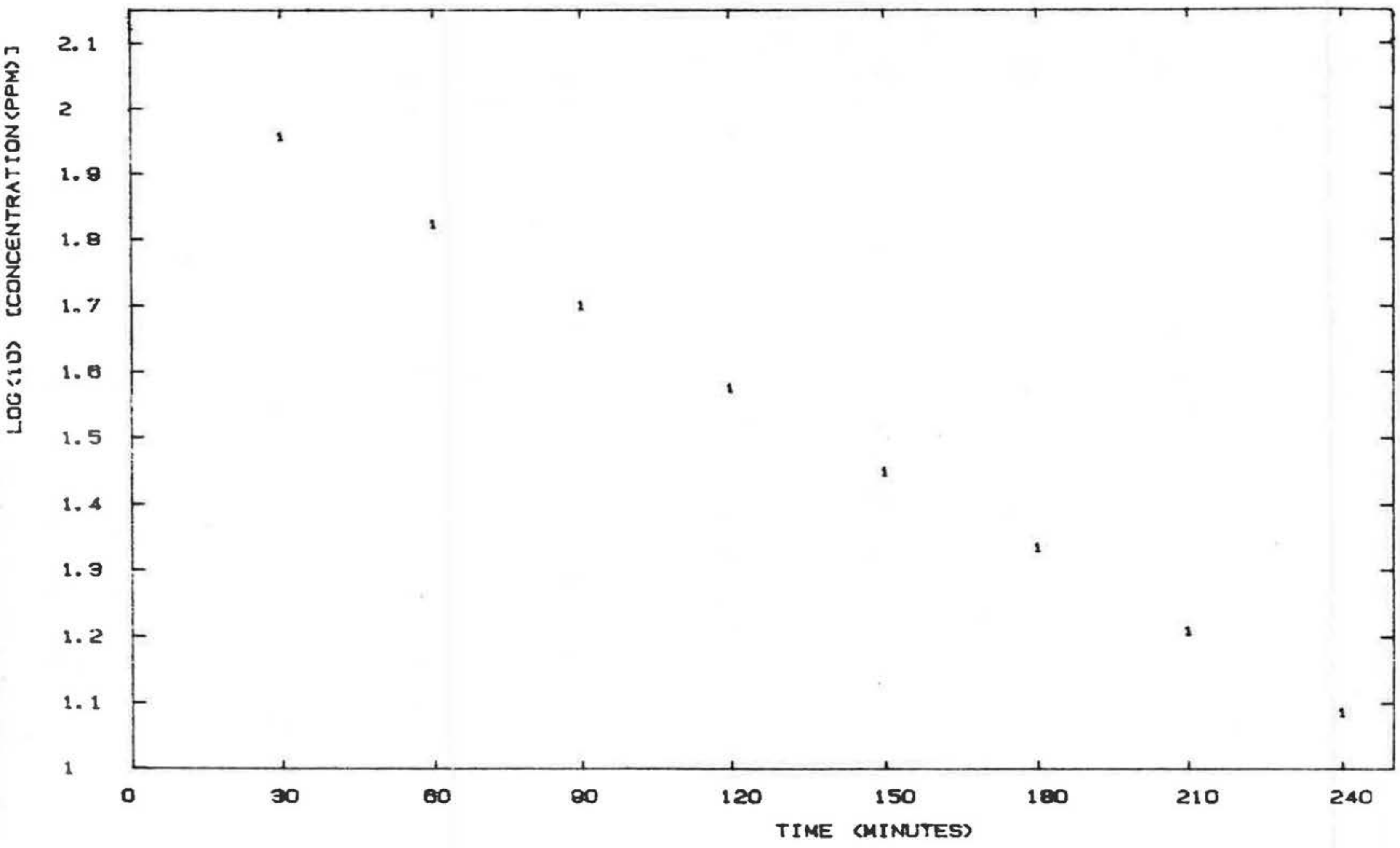


Figure 14 SF_6 decay in seeded room during Test L

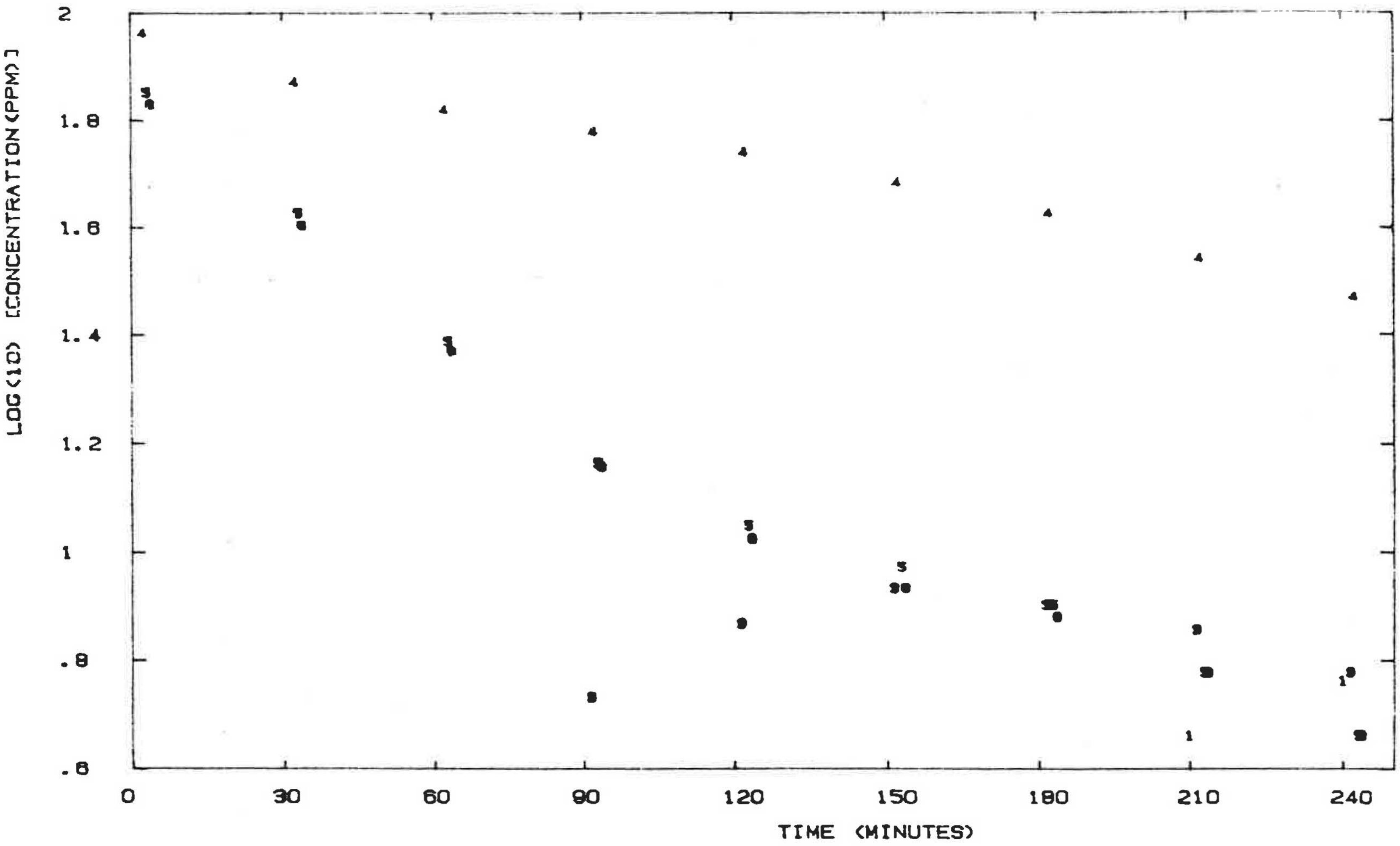


Figure 15 N_2O decay during Test L

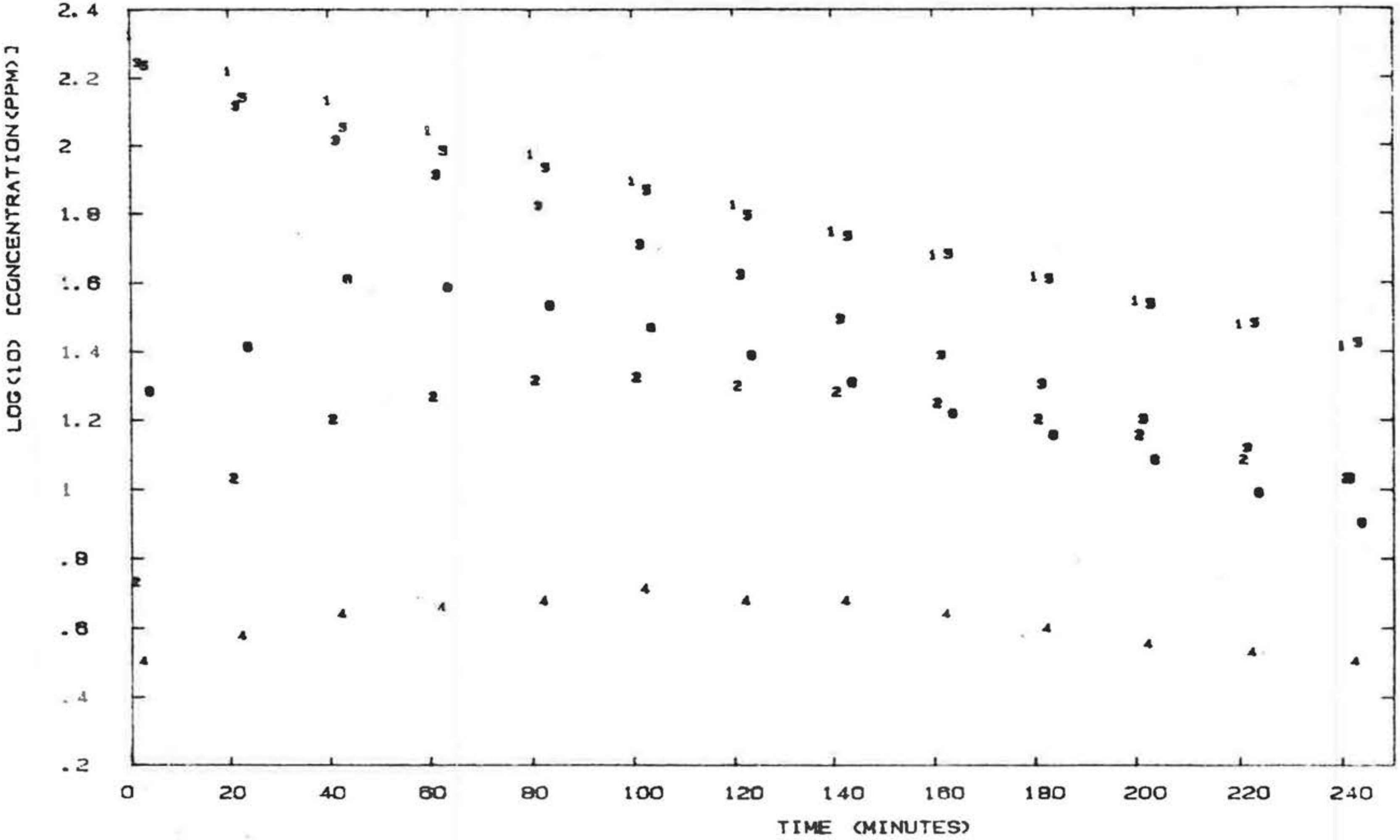


Figure 16 SF_6 concentration profiles from Test M

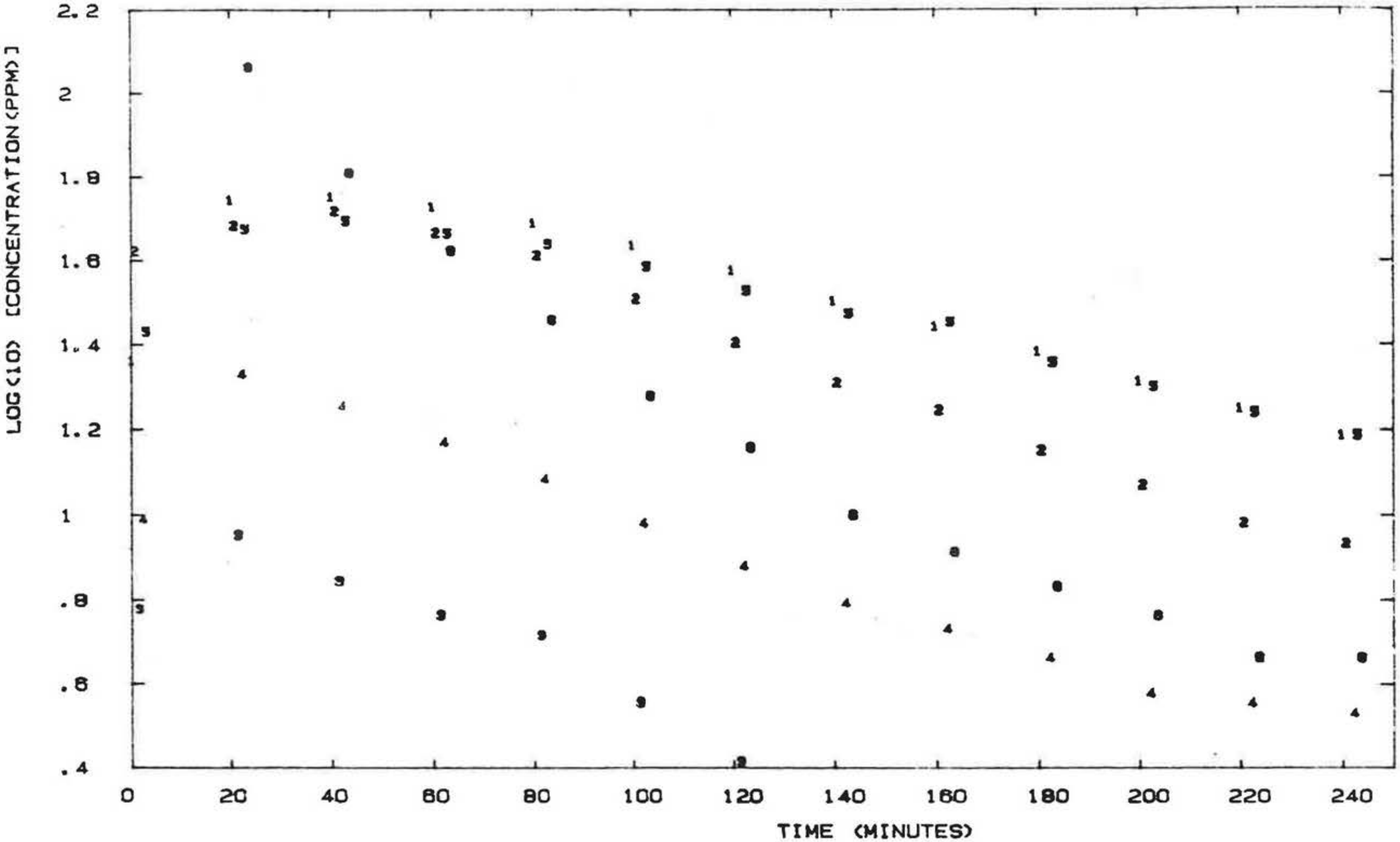


Figure 17 N_2O concentration profiles from Test M

CHAPTER 7

STRATEGY FOR MEASURING INFILTRATION RATES IN NATURALLY VENTILATED MULTICELLED BUILDINGS USING A SINGLE TRACER GAS

1. INTRODUCTION

In the previous Chapter, a simplified technique for measuring overall infiltration rates in large and multicelled buildings was proposed.

The main proposal of the technique was that the overall infiltration rate of such a building can be determined by seeding part of the building with a single tracer gas and then by monitoring the decay rate over a 'dominant' region. This technique was developed in the previous Chapter on the basis of a two-cell analytical model and field measurements.

The analytical approach showed that, in a two-cell representation, the dispersion of a tracer initially seeded within that building can be described by a two term eigenvalue solution. Of these two eigenvalues, one is smaller and thus dominant with increasing time. The results from that study showed that if,

- there is appreciable mixing between the cells, or
- in exchanges with the outside air, the infiltration balances exfiltration in each cell,

then the dominant eigenvalue tends towards the total infiltration rate.

Several part-seeding strategies were carried out during the field measurements. Concentration decay profiles obtained showed that nearly all profiles show two distinct regions of decay; an initial and a dominant separated by a transition phase.

The measurements also indicated that as internal mixing is enhanced and more zones of the building are seeded, the transition rate is arrived at sooner and the dominant decay rate tends towards the overall infiltration rate.

At the end of that Chapter, it was concluded that further work was necessary so as to tie down the essentials of the technique. Two main areas which required further investigation were;

- the conditions under which the simplified method, in multicelled buildings, would give good approximations towards overall infiltration rates and

- the influence of internal mixing and volume seeded on the position of the transition region and on the dominant decay rate.

An attempt to answer these questions is made in this Chapter by using computer simulations. In Section 2, a five zone model of building B18, under conditions of natural ventilation, is set up. The influence of factors such as,

- the proportion of the building volume initially seeded with the tracer,

- enhancing internal mixing,

and the effects of,

- stagnant zones, and

- over-ventilated spaces,

within the building are then considered and discussed in Section 3.

2. FIVE-ZONE REPRESENTATION OF BUILDING

2.1. Introduction

The eigenvalues for an N-cell model can, in theory, be obtained by solving an Nth degree polynomial. An analytical solution for a two-cell model is easy to obtain but as the degree of the polynomial increases to three or four, such a solution becomes more difficult. No general solution exists for fifth and higher degree polynomials. Recourse then has to be made towards numerical computation.

For an N cell model, Equation 3 in Chapter 6 can be rewritten as,

$$C_i(t) = \sum_{j=1}^{N} a_{ij} e^{\lambda_j t}$$

A computer program was written to evaluate the coefficients a_{ij} and the eigenvalues λ_j.

2.2. Modelling the building

For the case study, a five-zone model representation of building B18 was used as follows:

Zone No	Description	Volume (m^3)	Vol ratio
1	Rooms in central section of 2nd floor	574	0.109
2	Corridor in central section of 2nd floor	86	0.016
3	Ceiling void above Zone 2	29	0.005
4	West stairwell	170	0.033
5	Remainder of the building	4427	0.837

The volume ratios were calculated by dividing the zone volumes with the total usable volume (5286 m^3) of the building. A zone in the present context may be a single cell within which mixing is assumed perfect or a collection of such cells which can be taken to act as one aggregate cell.

2.3. Modelling the airflows

A model of the airflows within building B18, when naturally ventilated, were approximately derived using information gathered from the field measurements (Chapter 6). This model is shown in Figure 1.

When measurements to determine infiltration rates are carried out, it is probable that certain zones may be over- or under-ventilated with respect to the rest of the building. To assess these, as well as to determine the effect of using 'mixing' fans to enhance dispersion of tracer gas within the building, various airflows (denoted by β) were superimposed on the airflow pattern in Figure 1.They were configured so as to maintain the volume-flow balance within the model. The following cases were considered:

BETA	Value	To represent effect of:
β_1	0.0, 0.2, 0.4	over-ventilated zone
β_2	0.0, 0.1	stagnant or 'dead' space

β_3 0.0, 0.2, 0.4 enhanced internal mixing

3. RESULTS FROM FIVE-ZONE REPRESENTATION

3.1. Introduction

Table 1 contains details and results obtained from some of the computer 'runs' which are applicable to the discussion that follows. In all of these, only Zone 1 (i.e. rooms) was seeded with a tracer. In all cases, airflows (Fig 1) were normalised by the total fresh air flow into the building, Q_T, and volume ratios were used.

3.2. Eigenvalues

Hernandez and Ring [1] have pointed out that, if there is no connection between cells, then each of the eigenvalues obtained in a multicell solution could, in theory, be identified with one of the cells. This was seen earlier in the two-cell model and it occurs because, with zero intercell mixing, tracer gases will decay at a distinct rate, independent of the other cells. This 'association' of each eigenvalue with a cell is not strictly possible when the cells are well-connected.

However, using results from Run 4 (Table 1), the eigenvalues (relevant to those flow conditions) can be tentatively identified with a particular zone. This was done by seeding one zone, i, at a time and noting the $\lambda(j)$ associated with the dominant coefficient a_{ij}.

The eigenvalues were then compared with both the 'fresh air' infiltration rate and the 'total' air change rate into these zones. The total air change rate is evaluated by summing all the airflows, including the fresh air, flowing into that zone. Results are as follows:

Zone	Eigenvalue	Air change rate	Infiltration rate
1 - rooms	3.28	4.98	3.13
2 - corridor	41.3	31.9	0.
3 - roof void	12.2	20.0	0.
4 - stairwell	19.7	19.3	0.
5 - rest of the building	0.839	1.16	0.787

This example shows that the eigenvalues do not necessarily equate either to the fresh air infiltration or to the total airchange rate of a zone but can be an approximation to them.

3.3. Effect of partially seeding a building

Figure 2 shows concentration profiles in Zone 1 for the following seeding patterns:

Pattern of seeding	Percentage volume seeded
Zone 1	11
Zones 1, 2 & 4	16
All five zones	100

Figure 3 shows the same profiles plotted on a semi-logarithmic (base 10) scale and, covering a range from 100 parts per million (ppm) to 1 part per billion (ppb), for an initial concentration level of 100 ppm. The upper range (100 - 1 ppm) can, with a suitable tracer, be measured using conventional infrared gas analysers and the lower range (100 - 1 ppb) measured using gas chromatography.

Figure 3 shows that there are two distinct regions of decay. The initial part, called the 'transition' period [5], is made up from contributions from all the eigenvalues. A tracer gas 'decay' experiment will therefore show a continuously varying rate (as measured on a semilog plot) during this period. The consequence of this observation is that measurements carried out during the transition period do not necessarily reflect either the air change or infiltration rate of that zone or of the building.

An interesting point concerning the transition period arises when a seeding and decay experiment is carried out in a single zone. From Section 3.2., it is noted that the initial decay rate will closely approximate the eigenvalue 'associated' with that zone.

With increasing time, however, a 'dominant' decay mode is established. This period is almost entirely controlled by the smallest eigenvalue and the decay rate measured during this time is then equal to this dominant eigenvalue.

As more zones are seeded, the transition period gets shorter (Fig 3) as the initial distribution is made a better approximation to the first eigenvector. The dominant period is then established earlier and the amount of tracer lost from that zone is reduced. The implication of this to practical measurements is twofold;

- the final dominant decay rate is independent of both the amount of tracer released or the locations of its release and,
- dominant decay rate can be obtained sooner and at a higher concentration level, for ease of measurement, by seeding as large a volume as possible.

3.4. Effect of enhancing interzone mixing

Theory states, and computer simulations show, that the eigenvalues are,

- independent of the initial tracer gas concentrations or distributions, but are
- dependent on the interzone airflows.

Interzone airflows can be enhanced by various means, e.g. by opening internal doors or using mixing fans. The effect of such enhanced mixing within the building were considered by carrying out computer simulations where an added 'mixing' flow $\beta3$ (Fig 1) was superimposed on the measured airflows.

The effect of enhancing the internal mixing is seen (Fig 4) by considering Runs 1, 2 and 3 (Table 1). As the mixing increases, three out of the four relevant eigenvalues double in their value. The smallest, and the dominant, eigenvalue however increases only by about 4%. Other simulations carried out show that as the internal mixing increases above practical levels, all eigenvalues except the dominant become infinite.

The dominant eigenvalue, however, is seen to increase slowly towards the building infiltration rate of 1 air change per hour (using normalised airflows and volumes) as the mixing increases. It can be seen that, without any additional mixing, this eigenvalue was about 15% away from the final value.

There is a physical reason why all eigenvalues other than the dominant increase to infinity. In any solution to the equations governing decay of tracer concentrations, one eigenvalue (which turns out to be the dominant) must represent the air movement between the building and the outside which has been set up by the external pressure field. If the mixing is balanced, i.e. there is no net flow in any direction, then there is relatively little disturbance on the building envelope. The dominant eigenvalue therefore remains relatively unaffected with changes in intercell airflows.

The other eigenvalues, however, represent intercellular interaction. As the mixing gets better, the cells lose their individual identity and begin to communicate equally well with the outside. All eigenvalues, other than the dominant, then tend to infinity and the building approximates towards a single-cell structure.

A consequence of better internal mixing is that the transition period gets shorter and the 'dominant' decay is established earlier. The use of enhanced internal mixing (e.g. by using mixing fans) is therefore justified whenever whole building infiltration rates are required.

3.5. Effect of a stagnant zone

In most buildings, there are spaces (such as ceiling voids) which are not well-connected with the main ventilated space. To illustrate the possible effect of such a space, a simulation (Run 4 in Table 1) was carried out by connecting Zone 3 (ceiling void) to Zone 2 (corridor) with $\beta 2=0.1$.

The concentration profile generated in Zone 1 (rooms) from the resulting eigenvalues did not deviate to any discernible level from the profile (Figs 2 and 3) when $\beta 2=0$ for the same flow distribution (Run 1). Table 1 also shows that the influence of the void on the dominant eigenvalue was negligible.

In conclusion, it is suggested that a stagnant zone, provided its volume is relatively small, does not to any extent influence the overall dispersion of the tracer nor the magnitude of the dominant eigenvalue.

3.6. Effect of an over-ventilated space

Office buildings usually incorporate some space, such as a foyer area or a stairwell, which is over-ventilated in comparison to the rest of the building. In such instances there are two distinct airchange rates, one characterising the over-ventilated space and the other the rest of the building. It is usually the latter value which is of use for purposes of either quality of air (i.e. freshness) or for energy considerations.

To determine the effect of an over-ventilated space, Zone 4 (stairwell) was connected directly to the outside with β_1 set to 0.2 (Run 5) and 0.4 (Run 6). This meant that upto 20% and 40% of the total inflow of air into the building flowed into and out through Zone 4.

The resulting eigenvalues are given in Table 1. In both cases, the dominant eigenvalue has been reduced from 0.840 (Run 1) to 0.756 and 0.613. It can also be seen that they compare favourably with the infiltration rates, of 0.827 and 0.620 respectively, into the rest of the building, i.e. excluding the over ventilated Zone 4.

Figure 5 shows concentration profiles in Zone 1 (with tracer seeding in Zone 1) for Runs 1, 5 and 6. They all show the steady 'dominant' decay rate emerging after the transition period. The time, however, at which the breakpoint between the transition and the dominant period occurs increases with an increase in the over-ventilation in Zone 4.

4. CONCLUSIONS

The proposed simplified technique for measuring overall infiltration rates in multicelled buildings has been investigated further. A computer simulation was carried out on a five zone representation of building B18 when naturally ventilated.

The dispersion of a single tracer gas within the building was studied for various combinations of tracer seeding and internal airflow patterns. On the basis of this study, the following preliminary conclusions can be drawn:

- All concentration profiles contain information regarding the eigenvalues characterising the building regardless of the position of tracer seeding or the extent to which the building is seeded.
- All profiles consist of a transition period and a steady dominant period.
- Decay rates obtained during the early transition period of a tracer 'decay' experiment do not necessarily give any meaningful information with regard to infiltration rates.
- After the transition period, the dominant period occurs during which the tracer decays at a constant rate. This rate, if measurable, characterises the building.

The most important conclusion to come from this study is that, in a well-connected building, this final decay rate tends to a dominant eigenvalue which, provided certain conditions are satisfied, approximates to the total infiltration rate of the building, or at least to the infiltration rate of some significant portion of the building, e.g. the portion connected to an over-ventilated or a stagnant space.

In practical terms, the following points should be noted:

- Measurements should be localised to the zone of seeding thereby ensuring that air samples, with measurable tracer concentrations, can be obtained relatively easily.
- The transition region can be shortened and the dominant period reached quicker by
  - increasing the volume seeded
  - increasing the internal mixing by opening internal doors, using mixing fans etc.
- Monitoring in the dominant period will usually require a tracer gas capable of being detected over a wide range and at very low concentrations.

The approach presented here is, in principle, applicable to a wide variety of buildings whether they are small or large, single-celled or multicelled, naturally or mechanically ventilated. The range of field and theoretical studies have necessarily been limited and, thus, experimental studies to further evaluate, refine and improve this technique is required. The exploratory studies, described in Chapter 6, can also be looked at, and understood, in the light of the information gathered in this Chapter.

It is suggested that this technique provides a basis of a simple method by which the hitherto unresolved problem of measuring infiltration rates in large, multicelled buildings can be overcome.

REFERENCES:

1. Hernandez, T L and Ring, J W, Indoor radon source fluxes: experimental tests of a two-chamber model, Environment International, Vol 8, PP 45-57, 1982.

- Ch. 7 -

TABLES:

1. Details of computer 'runs' used in case study

FIGURES:

TABLE 1: DETAILS OF COMPUTER 'RUNS' USED IN CASE STUDY

	Superimposed flows			Eigenvalues					
Run	β_1	β_2	β_3	λ_1	λ_2	λ_3	λ_4	λ_5	Comment
1	0.0	0.0	0.0	31.6	15.2	3.37	0.840	0.0	Standard
2	0.0	0.0	0.2	52.0	19.2	3.80	0.859	0.0	Enhanced mixing
3	0.0	0.0	0.4	72.8	23.0	4.06	0.870	0.0	Enhanced mixing
4	0.0	0.1	0.0	41.3	12.2	3.28	0.839	19.7	Void usage
5	0.2	0.0	0.0	27.5	15.8	2.75	0.756	0.0	Stairwell over-ventilated
6	0.4	0.0	0.0	25.8	14.2	2.09	0.613	0.0	Stairwell over-ventilated

Notes: (1) β_1,β_2,β_3 are superimposed flows, and represent the following:

β_1 ... effect of stairwell over-ventilation
β_2 ... effect of 'void' usage
β_3 ... effect of 'enhanced' mixing

(2) λ_4 is the dominant eigenvalue

(3) Whole building infiltration rate, R, is 1.

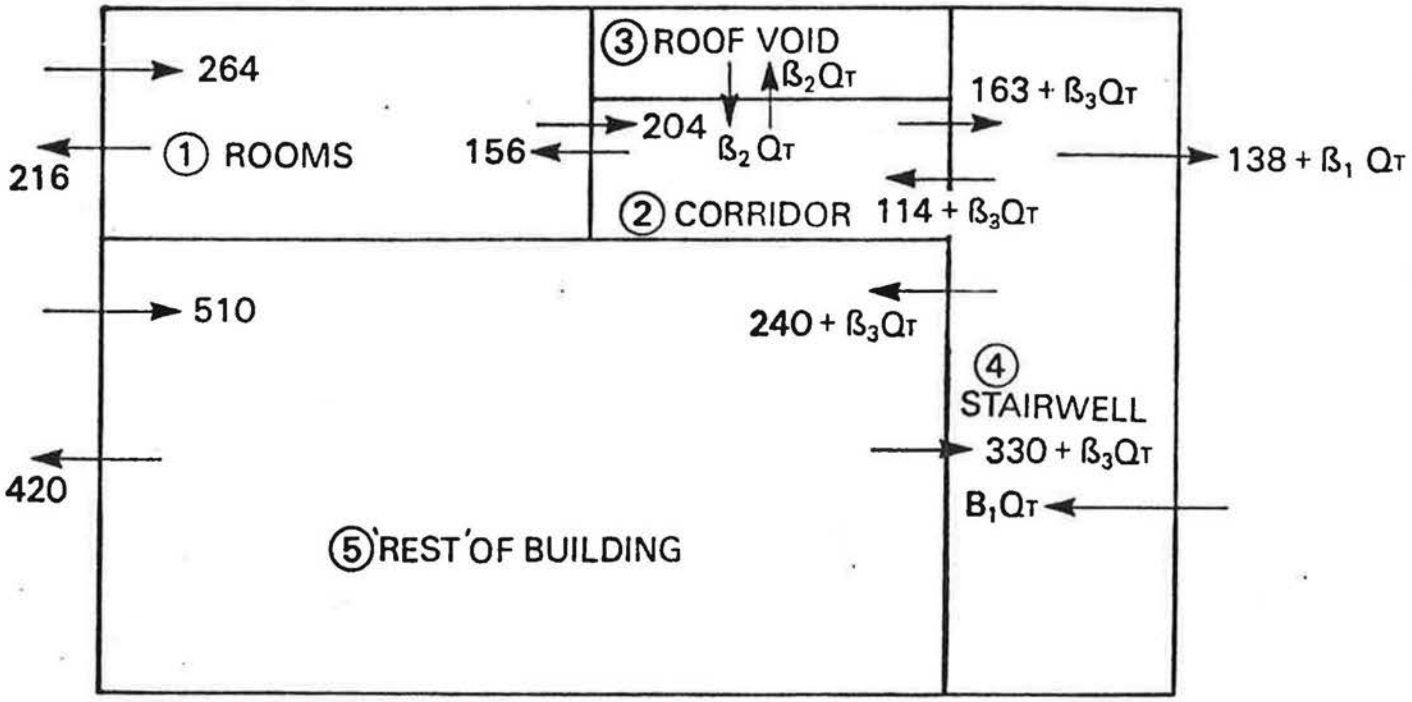


Figure 1 Airflows (m^3/hr) in building for simulation study (building drawn not to scale)

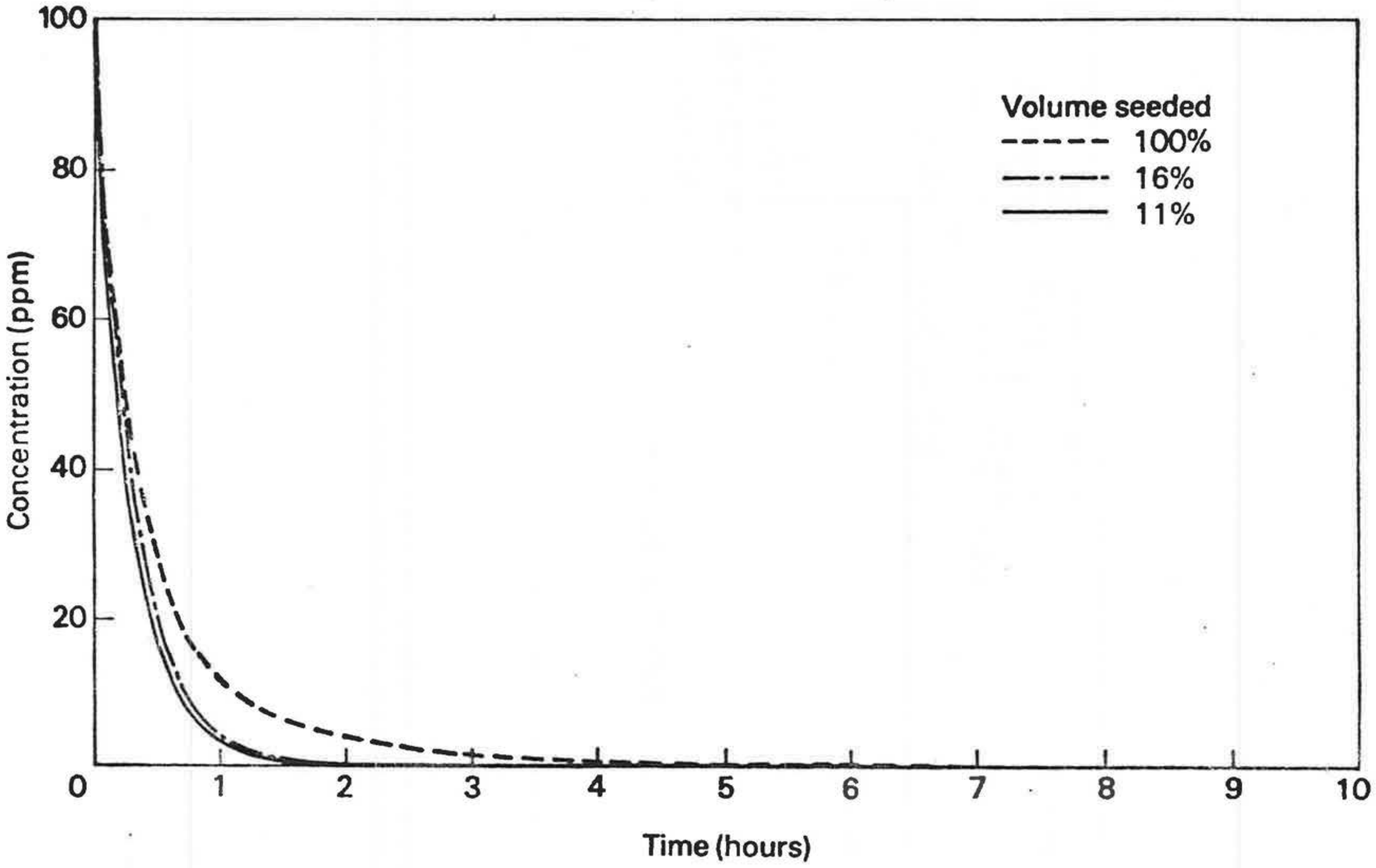


Figure 2   Concentration profiles in Zone 1 for varying amount of 'seeded' volume

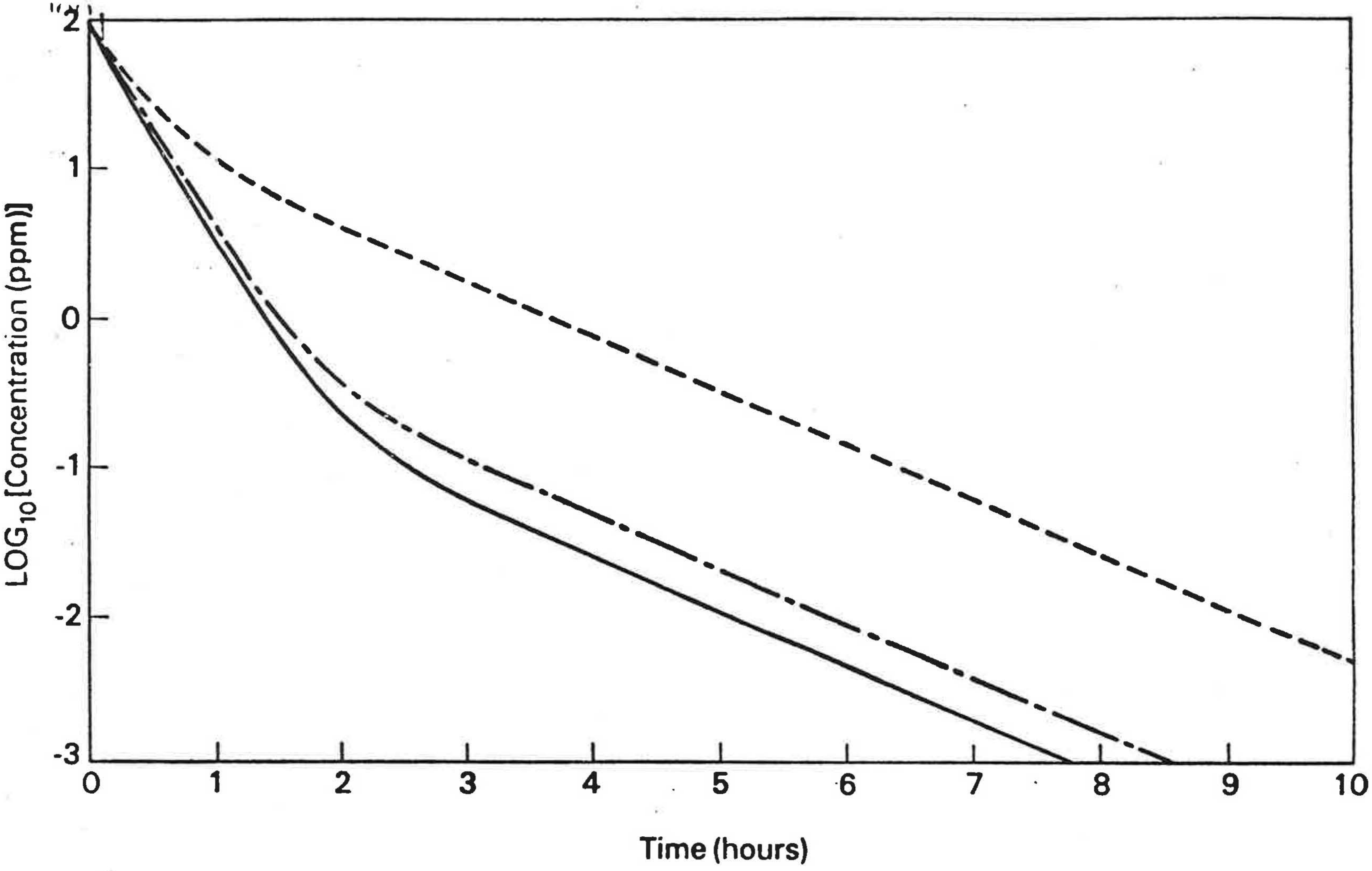


Figure 3 Concentration profiles of Figure 3 plotted logarithmically

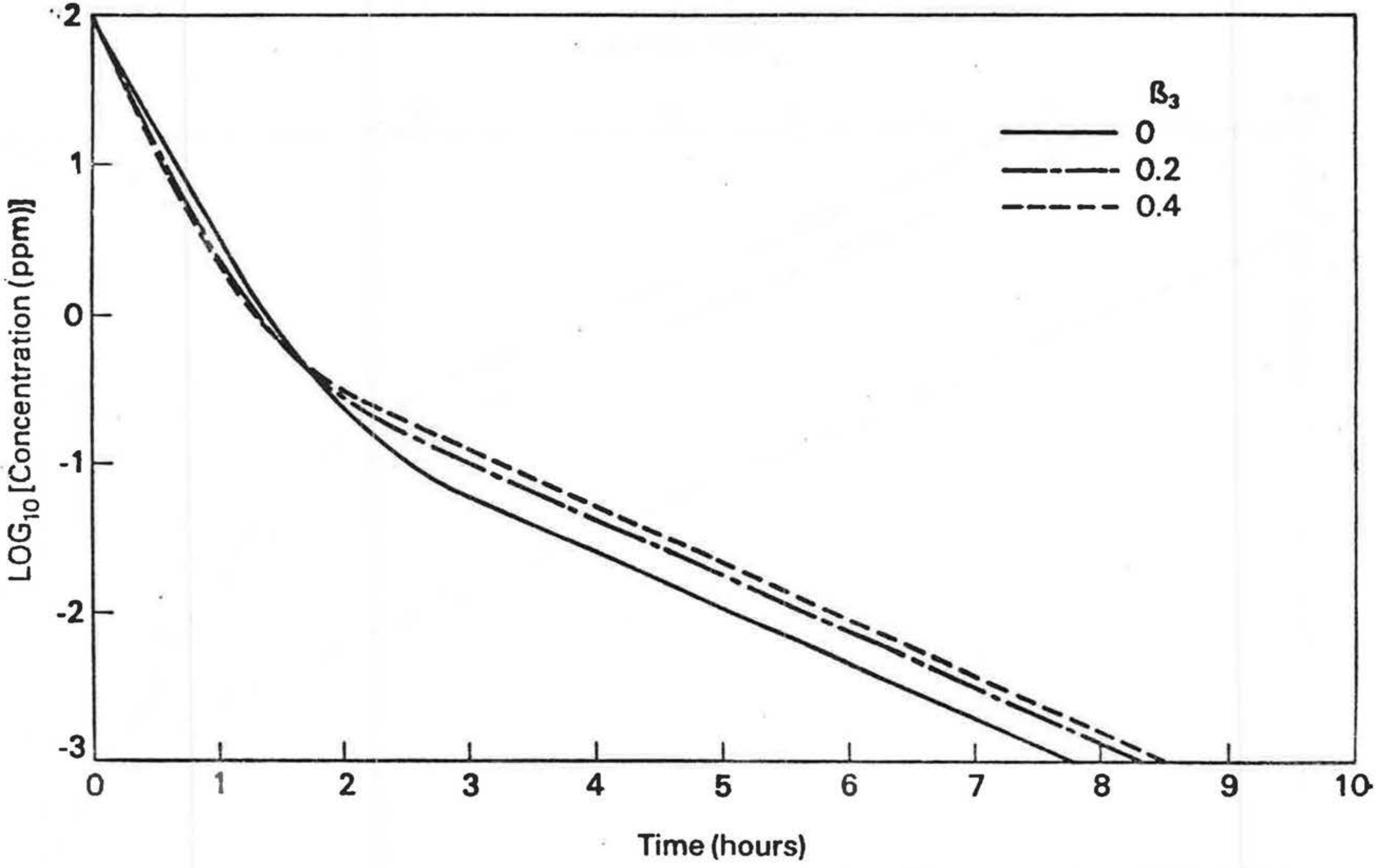


Figure 4 Effect of enhanced mixing on Zone 1 concentration profiles

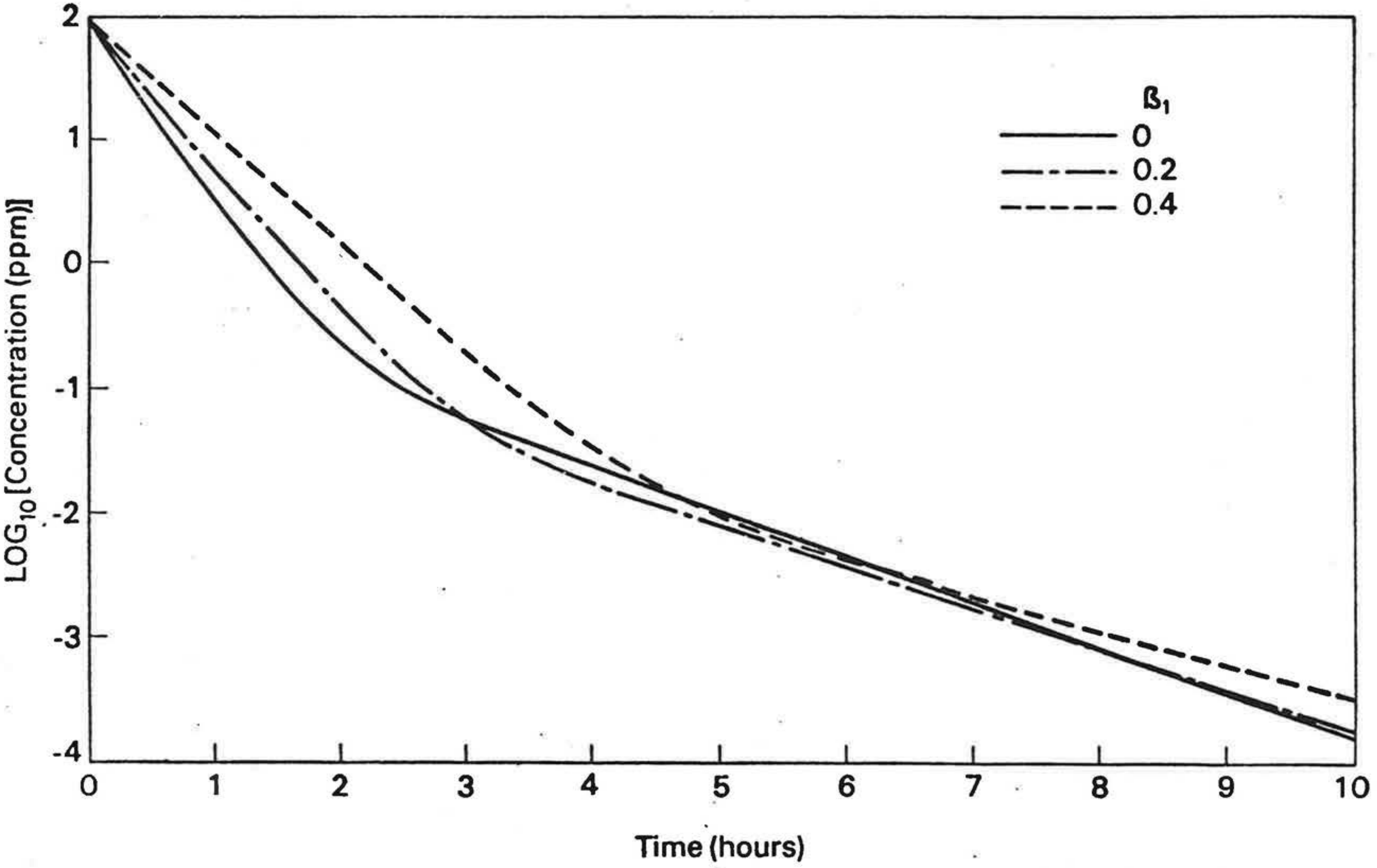


Figure 5   Effect of an over-ventilated stairwell on Zone 1 concentrations

CHAPTER 8

EVALUATION OF SIMPLIFIED EQUIPMENT AND TECHNIQUES OF TRACER SAMPLING

1. INTRODUCTION

In the previous two Chapters a relatively simple method for measuring infiltration rates in complex buildings was proposed. In order to develop this method of measurement for general use, it is necessary to develop and evaluate simplified equipment and techniques for sampling the tracer gas and air mixture during the measurement periods.

Such reasoning leads to the replacement of continuous on-line sampling by discrete or 'time averaged' sampling. The samples can then be analysed 'off line' at some subsequent time. The services of skilled operators to install and operate expensive equipment in-situ becomes no longer necessary.

Discrete spot measurements are defined here to mean the estimation of a true tracer concentration history in a zone by use of a few, or a series, of discrete air samples taken at a specific location in the zone. A 'medium term average', on the other hand, refers to a sample collected continuously (e.g. over a period of hours) at such a location.

The simplified approach in taking off-line samples depends on using suitable containers which can take and store (for some time) an air/gas sample. The suitability of these containers then depends on,

- whether the collected sample truly represents the tracer concentration in the air at the point of and during the period of measurement, and

- whether the sample in the container has deteriorated before it can be analysed.

This Chapter attempts to answer these questions with reference to the simplified sampling equipment used during the present programme of work. In addition to laboratory work, results from field measurements when these equipment were used and evaluated will be presented. The field measurements will, where appropriate, include 'averaged' measurements as well as 'discrete' measurements. The equipment that will be described are;

- polyethylene sample bottles,

- Tedlar sampling bags,
- adsorption tubes, and
- evacuated glass tubes.

Simplified techniques for distributing the tracer gas are relatively straightforward and will not be considered further here. Two such methods of injecting the tracer, i.e. injecting directly from the cylinder or using gas filled balloons, were discussed in Chapter 6.

2. POLYETHYLENE SAMPLE BOTTLES

2.1. Introduction

Common laboratory 500 ml polyethylene 'wash' bottles were adapted for taking discrete 'spot' samples. The bottles were modified by removing the delivery tube from the screw cap and inserting, into the bottle cap, a disc of silicone rubber septum material (supplied by Field Instruments Co. Ltd) to act as a seal.

To take a sample, the cap is simply unscrewed and the bottle squeezed (contracting the bottle volume approximately by 50%) for about ten times. This ensured the almost complete flushing of the bottle and replacement of the bottle contents by the ambient air. The contents were subsequently extracted for analysis by using a syringe to pierce the septum.

2.2. Sample integrity with time

To investigate the possibility that tracer gas, contained in the polyethylene bottles, might be lost by adsorption on the bottle walls or permeation through the wall material, some shelf-life tests were carried out.

Three sets of four bottles were filled with two tracer gases, sulphur hexafluoride (SF6) and Freon 12 (each at 1% concentration) as follows:

Set No.	Bottle Nos.	Tracers contained
1	1 - 4	Freon-12
2	5 - 8	Freon-12 + SF6
3	9 - 12	SF6

Samples were taken from these bottles at weekly intervals over a four week period. Each sample, of 5 ml volume, was injected into the measurement cell of a Miran 1A variable wavelength infrared analyser. The cell, operating as a closed-loop with a total volume of 0.564 litres, was set up to indicate a 9 ppm reading if the sample had not deteriorated. The analyser was regularly calibrated, during measurements, by injecting 50 microlitres of neat gas into the cell.

The results from these measurements are shown in Table 1. It should be noted that, for convenience, the initial value for each sample is in terms of microlitres of neat gas found within the cell for that measurement. These have then been normalised by the values obtained at the beginning of the shelf-life test.

The results indicate that Freon 12 is not retained within polyethylene bottles. Although there is some scatter for the SF6 data, the overall indication is that there is no significant loss. It was therefore concluded that polyethylene bottles should not be used if and when Freon 12 was being used as a tracer.

It was also decided that, until further comprehensive and more statistically valid shelf-life tests were carried out, it would be prudent to keep to a minimum the interval between sampling SF6 and analysing its concentration.

2.3. Field measurement

For illustrative purposes only, Figure 1 shows the results of a ventilation test in a building in which SF6 was used as the tracer. During the test, samples of the internal air were taken using polyethylene bottles. These were later analysed and compared with on-line measurements obtained with a Leybold-Heraeus infrared analyser sampling near the same location. The correspondence between the two sets of measurements is seen to be good.

2.4. Discussion

The work described above suggest that modified polyethylene sample bottles can be reliably used to take discrete spot samples when SF6 is used as the tracer. Field comparisons suggest that such samples are within 5% of corresponding on-line measurements.

3. SAMPLING BAGS

3.1. Introduction

There are several types of sample bags available. These vary in,

- the materials used (usually multilayered),
- the facilities provided for filling and extracting a sample (usually including a septum and a valve port), and
- size and shape (usually of several litres capacity).

They are intended for holding a large range of gas concentrations, from pure gas down to ppb and lower concentrations. The type of bags selected for the present work, and used extensively in the tests in Chapter 6, were supplied by SKC Ltd. They are made from 0.5 mm thick single layer of Tedlar (polyvinylfluoride) material. A stainless steel valve is attached to each bag for purposes of filling or emptying. Syringe samples can also be extracted from these bags by using, on each bag, the separate port with a septum in a screw-on cap. The septum has an inner face of PTFE.

The following Section describes a shelf-life test lasting over four weeks during which SF6 was stored within three of the sampling bags. Field tests, during which bag samples (both discrete and time averaged) were compared with on-line measurements are described in Section 3.3.

3.2. Sample integrity with time.

Three new 10 litre bags were each filled with, nominally, 60.5 ppb SF6 from a cylinder containing this standard as made-up by the gas supplier. Once a week, and over a period of four weeks, the concentration in each bag as well as in the cylinder standard were measured. The concentration in each bag was measured twice on each occasion using a Model 8300 Perkin Elmer gas chromatograph (GC).

The results, tabulated in Table 2, are in two parts. The first contains the 'raw' data, in the form of area counts, as given by the chromatograph integrator of the GC. The area count relates to the integrated area under the chromatographic peak corresponding to the gas being analysed. Since this count is directly proportional to the concentration in which these measurements were carried out, it is a simple matter to determine the concentration as ppb units.

In the second part of Table 2, for each weekly set of measurements, the bag readings have been normalised by the averaged reading of the standard determined for that set.

Statistical tests, in the form of a two-way analysis of variance showed that,

- for each weekly set of measurements, variations within samples and between bags, were not significant at the 5% level, but
- there is, however, a significant difference, at the 0.1% level, between each weekly set of measurements.

The averaged results are as follows:

Elapsed time (hrs)	Averaged ratio	Concentration (ppb)
43	0.9405	56.90
332	0.9786	59.21
648	0.9673	58.52
786	0.9903	59.91

These show a 5% spread between the sets of measurements. No decrease in concentration is shown implying that no tracer is lost during the four week storage period or, if it is lost, it is well submerged within the overall variation.

The cause of this variation between sets of measurement is not clear. It may be caused changes in chromatographic column characteristics with time or ambient temperature.

The results, therefore, indicate that if many samples are taken during a ventilation experiment, then they should be analysed at as near as possible to the same time. In addition, experimental errors of 5% should be anticipated.

3.3. Field test

In order to evaluate the sampling bags under field conditions, a sequence of spot samples and time-averaged samples of the air were taken in building B18 during Test D (Chapter 6).

As the tracer concentration decayed, ten discrete samples were taken at a location approximately 30 cms below sample location No. 1 (Figure 4 of Chapter 6). The samples were taken initially at 20-minute intervals for the first hour, and subsequently at 15-minute intervals over the final 90 minutes. Each discrete sample was taken in less than half a minute using an Austen diaphgram pump.

Time averaged samples were taken using two Calibrated Instruments pumps operating in a 'pulsed' mode. The first pump was set and calibrated to deliver 3.6 litres over a one-hour period. This was used to take an average sample over the first 90 minutes into a 10-litre bag.

After 90 minutes into Test D, the second similar pump, set to deliver 2.1 litres over a one hour period, was used to fill a second bag over a period of 30 minutes.

The contents of all bags were analysed directly using the same Leybold-Heraeus infrared analyser as used for the on-line sampling.

Figure 2 shows the discrete bag sample concentrations superimposed on the on-line measurements. The comparison is excellent.

In addition, the time-averaged concentration over the first 90 minutes of the test was 72 ppm. This corresponds exactly to the average computed by integrating the on-line concentration profile over that time period. The second time averaged bag, over the 90 to 120 minute period, gave a concentration reading of 29 ppm which compares well with the on-line integrated value of 30 ppm.

The results show that the bags can be reliably used to take spot or medium term average samples at ppm levels within 1% of the on-line analysis. Further good comparisons, between time-averaged bags and on-line integrated values, can be seen in

Tables 5 to 8 in Chapter 6.

3.4. Discussion

The results described in this Section have shown that Tedlar sampling bags can be used to take discrete or time averaged samples. Tests were carried out with SF6 as the tracer and the results showed that these samples give a correct representation of on-line measurements.

Samples at ppm levels can be measured using infrared analysers to within 1 ppm of on-line readings. At ppb levels, the accuracy is limited to 5% of the 'true' value. This measurement error is caused by the gas chromatograph used for these low concentration measurements.

'Shelf-life' tests have shown no stored sample deterioration over periods of upto one month.

4. ADSORPTION TUBES

4.1. Introduction

An alternative method of taking spot samples of tracer gas is to use adsorption tubes. By using a solid adsorbent for the sampling, the tracer gas is preconcentrated, hence allowing measurements to be made of lower concentrations of tracer gas in air. Further advantages are portability and ease of use on site.

Though solid adsorbents have been used previously (e.g. trapping perfluorocarbons, see Chapter 3) for infiltration measurements, no method of trapping SF6 on a solid adsorbent had been reported previous to this present work.

The sample is collected by using a low-flow pulsed pump to pull the sample through a tube containing a solid adsorbent. In the present work, stainless tubes 89 mm long by 6 mm O.D. were packed with the adsorbent. Two different adsorbent were tested; charcoal (550 mg, 40/50 mesh) held in place by inert glass wool plugs and spherocarb (500 mg, 60/80 mesh) held in place by sintered steel discs.

4.2. Method of analysis

Once the sample was collected, the solid adsorbent used for trapping SF6 was thermally desorbed by preheating the adsorbent tube to 325 °C for five minutes and then flushing the tube for four minutes with a carrier gas (5% methane in argon) at a flow of 20 cm^3/min. The effluent was collected in a 100 cm^3 gastight syringe and analysed by injection via the gas sample valve of the gas chromatograph.

An Analytical Instrument Development Model 511 gas chromatograph equipped with a 200 mCi tritium foil, parallel-plate type electron capture detector, operating under pulsed mode, was used in this study. The carrier gas was a mixture of 5% of methane in argon flowing at 30 cm^3/min.

The 1.8 m by 3 mm GC-column was made out of stainless steel tubing and was packed with Molecular Sieve 13X 40/60 mesh adsorbent. Before use, the column was conditioned overnight at 150 °C but operated at 100 °C during measurements. The samples were injected using a 2 cm^3 gas sample valve.

The GC was calibrated for SF6 and showed a linear response (correlation coefficient = 0.998) for the range of 0.3 - 80 ppb. At concentrations above 80 ppb, the detector gradually became saturated to give a non-linear response.

4.3. Solid adsorbent

Trapping weakly adsorbed low boiling (BP = -68 °C) requires a large bed of a strong adsorbent. As stated before, charcoal and spherocarb were investigated as adsorbents. Stainless steel tubes packed with these adsorbents were provided by Dutom Meditech.

4.3.1. Breakthrough volume

'Breakthrough volume' tests were carried out to determine the suitability of these packing materials. The breakthrough volume of an adsorbent bed is the volume that can be sampled before the gas breaks through the bed; that is, the amount of air which is just enough to produce an effluent concentration equivalent to 1% of the input concentration. These measurements showed that charcoal had to be excluded from further studies because of its low breakthrough volume.

4.3.2. Recovery

The effect of storing the exposed at two different (4 and 15-20 °C) temperatures and four time intervals (1, 2, 3 and 4 days) was investigated in a 2 x 4 factorial design experiment with five replications. For these tests, a known mass (10-15 ng) of SF6 was deposited on the adsorbent bed by pulling the gas mixture through the tubes.

The effect on the recovery of depositing different amounts of SF6 was investigated by putting down various quantities, ranging from 10 to 50 ng, of the gas on the adsorbent and carrying out the analysis within an hour.

The results showed that the percentage of tracer recovered decreased with,

- storage at room (i.e. 15-20 ^{o}C) rather than at 4 ^{o}C,
- time of storage, and
- an increase of the amount of tracer deposited.

Therefore a correction has to be made to obtain the true amount, Z, originally deposited from the measured amount M of SF6. The correction requires using the recovery factor, R, which consists of two multiplicative terms,

$$R = r_{st} \times R_{am}$$

where R_{st} is the correction due to storage and R_{am} is the correction due to the deposited amount of SF6. Values for these two factors can be found from Table 3.

The true amount of SF6 collected is then calculated as, $Z = M/R$. In the range investigated, the precision of the analytical procedure is estimated to be better than 9% for tubes containing 10 ng SF6 and better than 6% for tubes containing 50 ng of SF6.

4.4. Field study

The application of Spherocarb as a solid adsorbent for measuring the ventilation rate was evaluated in a simulated field study using a test chamber (7.83 m^3) from which air was extracted at a constant rate. The air in the chamber was mixed continuously using a desk fan. The methods used to determine the ventilation rate, N, and the results obtained were as follows:

- Using a calibrated orifice plate in the outlet duct to measure the extracted volume of air .... N = 2.59 ach.
- Using an infrared Miran 1A gas analyser to measure the decay rate from an initial concentration of 50 ppm SF6 .... N = 2.68 ach.
- Measuring the decay rate using a syringe for sampling and the GC for the analysis and starting with an initial SF6 concentration of 30 ppb .... N = 2.42 ach.

- Using an averaging procedure given in Reference 1, by employing the adsorption tubes and an initial SF6 concentration of 20 ppb .... N = 2.80 ach.

4.5. Discussion

It was found that Spherocarb was a better adsorbent for SF6 than the more common charcoal packing used in adsorbent tubes. the precision of the analytical procedure for the applied adsorbent was estimated to be better than 9%.

The solid adsorbent technique developed for measuring ventilation rates by spot sampling of the SF6 tracer was evaluated using a test chamber. It was found to agree within 5% of values obtained with other, more conventional, techniques.

5. VACUTAINERS

5.1. Introduction

'Vacutainers' were bought from Becton Dickinson, UK. These are inexpensive (£ 0.08 per tube) 20 ml evacuated glass tubes which are normally used to store blood samples. Using a technique described by Tamura and Evans [Ref 2], these tubes were evaluated in the laboratory as a device for obtaining 'spot' samples in the ppb concentration range.

5.2. Experimental evaluation

A calibration bag of 50 ppb SF6 gas was prepared and 40 ml samples of this were injected into ten vacutainers using a 100 ml gastight syringe. For each injection, 40 ml of the sample was injected into the vacutainer through the butyl rubber stopper. The tube was then pressurised to about one atmosphere above ambient. Masking tape was wrapped around the junction of the tube and the stopper to prevent the stopper being ejected by the excess pressure.

The Analytical Instruments GC was used to measure the gas concentration. To achieve this, a hypodermic needle was attached to the inlet port of the GC. The stopper of the vacutainer was then pushed against the needle and sufficient time given for the escaping sample (approximately 20 ml) to flush and fill the 2 ml sampling-loop. The concentration was then measured.

All 10 measurements were within 1 ppb of 50 ppb. It was decided that this evaluation was satisfactory to establish the integrity of samples captured through this method.

No tests were carried out on the stability of samples during extended storage. The findings from Reference 2 do, however, show that the samples remain unimpaired even when stored up to three weeks.

6. CONCLUSIONS

Polyethylene bottles are satisfactory for taking grab samples of SF6. Storage of SF6 samples over periods of weeks is possible. They are, however, not suitable for Freon 12 since there is a considerable loss of sample during storage.

Sample bags generally prove to be useful, accurate and reliable for taking both spot and medium term average samples. They have the following advantages:

- They can be used for spot sampling SF6 to accuracy comparable with on-line analysis.
- They can be used for average-sampling over hours, or days.
- Shelf-life of contents are shown to be of the order of at least a month.
- Large sample allows repeat analyses.

They are, however, bulky and somewhat delicate. They are thus potentially vulnerable during transport. The effects of repeated use also need to be established.

Adsorption tubes were found to be less accurate than other sampling methods. Advantages are that they can be used at lower concentrations because the sample is preconcentrated. They are robust and convenient to use, but in the system described this is offset by the requirement for an accurate, calibrated, reliable sample pump, which must be operated for an accurately recorded time. Although only tested for taking samples over several minutes, there is no reason why this should not be extended, as long as the 'breakthrough volume' is not exceeded.

Vacutainers are as accurate as on-line analysis for taking spot samples. They are easy to use and analyse, are compact in transit and cheap. Contents have a shelf-life of several weeks or longer. Reservations are that they are a 'one-shot' method, and as such require several duplicate samples to provide replication. Also, the use of a syringe is involved to take the samples, and this requires a safety procedure and perhaps some safety modification to the syringe to guard the needle.

Cautionary notes which apply generally to these sampling techniques, but excluding bag sampling, are that some prior thought is required to arrange for the desired range of concentration to be sampled which is compatible with the intended method of analysis. Two related disadvantages that apply generally are the lack of an immediate indication of tracer concentration and the possible loss or deterioration of the sample.

In theory, however, any of these simple techniques could replace on-line methods of analysis, and in so doing remove the need for a skilled operator and complex equipment on site.

REFERENCES

1. Breum, N O and Perera, M D A E S, Ventilation measurement using spot sampling of sulphur hexafluoride on a solid adsorbent, Building and Environment, Vol 19(3), pp 175-178, (1984).

2. Tamura, G T and Evans, R G, Evaluation of evacuated glass tubes for sampling of SF6/air mixture for air exchange measurement, ASHRAE Journal, pp 40-43, (October 1983).

TABLES

FIGURES

Bottle No.	Contents (tracer)	µl in 5ml sample	Weekly analyses normalised units				
		wk 0		wk 1	wk 2	wk 3	wk 4
1	F12	51.5	100	61.9	-	-	-
2	"	46.5	"	-	50.6	-	-
3	"	50.0	"	-	-	36.5	-
4	"	50.0	"	-	-	-	25.6
5	F12	47.5	100	60.2	-	-	-
6	"	51.5	"	-	50.7	-	-
7	"	50.5	"	-	-	38.2	-
8	"	52.0	"	-	-	-	23.8
5	SF_6	53.0	100	87.9	-	-	-
6	"	50.0	"	-	99.0	-	-
7	"	49.0	"	-	-	100.8	-
8	"	49.5	"	-	-	-	95.9
9	SF_6	52.0	100	94.6	-	-	-
10	"	52.0	"	-	81.5	-	-
11	"	51.5	"	-	-	86.0	-
12	"	51.5	"	-	-	-	85.6

Bottle volume nominally 500 ml (air)

Bottles 1 - 4 initially injected with 5 ml of F12
5 - 8 " " " " F12 and 5 ml of SF_6
9 - 12 " " " " SF_6

5 ml samples removed for analysis with Miran 1a IR analyser

Analysis accuracy approximately +/- 1% for F12; +/- 2% for SF_6

Table 1 Shelf life test for polyethlene bottles.

Area count from gas chromatograph integrator.

Elapsed time (hours)	Standard*	Bag No. 1	Bag No. 2	Bag No. 3
43	410.01 410.46 410.95	394.70 393.69	399.78 402.18	399.08 400.07
332	418.77 418.76 418.19	410.14 408.94	409.97 410.32	409.30 409.40
648	429.26 432.26	418.88 420.07	419.01 418.68	410.09 413.69
786	432.32 432.85	425.61 426.71	429.48 430.84	428.23 429.64

* Standard contains 60.5 ppb. SF_6

Areas normalised by the weekly standard.

Elapsed time (hours)	Averaged area counts for standard	Bag No. 1	Bag No. 2	Bag No. 3
43	410.47	0.961 0.959	0.973 0.979	0.972 0.974
332	418.57	0.980 0.977	0.979 0.980	0.978 0.978
648	430.81	0.972 0.975	0.973 0.972	0.952 0.960
786	432.58	0.984 0.986	0.993 0.996	0.990 0.993

Table 2 Shelf life test for Tedlar sampling bags.

Recovery for the adsorption tubes stored at different time intervals and temperatures.

Storage interval (hours)	Storage temperature (°C)	Recovery (%[x])
24	4	94.1 ± 4.7
	15 - 20	92.9 ± 4.4
48	4	81.2 ± 2.9
	15 - 20	83.2 ± 5.0
72	4	78.1 ± 1.3
	15 - 20	73.0 ± 1.7
96	4	77.2 ± 1.8
	15 - 20	70.5 ± 1.4

[x] Arithmetic mean and standard deviation of one measurement on five different adsorption tubes.

Recovery from adsorption tubes with different amounts of SF_6 deposited.

SF_6 deposited (ng)	Recovery (%*)
10	100.0 ± 4.2
15	89.8 ± 2.1
20	88.1 ± 3.4
30	86.0 ± 1.2
40	83.8 ± 0.7
50	83.2 ± 0.9

* Arithmetic mean and standard deviation of one measurement on four different adsorption tubes.

Table 3 Recovery factors for adsorption tubes.

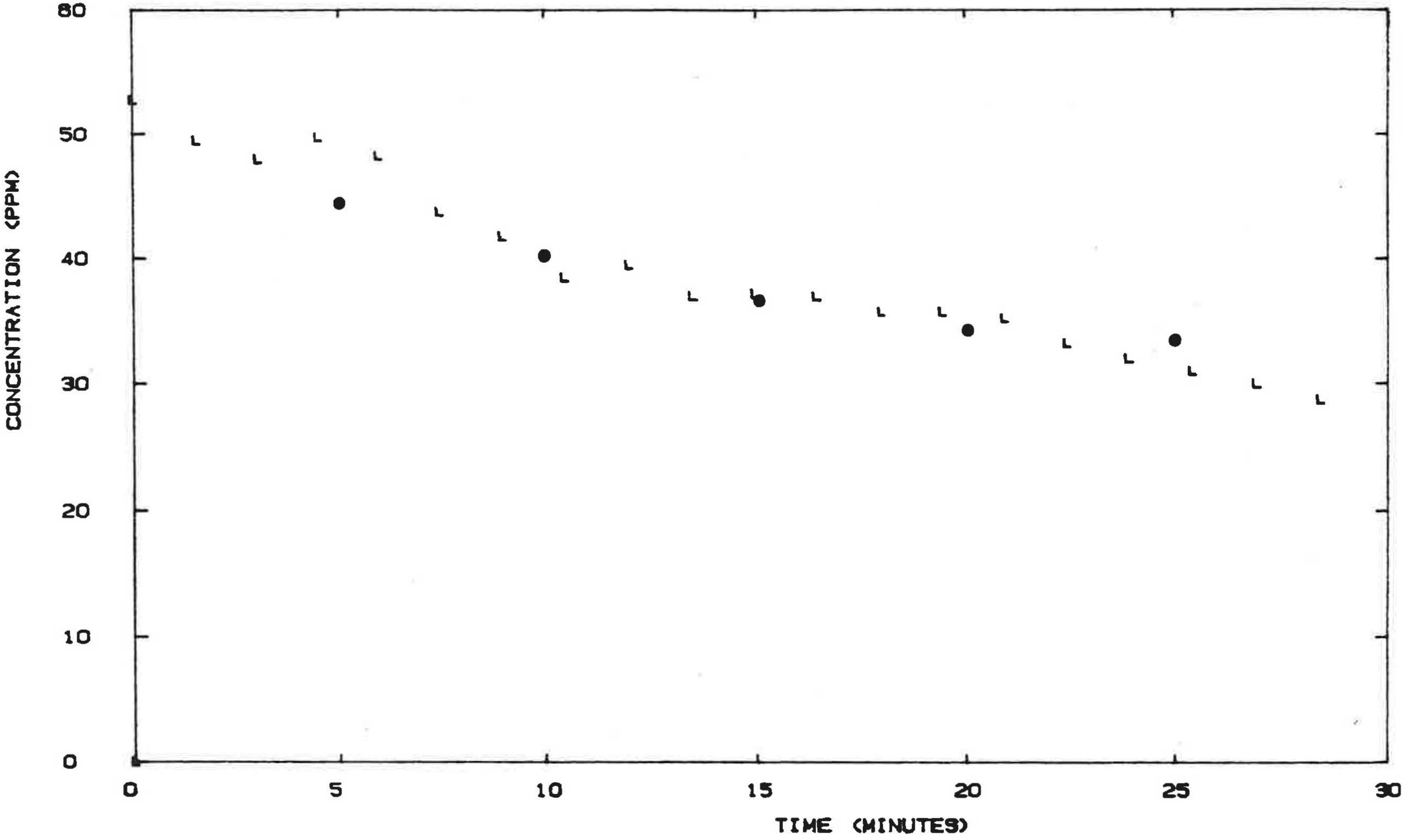


Figure 1 Comparison of polyethlene bottle samples (●) with on-line (L) measurements.

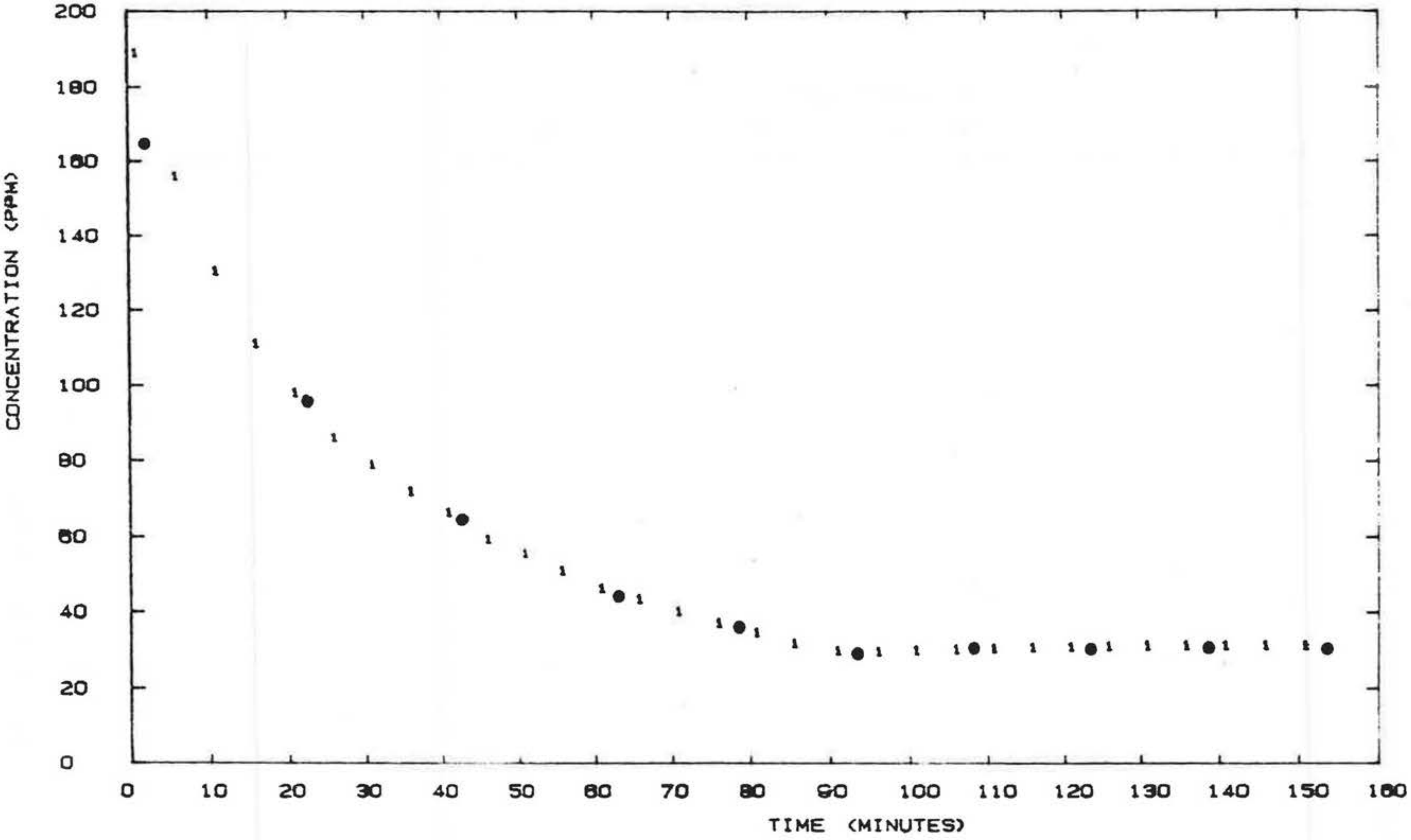


Figure 2 Comparison of polyethlene bottle samples (●) with on-line (1) measurements.

CHAPTER 9

EFFECT OF DRAUGHTSTRIPPING WINDOWS ON THE ENERGY CONSUMPTION OF AN OFFICE BUILDING

1. INTRODUCTION

One of the objectives of this programme of work was to determine the effect of ameliorative measures such as draughtstripping on the energy consumption of office buildings.

Measurements of infiltration rate were carried out (Chapter 6) in building B18 (Appendix I) before and after all windows were draughtstripped. Before draughtstripping, the infiltration rates ranged from 0.35 to about 0.55 ach for a variety of weather conditions. After the windows were weatherstripped, the rates were reduced to the range 0.18 to 0.26 ach. These results can therefore be seen to indicate that draughtstripping windows can reduce the overall infiltration by a sizeable amount.

It was, however, considered that in the majority of the time, measurements before and after a retrofit would not be available. In such situations, there must be another way the effectiveness of remedial measures could be evaluated prior to implementing these measures.

This Chapter will demonstrate that, in the absence of measured infiltration rates before and after an energy-saving remedial retrofit, existing computer programs can be used to determine the effectiveness of such measures, in particular, the draughtstripping of windows.

To do this, an BRE in-house computer program called BREEZE (Section 2) was used to predict the effect that draughtstripping of windows had on building B18. In this way, the predictions could be matched with the experimental results detailed above.

Apart from the correctness of the model used to describe the physical processes, an important prerequisite in any simulation is the validity of the input data. Sufficient care, therefore, must be taken when preparing an input data file for any computer prediction. The structure and the setting up of data input files for the present computer simulation is described fully in Section 3.

The results of the computer predictions are discussed in Section 3. The predicted infiltration rates, before and after draughtstripping, are evaluated against the field measurements.

The energy savings, associated with the reduced overall infiltration rate, are then discussed in Section 5. Finally, in Section 6, overall conclusions are drawn.

2. BREEZE COMPUTER PROGRAM

2.1. Introduction

BREEZE is a computer program written for the Building Research Station under an extramural contract by SCICON. It was written in FORTRAN-4 and has been implemented in-house on a VAX mainframe computer. The program was a modified version of the SMOKE program [1] written by SCICON for the Fire Research Station, Borehamwood, UK.

BREEZE considers the building as a network of spaces (nodes), each at a specific pressure with air moving between them from regions of high pressure to those of low pressure. Using an iterative technique, movement of air between spaces are determined. Three differing sets, of which the first set is optional, are usually required as data inputs (Fig 1) to the program.

2.2. 'New values' data set

This optional first set, identified by the starting line *NEWVAL, defines values which overwrite 'dictionary' variables (i.e. values built-in to the program) when the program is run.

For the present simulation, those overwritten were;

- wind speed (VW),
- internal and external temperatures (TMPIN, TMPOUT),
- maximum number of iterations (ITSOL) allowed for solutions to converge in order to satisfy the maximum permitted changes in
  - . pressure difference (PREMAX), and
  - . mass flow rate (FLOMAX)

  before convergence is assumed for the flow paths.
- HCEILG sets the height of the room ceilings.

The *EOD indicates the end of that current data set.

2.3. Building data

The second data set, identified by the first line *BUILD, gives details of the nodes into which the building is divided. All data cards within this set are in free format. The data items on each line must, however, appear in a specific order and must be separated from each other by one space. Also, no blank lines are allowed within the data pack.

Building data are specified floor by floor. A card of the form, FLOOR n, indicates that the data cards that immediately follows it describes the layout of floor number n. Each card in this group describe a single node and contains the following information;

- six character identifier for the node type,
- number of the node on that floor, and
- details of the node.

Information regarding node types and details required about these nodes are given in Reference 2. The nodes, starting with 1 on each floor, are numbered consecutively. The outside air is always specified as the first node on each floor. Other nodes are specified in any order.

Each vertical shaft, such as a staircase or a lift shaft, has a shaft number which is used to identify it as it passes from floor to floor. The first vertical shaft is assumed to be the outside air so that each shaft is numbered consecutively starting from 2. Though shaft numbers need not necessarily be the same as node numbers, the same shaft must have the same shaft number on each floor.

2.4. Flow path data

The final data section is that dealing with the flow paths between various nodes. The group of cards that describe these are headed by the declaration, *PATHS. The details required for each path depend on the type of flow path and are defined in Reference 2.

The program allows for only one flow path between any two nodes and therefore presents a serious problem when used on most buildings. To avoid this, modifications have to be made to the 'building data' set by introducing 'ghost' nodes. Each 'ghost' node, of node type ROOM or CORDOR, isolates an illegal flowpath and is joined to its 'home' node by a 'ghost' flowpath. The concept of ghost nodes will be further clarified in Section 3.2.

Flow path data are specified floor by floor in the same way as building data. After each FLOOR card (Fig 1), the details of the air flow paths are read from data cards, each of which describes one flow path and contains the following items in the order,

- data card identifier, NODE,
- node numbers of the end points,
- flow path type, and
- details of the flow path.

3. INPUT DATA

The data (Figure 1) for the present simulation were input into BREEZE as the three sets of information described above.

3.1. New values

The internal temperature, TMPIN, used in the simulation was taken as the 'running' temperature of the low-energy building. The values of wind speed, VW, and external temperature, TMPOUT, used were obtained by considering the average values experienced at Kew, UK during the standard 'weather year' from 1st October 1967 to 31st March 1968. During this period of 182 days, the predominant wind direction was 209 degN, i.e. from the south-west. The following values were therefore used in this simulation:

Parameter	Variable name	Value
wind speed (m/s)	VW	4.1
internal temperature (°C)	TMPIN	18.5
external temperature (°C)	TMPOUT	7.3

3.2. Building data

Building B18 has three storeys. Figure 2 shows the floor plans. The building was idealised into various nodes as shown in Figure 3. Within the data pack, the ground storey is designated FLOOR 1 and the first and second storeys as FLOOR 2 and 3 respectively. Node 1 in each floor is the outside air.

3.2.1. Stairwells

In each floor, Nodes 2 and 3 are the stairwells with shaft numberings of 2 and 3 respectively. Their respective cross-sectional areas of 9.0 and 7.5 m^2 are the areas of these openings in the horizontal plane between one floor and the next.

3.2.2. Corridors

The following nodes represent the corridors:

FLOOR	NODES
1	9, 13
2	6, 10, 11
3	6, 10, 11

3.2.3. Rooms

All other nodes, except the ones listed above are considered as ROOMs. It should be noted that each ROOM in the idealised layout of Figure 3 is, in reality, an aggregate of various offices as shown in the building floor plans (Fig 2).

3.2.4. 'Ghost' nodes

Some ROOMs have more than one flow path connecting it to the outside, usually through windows. To overcome the 'one flow path' condition (Section 2.3), 'ghost' nodes of the type ROOM were added to the idealised layout. These are as follows:

FLOOR	NODES
1	4, 12
2	4, 14
3	4, 14

3.3. Pressurisation measurements to determine leakage areas

Leakage areas of the various openings are required as part of the 'flow path' data input. This information is usually gathered by carrying out 'pressurisation' tests [3] on the various components, e.g. windows and doors, of interest. From such tests, the equivalent area, A, of the opening can be obtained. This value is used within the program to determine the volume flow rate, Q, where

$$Q = C\ A\ (2\ \Delta P/\rho)^{n}$$

and C is a flow coefficient (taken as 0.65), ΔP is the pressure difference across the opening, ρ is the density of air and n is an exponent (taken as 0.5).

Pressurisation tests were carried out in building B18 after the windows had been weatherstripped. South facing windows are different to those on the north facing side and are much tighter. This is reflected on the 'pressurisation test' results that were obtained;

Window	Leakage area (m^2)	Leakage area per metre length (m^2 / m)
South facing	0.00321	0.00031
North facing	0.00533	0.00052

A similar pressurisation test had not been carried out before the windows were draughtstripped. For the present simulation excercise, recourse was therefore made (Section 3.5) to published material regarding the leakiness of similar but non-draughtstripped windows.

3.4. Wind pressure coefficients

For flow path connecting interior nodes to the outside, BREEZE requires the external surface pressure coefficients, Cp, to be known at these points. The pressure on the external fabric of the building at any of these points is then,

$$P = (\rho/2)\ U^{2}\ \ Cp$$

where U is the wind speed. The wind speed should be measured at a location and at a height used to initially determine the pressure coefficient.

Using a 1 in 200 scale model of the building together with adjacent buildings, wind tunnel test were carried out in the BRE Environmental Wind Tunnel (Fig 4). The airflow over the model was simulated to be that of the atmospheric boundary layer flowing over a suburban site. Further details of the wind tunnel and the simulated boundary layer are given in Reference 4.

The tests were carried out for twelve wind directions in intervals of 30 degrees. The reference wind speed was determined at a model height equivalent to 10 m full scale and at a point upstream of the model. In the present study, only the pressure coefficients obtained for winds blowing from the dominant south-west direction (Section 3.1) were used in the present study. These values are shown in parenthesis in Figure 3.

3.5. Flow path data

Though BREEZE has provision for recognising eleven different flow paths, only the following three type were used. These are identified by the type number (Section 2.4) as follows:

Identifier	Flow path type
3	Outside door
4	Inside door
5	Window with one opening

3.5.1. External doors

On FLOOR 1, there are two doors connecting the building to the outside. Since no 'pressurisation test' results were available, a crack width of 2 mm was assumed. This is in keeping with some previous computer simulation work carried out by Wright [5]. This gave the following crack areas:

NODE		Crack length	Crack area
From	To	(m)	(m^2)
1	2	16.0	0.032
1	3	8.0	0.016

3.5.2. Internal doors

All internal doors were assumed to be kept open. The equivalent leakage areas of these open doors have been taken to be equal to 20% of the openable area. This percentage has been previously used in a 'house' simulation [6]. In the absence of 'pressure test' results, this approximation was considered to be the best available for the present work.

3.5.3. Windows

The main emphasis on the present simulation was to determine the effect of draughtstripping windows on the energy consumption of the 'low energy' office building. As stated earlier (Section 3.3), no experimental data were available on the leakage areas of the windows before they were draughtstripped.

To overcome this lack of information, recourse was made to published material [7] regarding crack widths of various window types. Most of the windows in the 'low energy' office are of the centrally-pivoted (horizontal) wood type. From Table 8 in Reference 7, the average gap width of this type of window was taken as being 2 mm. The gap widths after draughtstripping were taken from the experimental results given in Section 3.3. of Reference 7.

4. RESULTS

4.1. Introduction

The program BREEZE was run on the VAX mainframe computer using the two data sets shown in Figure 1. The solutions converged after about nine iterations and each run took approximately 33 seconds of central processor time. The evaluated airflows in the office building for the two cases of non-draughtstripped and draughtstripped windows are shown in Figures 5 and 6 respectively. The simulation was evaluated by comparing the computed whole building infiltration rate obtained with non-draughtstripped windows with results obtained from field tests.

4.2. Windows without draughtstripping

Figure 5 shows the airflows within the office building with non-draughtstripped windows. The volume flows of the fresh air entering (infiltrating) and the air leaving (exfiltrating) the building are as follows:

Space	Infiltration (m^3/hr)	Exfiltration (m^3/hr)
Ground floor	1626	259
First floor	823	1072
Second floor	323	1440

Taking the volume of the building as 5286 m^3, the whole building infiltration rate, I, works out at 0.52 airchanges per hour (ach). Figure 5 also shows that more than half the total infiltration occured through the south facing windows on the ground floor.

4.3. Windows with draughtstripping

Figure 6 shows the airflows within the office building with the windows draughtstripped. The volume flows of air entering and leaving the building are as follows:

Space	Infiltration	Exfiltration
	(m^3/hr)	
Ground floor	412	44
First floor	150	249
Second floor	78	346

The results indicate that with draughtstripped windows, the whole building infiltration rate has been reduced to 0.12 ach from a rate of 0.52 ach.

4.4. Validating the computer simulation

The airchange rates predicted above were compared with the experimental measurements described in the Introduction (Section 1).

The whole building rates as measured (Section 4.2. of Chapter 6) without window draughtstripping are shown, for a variety of windspeeds and directions, in Figure 7. They are plotted as I/U (i.e. ach/windspeed) against wind direction.

Figure 7 shows that for a wind direction of 210 degN and a windspeed of 4.1 m/s (i.e. the values used in the computer simulation), the experimental results indicate a whole building infiltration rate in the region of 0.57 ach.

The predicted rate, with the windows draughtstripped, can be compared with the experimental measurements of Test F (Section 4.3. of Chapter 6). During this test, with the wind blowing from 210 degN with a speed between 3.3 to 4.1 m/s, localised measurements off overall infiltration rates ranged between 0.18 to 0.26 ach. When blended samples were taken, by manifolding together all local sample lines, an infiltration rate 0.18 ach was measured.

The predicted overall infiltration rates can be compared with experimental measurements and summarised as follows:

Condition	Infiltration rate (ach)	
	Predicted	Measured
Without draughtstripping	0.52	0.57
With draughtstripping	0.12	0.18

The predicted values compares well with the experimental value and, therefore, gives some confidence in the computer simulation.

5. ENERGY ASPECTS OF DRAUGHTSTRIPPING WINDOWS

According to the predicted values, draughtstripping the windows has reduced the infiltration rate of the low-energy office building from 0.52 ach to 0.12 ach. It is now possible to make an approximation to the energy savings associated with this reduction summed over the heating season. The simplifications used in arriving at these rates (i.e. average values of windspeed, wind direction and internal/external temperatures) should, however, be remembered.

The reduction, dQ (kWh), of the daily heat loss from the building is given by,

$$dQ = 0.024\ (V.dI/3)\ dt$$

where $V = 5286\ m^3$ is the volume of the building,
$dI = 0.4$ ach is the reduction in the infiltration rate,
$dt = tmpin - tmpout$
$tmpin = 18.5\ ^oC$ is the seasonal mean internal temperature,
and
$tmpout = 7.3\ ^oC$ is the seasonal mean external temperature.

This can be translated [8] into a reduction in the seasonal energy requirement, dQ(season), from the heating system for space heating as,

$$dQ(season) = 0.0036\ (D/e)\ (dQ) \qquad GJ$$

where $D = 182$ is the number of days in the heating season,
and e is the efficiency of the heating system.

The 'low energy' office uses gas boilers for space heating. Measurements have shown [9] that the realised seasonal efficiencies of these boilers are about 60%.

Using this value for the efficiency e, the reduction in the seasonal energy consumption through window draughtstripping is then calculated to be 207 GJ.

The gas consumption in the low-energy building is about 30 GJ per week [9] for a weekly external air temperature of 7 °C. Over the heating period of 182 days, i.e. 26 weeks, this translates to a total consumption of 780 GJ. Hence, according to these simplified calculations, draughtstripping has reduced the total gas consumed within the building by about 21%.

6. CONCLUSIONS

The objective of this Chapter was to determine the effectiveness of a remedial measure, such as draughtstripping, on the energy consumption of an office building.

It was, however, recognised that in the majority of the time, experimental measurements before and after a retrofit may not be available and recourse then needs to be made towards prediction techniques.

In this Chapter, a computer program called BREEZE was used to predict the effect draughtstripping windows had on the overall infiltration rate into building B18. It was noted that an important prerequisite to the correct functioning of a prediction technique is the integrity of the input data. Considerable attention was, therefore, devoted to detailing how such a data set could be gathered and set up.

Predictions showed that the overall infiltration rate of building B18 was reduced to 0.12 ach from 0.52 ach when the windows were draughtstripped. These predicted values were shown to compare well with measured values.

The energy saving associated with this reduction in infiltration was calculated. This showed that for this particular building, draughtstripping has reduced the total gas consumed within the building by about 21%. This saving compares well with a saving of 22% obtained (Chapter 1) in a large office building in London when the windows of that building were weather-stripped.

It can, therefore, be concluded that draughtstripping windows can provide a considerable saving in the energy consumption of a building. It is also seen that prediction techniques can be used to good effect to determine the effectiveness of such ameliorative measures.

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FIGURES

```
***
    4th Nov 1984 (1145) -- BUILDING 18 AIRFLOW PREDICTION
\IEP
*NEWVAL
VW 4.10
TMPIN 16.5
TMPOUT 7.3
ITSOL 1000
FREMAX 0.001
FLOMAX 0.001
HCEILG 2.30
*EOD
*BUILD
FLOOR 1
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
ROOM 6
ROOM 7
ROOM 8
CORDOR 9
ROOM 10
ROOM 11
ROOM 12
ROOM 13
CORDOR 14
FLOOR 2
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
CORDOR 6
ROOM 7
ROOM 8
ROOM 9
CORDOR 10
CORDOR 11
ROOM 12
ROOM 13
ROOM 14
FLOOR 3
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
CORDOR 6
ROOM 7
ROOM 8
ROOM 9
CORDOR 10
CORDOR 11
ROOM 12
ROOM 13
ROOM 14
*EOD
*PATHS
FLOOR 1
NODE 1 2 3 0.032 0.500 3.0000 -0.02
NODE 1 3 3 0.016 0.500 3.000 -0.04
NODE 1 4 5 0.01138 0.500 1.380 0.10
NODE 1 5 5 0.01107 0.500 1.380 -0.11
NODE 1 6 5 0.00351 0.500 1.450 0.36
NODE 1 7 5 0.00709 0.500 1.450 0.38
NODE 1 8 5 0.01422 0.500 1.380 -0.04
NODE 1 10 5 0.01892 0.500 1.450 0.29
NODE 1 11 5 0 01033 0.500 1.380 -0.11
NODE 1 12 5 0.00530 0.500 1.380 -0.37
NODE 1 13 5 0.00764 0.500 1.450 0.03
NODE 2 5 4 0.167 0.500
NODE 2 7 4 0.167 0.500
NODE 2 9 4 0.6 0.500
NODE 3 9 4 0.6 0.500
NODE 3 14 4 0.6 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 5 6 4 0.335 0.500
NODE 5 7 4 999. 2.0
NODE 6 7 4 0.335 0.500
NODE 8 9 4 1.340 0.500
NODE 9 10 4 2.345 0.500
NODE 11 12 4 999. 2.0
NODE 11 14 4 1.005 0.500
NODE 12 13 4 999. 2.0
NODE 12 14 3 0.016 0.500 3.0 -0.37
NODE 13 14 4 1.005 0.500
FLOOR 2
NODE 1 4 5 0.01138 0.500 1.380 0.11
NODE 1 5 5 0.01637 0.500 1.380 -0.14
NODE 1 7 5 0.01011 0.500 1.450 0.25
NODE 1 8 5 0.02062 0.500 1.380 -0.07
NODE 1 9 5 0.01443 0.500 1.380 -0.11
NODE 1 12 5 0.01750 0.500 1.450 0.25
NODE 1 13 5 0.00758 0.500 1.450 0.03
NODE 1 14 5 0.01138 0.500 1.380 -0.36
NODE 2 6 4 0.8 0.500
NODE 3 11 4 0.8 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 4 7 4 999. 2.0
NODE 5 6 4 1.340 0.500
NODE 6 7 4 1.005 0.500
NODE 6 10 4 0.6 0.500
NODE 8 10 4 1.340 0.500
NODE 9 11 4 1.005 0.500
NODE 9 14 4 999. 2.0
NODE 10 11 4 0.6 0.500
NODE 10 12 4 2.345 0.500
NODE 11 13 4 1.005 0.500
NODE 11 14 4 999. 2.0
NODE 13 14 4 999. 2.0
FLOOR 3
NODE 1 4 5 0.01138 0.500 1.380 0.02
NODE 1 5 5 0.01511 0.500 1.380 -0.15
NODE 1 7 5 0.00813 0.500 1.450 0.31
NODE 1 8 5 0.01312 0.500 1.380 -0.06
NODE 1 9 5 0.01207 0.500 1.380 -0.13
NODE 1 12 5 0.01645 0.500 1.450 0.28
NODE 1 13 5 0.00813 0.500 1.450 0.06
NODE 1 14 5 0.01138 0.500 1.380 -0.36
NODE 2 6 4 0.5 0.500
NODE 3 11 4 0.8 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 4 7 4 999. 2.0
NODE 5 6 4 1.005 0.500
NODE 6 7 4 0.670 0.500
NODE 6 10 4 0.6 0.500
NODE 8 10 4 1.340 0.500
NODE 9 11 4 1.005 0.500
NODE 9 14 4 999. 2.0
NODE 10 11 4 0.6 0.500
NODE 10 12 4 0.0616 0.500
NODE 11 13 4 1.005 0.500
NODE 11 14 4 999. 2.0
NODE 13 14 4 999. 2.0
*EOD
\END
\SIM
\END
\EEP
*FLOWS
\END
\FIN
```

Figure 1.a.   Data pack for building with weatherstripped windows.

```
***  4th Dec 1984 (1430) -- BUILDING 18 AIRFLOW PREDICTION ***
\INP
*NEWVAL
VW 4.10
TMFIN 18.5
TMPOUT 7.3
ITSCL 1000
PREMAX 0.001
FLOMAX 0.001
HCEILG 2.30
*EOD
*BUILD
FLOOR 1
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
ROOM 6
ROOM 7
ROOM 8
CORDOR 9
ROOM 10
ROOM 11
ROOM 12
ROOM 13
CORDOR 14
FLOOR 2
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
CORDOR 6
ROOM 7
ROOM 8
ROOM 9
CORDOR 10
CORDOR 11
ROOM 12
ROOM 13
ROOM 14
FLOOR 3
OUTAIR 1
SHAFT 2 9. 2
SHAFT 3 7.5 3
ROOM 4
ROOM 5
CORDOR 6
ROOM 7
ROOM 8
ROOM 9
CORDOR 10
CORDOR 11
ROOM 12
ROOM 13
ROOM 14
*EOD
*PATHS
FLOOR 1
NODE 1 2 3 0.0320 0.500 3.0000 -0.02
NODE 1 3 3 0.0160 0.500 3.000 -0.04
NODE 1 4 5 0.0434 0.500 1.380 0.10
NODE 1 5 5 0.0420 0.500 1.380 -0.11
NODE 1 6 5 0.0228 0.500 1.450 0.36
NODE 1 7 5 0.0460 0.500 1.450 0.38
NODE 1 8 5 0.0542 0.500 1.380 -0.04
NODE 1 10 5 0.1228 0.500 1.450 0.29
NODE 1 11 5 0.0394 0.500 1.380 -0.11
NODE 1 12 5 0.0202 0.500 1.380 -0.37
NODE 1 13 5 0.0496 0.500 1.450 0.03
NODE 2 5 4 0.167 0.500
NODE 2 7 4 0.167 0.500
NODE 2 9 4 0.6 0.500
NODE 3 9 4 0.6 0.500
NODE 3 14 4 0.6 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 5 6 4 0.335 0.500
NODE 5 7 4 999. 2.0
NODE 6 7 4 0.335 0.500
NODE 8 9 4 1.340 0.500
NODE 9 10 4 2.345 0.500
NODE 11 12 4 999. 2.0
NODE 11 14 4 1.005 0.500
NODE 12 13 4 999. 2.0
NODE 12 14 3 0.016 0.500 3.0 -0.37
NODE 13 14 4 1.005 0.500
FLOOR 2
NODE 1 4 5 0.0434 0.500 1.380 0.11
NODE 1 5 5 0.0624 0.500 1.380 -0.14
NODE 1 7 5 0.0656 0.500 1.450 0.25
NODE 1 8 5 0.0786 0.500 1.380 -0.07
NODE 1 9 5 0.0550 0.500 1.380 -0.11
NODE 1 12 5 0.1136 0.500 1.450 0.25
NODE 1 13 5 0.0492 0.500 1.450 0.03
NODE 1 14 5 0.0434 0.500 1.380 -0.36
NODE 2 6 4 0.8 0.500
NODE 3 11 4 0.8 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 4 7 4 999. 2.0
NODE 5 6 4 1.340 0.500
NODE 6 7 4 1.005 0.500
NODE 6 10 4 0.6 0.500
NODE 8 10 4 1.340 0.500
NODE 9 11 4 1.005 0.500
NODE 9 14 4 999. 2.0
NODE 10 11 4 0.6 0.500
NODE 10 12 4 2.345 0.500
NODE 11 13 4 1.005 0.500
NODE 11 14 4 999. 2.0
NODE 13 14 4 999. 2.0
FLOOR 3
NODE 1 4 5 0.0434 0.500 1.380 0.02
NODE 1 5 5 0.0576 0.500 1.380 -0.15
NODE 1 7 5 0.0528 0.500 1.450 0.31
NODE 1 8 5 0.0500 0.500 1.380 -0.06
NODE 1 9 5 0.0460 0.500 1.380 -0.13
NODE 1 12 5 0.1065 0.500 1.450 0.25
NODE 1 13 5 0.0528 0.500 1.450 0.06
NODE 1 14 5 0.0434 0.500 1.350 -0.36
NODE 2 6 4 0.8 0.500
NODE 3 11 4 0.8 0.500
NODE 4 5 4 999. 2.0
NODE 4 6 4 999. 2.0
NODE 4 7 4 999. 2.0
NODE 5 6 4 1.005 0.500
NODE 6 7 4 0.670 0.500
NODE 6 10 4 0.6 0.500
NODE 8 10 4 1.340 0.500
NODE 9 11 4 1.005 0.500
NODE 9 14 4 999. 2.0
NODE 10 11 4 0.6 0.500
NODE 10 12 4 0.0616 0.500
NODE 11 13 4 1.005 0.500
NODE 11 14 4 999. 2.0
NODE 13 14 4 999. 2.0
*EOD
\END
\SIM
\END
\REP
*FLOWS
\END
\FIN
```

Figure 1.b.   Data pack for building with unsealed windows.

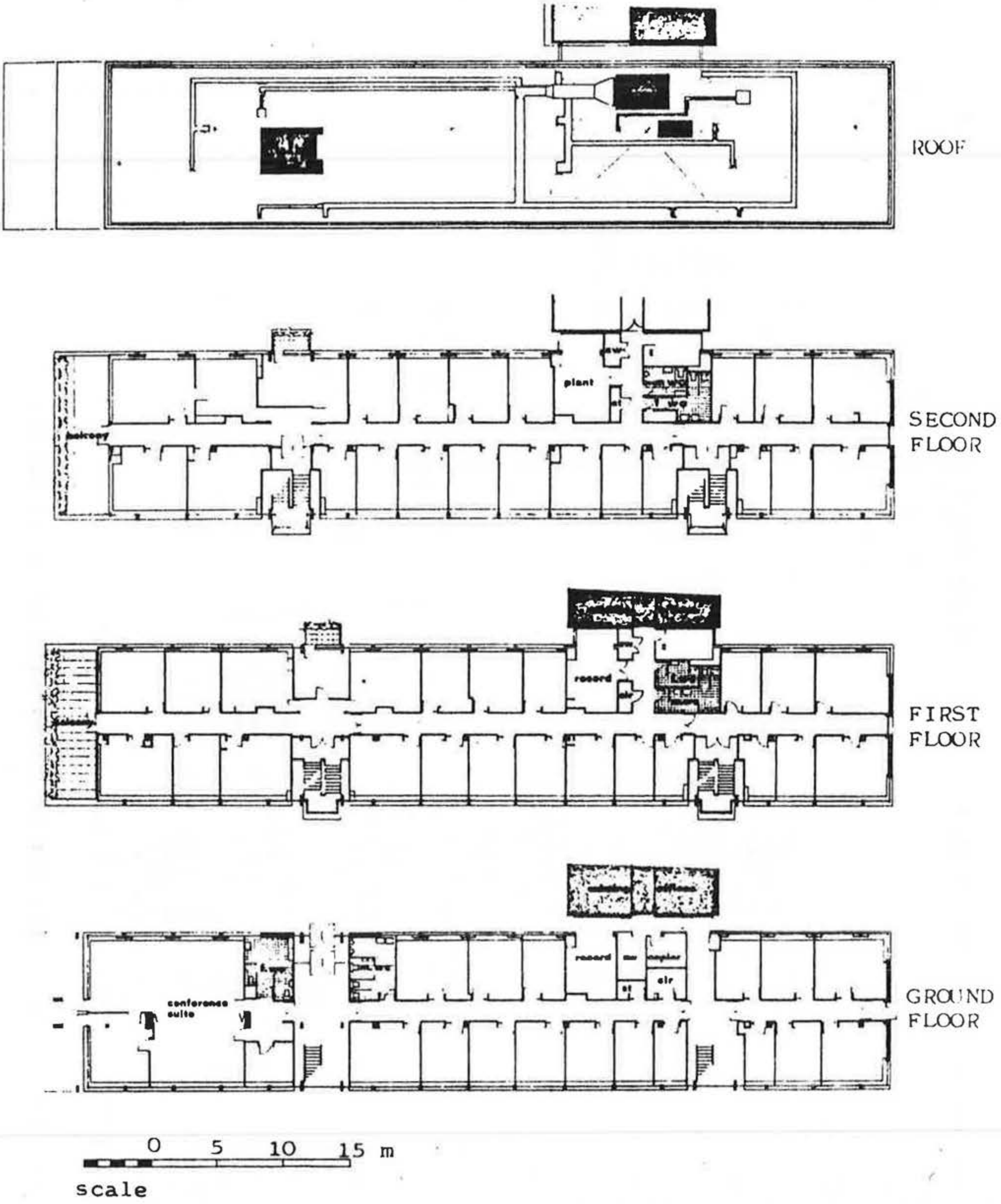

Figure 2 Floor plans of the BRE Low-energy office building.

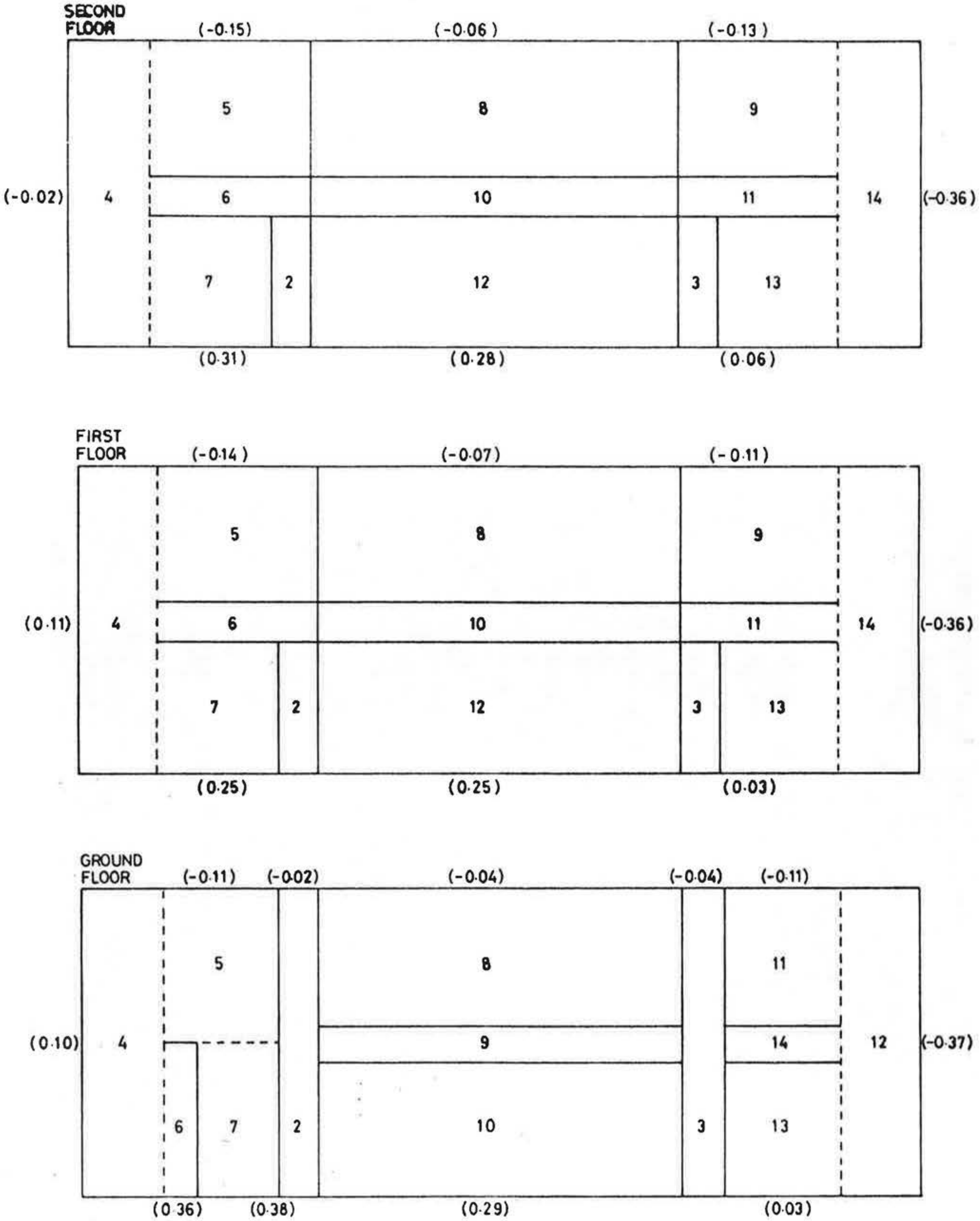

Figure 3 'Low-energy' building idealised as nodes together with wind pressure coefficients (in parenthesis).

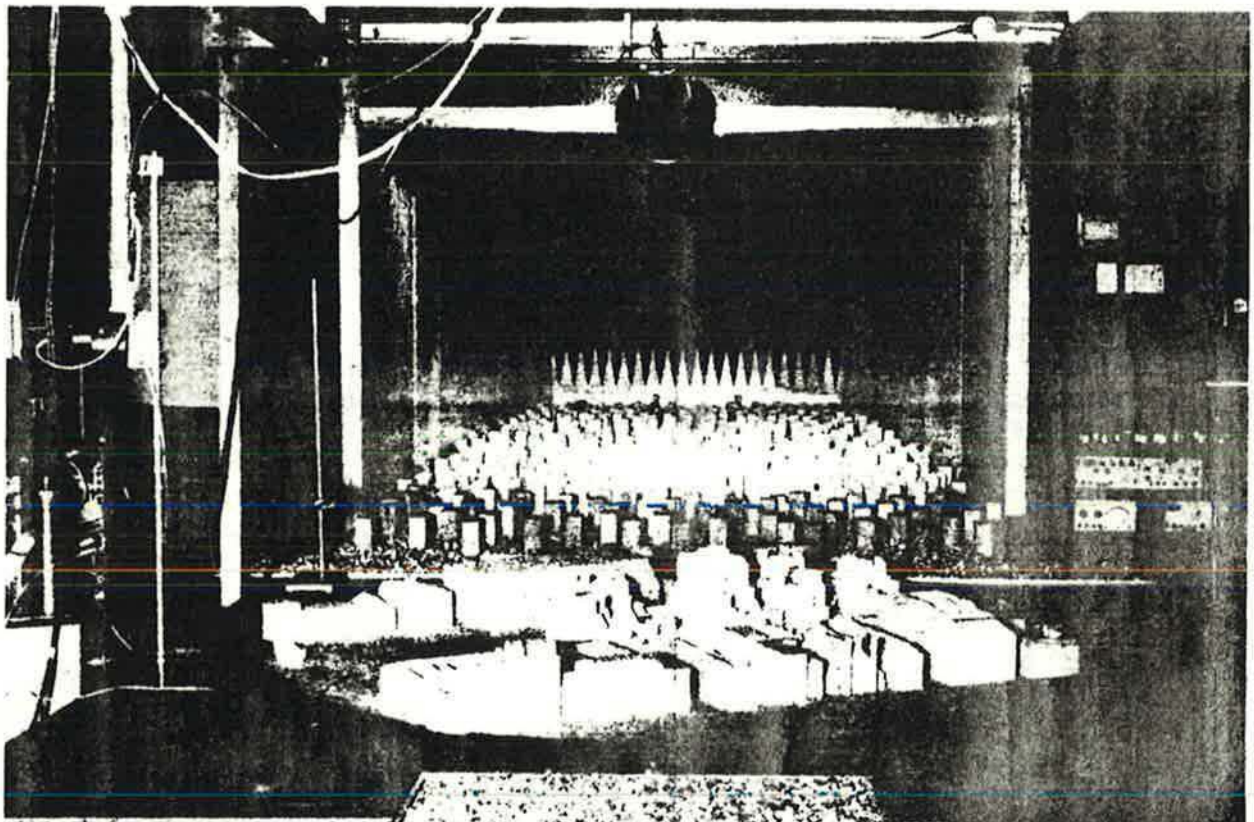

Figure 4 Inside the BRE Environmental Wind Tunnel and looking upstream

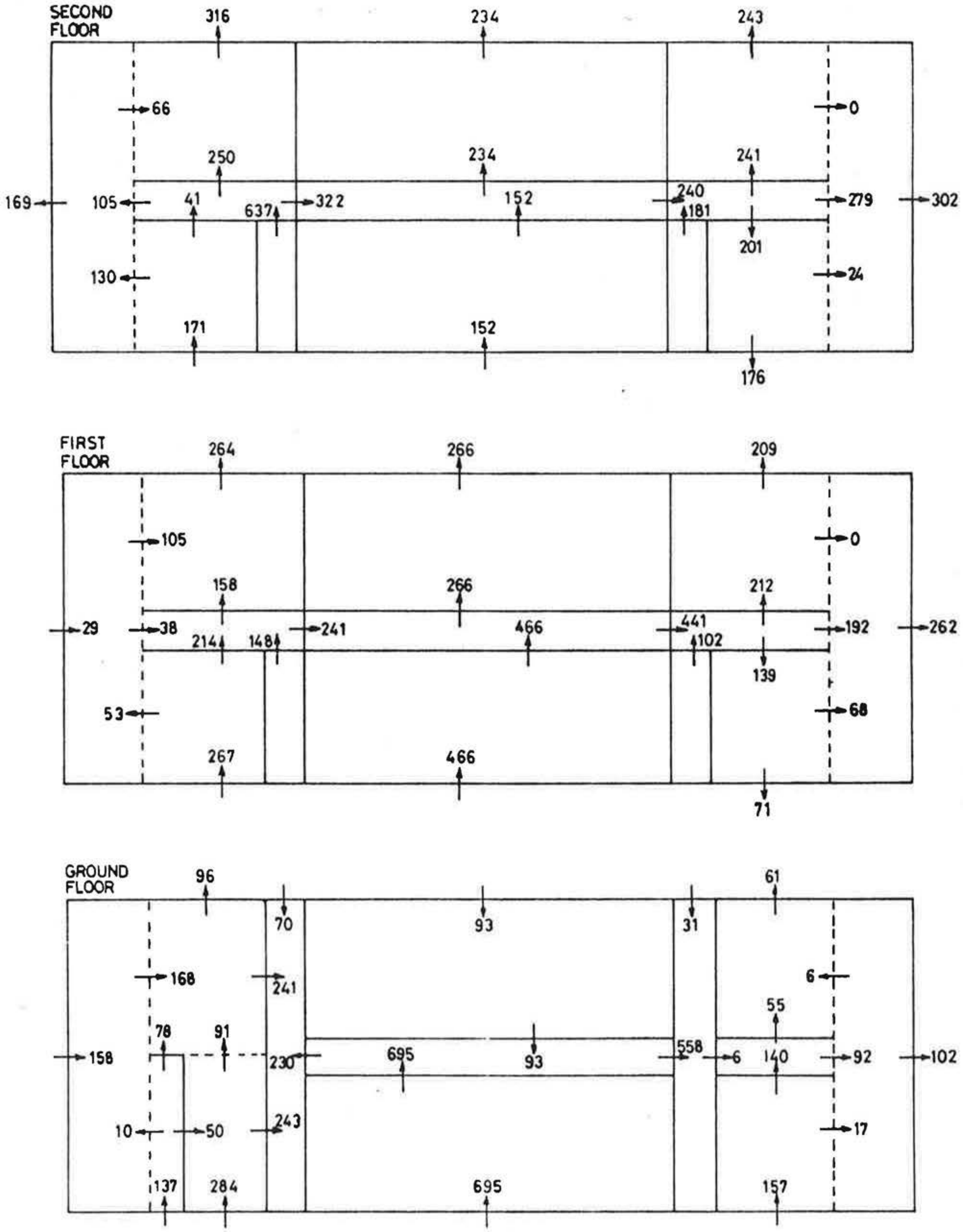

Figure 5 Airflows (m^3/hr) in the low-energy building with non-draughtstripped windows.

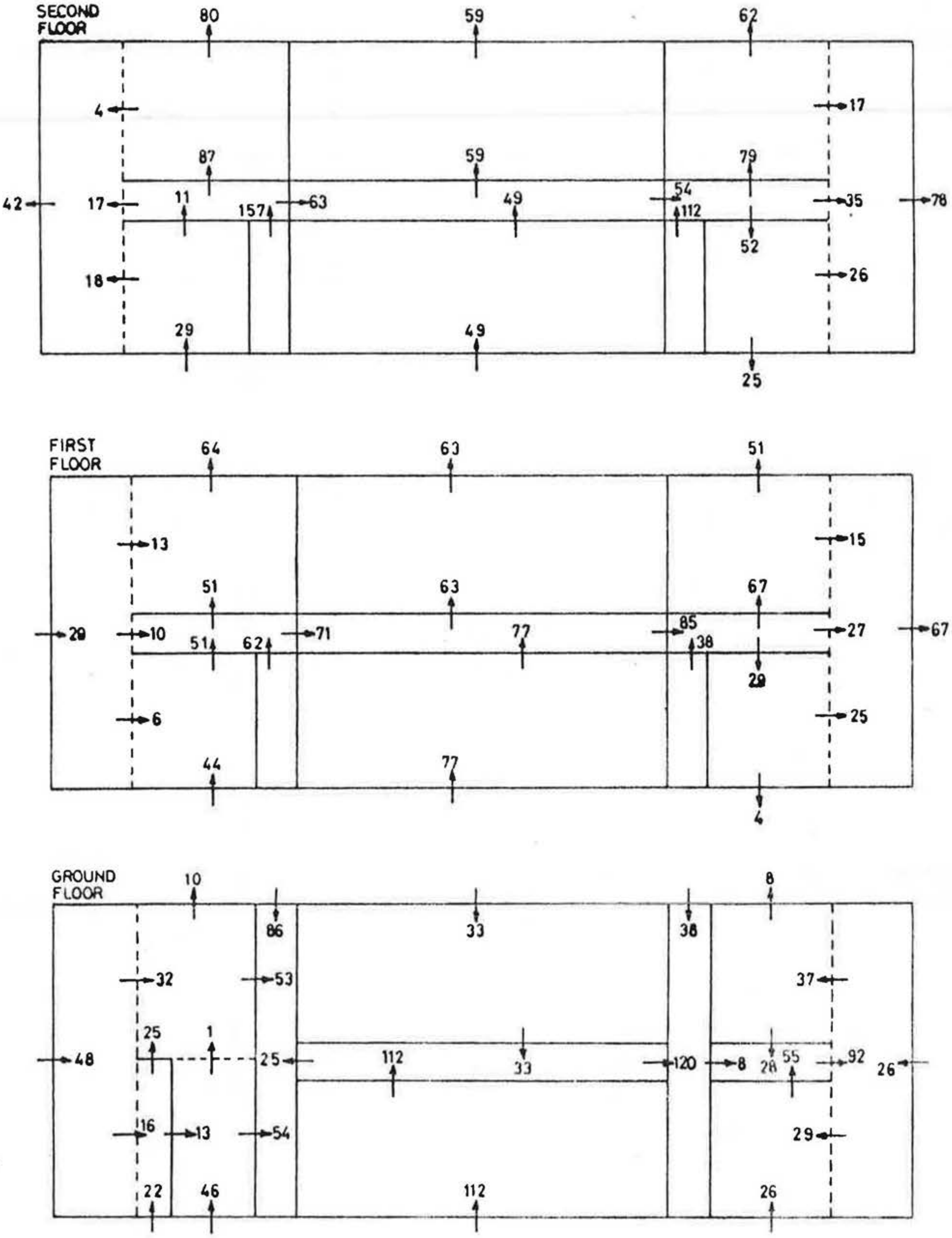

Figure 6 Airflows (m^3/hr) in the low-energy building with draughtstripped windows.

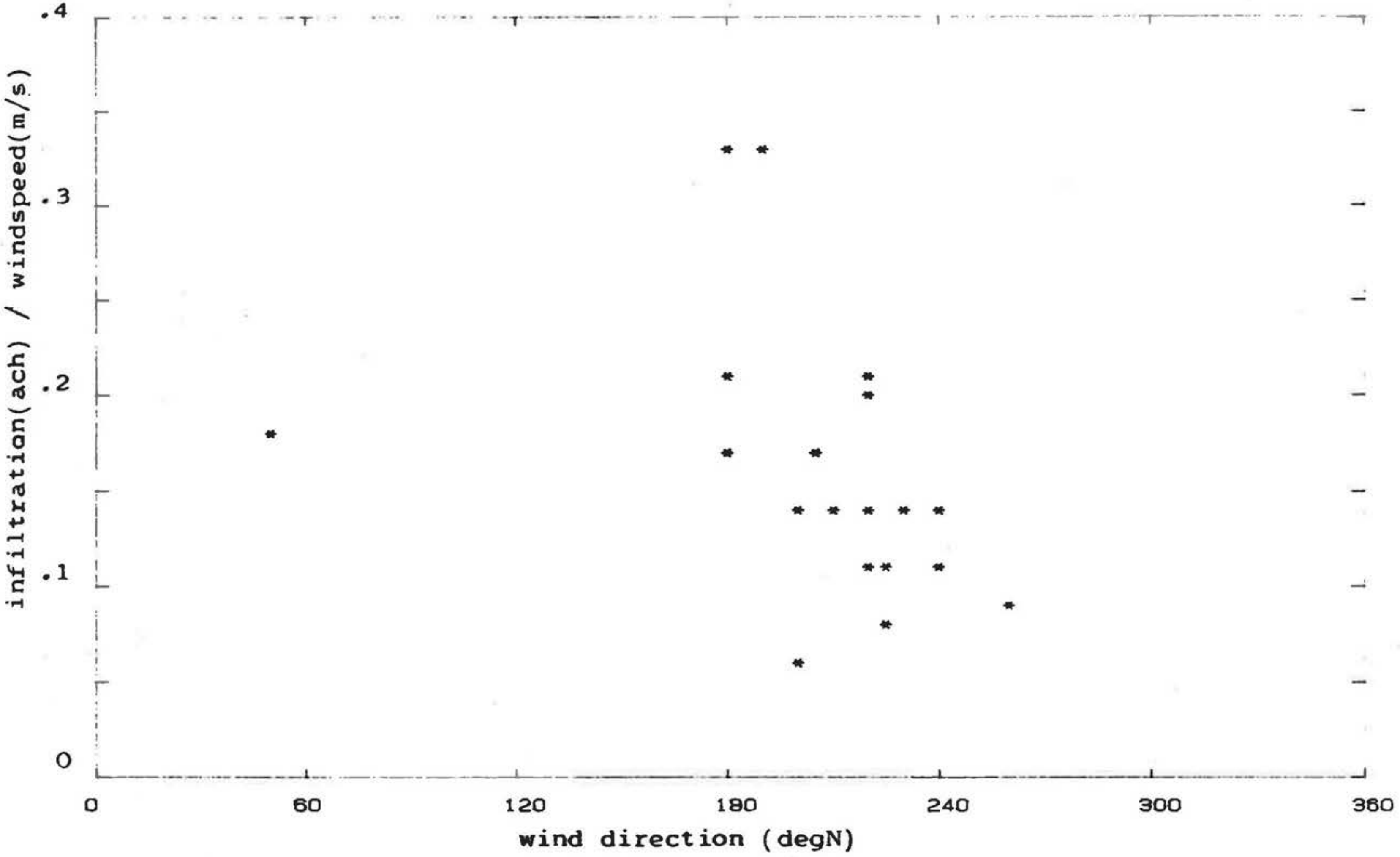

FIGURE 7 Tracer gas measurements of whole building infiltration rates obtained with non-draughtstripped windows

CHAPTER 10

FINAL CONCLUSIONS

Infiltration is an important aspect of heat loss in all buildings during the heating season. Because of the wide range and, in some cases, indeterminate nature of the factors which determine infiltration, its prediction and measurement have always been among the more difficult aspects of evaluating building performance. For this reason, much work has been directed at measuring infiltration. Most of this effort, however, has been concentrated on smaller buildings such as dwellings or relatively simple single-cell buildings. The measurement of infiltration in large, multicelled and naturally ventilated buildings has been almost totally neglected because of its difficulty and the lack of appropriate techniques. The work carried out in this project addressed this challenge.

Following a review of existing tracer gas methods and the setting out of the required underlying theoretical analysis, two techniques were identified for further development:

- Multiple tracer gas.
- Constant concentration.

Appropriate automated systems, based upon infrared (IR) gas analysers, were developed for testing in the field. Most effort was concentrated on the multiple tracer gas technique and, in this case, preliminary experience was obtained on a Mk I system based upon separate analysers. This was an interim development whilst awaiting delivery of a multicomponent analyser which formed the basis of a Mk II system.

In the course of developing these techniques, measurements were made in office buildings. Although the nature of the problem precludes direct validation, the results were self-consistent. In the case of the multiple tracer technique tested in a mechanically ventilated office building, the results were compared with whole building ventilation rates measured by other methods, including a constant-injection method which was also developed as part of the programme.

The multiple tracer technique was able to give both the exchange of air between zones and between each zone and outside air. It was however difficult to operate for logistic reasons, required costly instrumentation and skilled and experienced personnel. The constant concentration technique gave a continuous record of the infiltration rate into a small zone within the building and was considered most appropriate for assessing the local effect of remedial measures such as draughtstripping. It was, however, difficult to operate in an occupied building and again required complex and expensive equipment. Neither method was found to be fully suitable for obtaining general whole-building infiltration rates on a wide scale.

Substantial effort was, therefore, placed on the development of a simpler method using a single tracer gas. Earlier work had indicated that, as in dwellings, this could be accomplished by substantial internal mixing by special fans so as to effectively create a single perfectly-mixed space. Again, this would not be a practical solution for general use. A computer program was developed to analyse the variation of tracer gas concentration for various distribution strategies and air exchange patterns. Using this, together with exploratory field measurements, the basis for a new method was established. Provided certain conditions are observed, this method allows whole building ventilation rates to be determined with a reasonable degree of accuracy. This can be accomplished without the need for complete and uniform initial distribution of tracer gas and without the need for perfect mixing.

The method requires the measurement of relatively low concentrations of suitable tracer gases. In this context, IR analysis which requires concentrations in the parts per million range, is not appropriate and methods using gas chromatography for parts per billion concentration measurements have been developed. These have the added benefit of allowing samples to be collected on site and analysed in the laboratory thereby obviating the need for expensive on-site equipment. Several collection methods were identified:

- Tedlar sampling bags.
- Polyethylene bottles.
- Adsorption tubes.
- Evacuated glass tubes.

These were evaluated both in the laboratory and in the field for suitability. Whilst the latter three collection methods may be appropriate for many uses, sampling bags has the particular advantage of allowing repeated analysis of the same sample for checking and also, when used with a simple pump, allows an integrated concentration to be obtained over a chosen period.

Although the simple technique needs to be further evaluated and appropriate protocols developed for use by inexpert personnel, it provides a substantial breakthrough in providing a relatively cheap and simple method for determining natural ventilation rates in multicelled large buildings.

In the course of developing and testing the techniques set out above, measurements were made in three office buildings. In particular, the multiple tracer gas measurements in a mechanically ventilated building indicated the ineffectiveness of the dampers. This gave rise to substantial air leakage, of the order of 0.5 ach above infiltration, where the infiltration was of the order of 0.3 ach. Measurements also made prior to the installation of improved window draughtstripping indicated a saving of the order of 0.4 ach. The energy savings associated with this reduction was estimated and it was found that draughtstripping windows had reduced the total gas consumed within the building by about 21%.

Detailed changes in infiltration performance are best determined by using the constant concentration technique. Other techniques are not generally sensitive enough to allow accurate estimates. An alternative approach is to use computer predictions. These, however, require validation. As part of this project, the BRE BREEZE computer model was used to predict the air exchange rate for building B18, both before and after draughtstripping. Excellent agreement was obtained with the measured flow rates, thereby, giving confidence in the prediction method.

Future work should include further development of the simplified method and its application to measuring ventilation rates in both office and other non-domestic buildings. Such measurements will provide a range of data for further validation of prediction programs such as BREEZE. Together with more knowledge of the leakage characteristics of building envelopes, they will provide the best method for assessing improvements in building performance by the use of such ameliorative measures as draughtstripping.

Multiple tracer gas techniques, possibly using the simpler collection techniques developed and described in this project, should be used to determine interzonal interchange rates for different conditions, both to identify conditions under which the simple technique can be applied and to provide a basis for determining contaminant and heat distribution.

ACKNOWLEDGEMENTS

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- Mr B C Webb (Ventilation and Heat Recovery Section)

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APPENDIX I

DESCRIPTION OF THE THREE OFFICE BUILDINGS

As part of the programme of work described in this report, field measurements were carried out in three office buildings which were all located at the Building Research Station, Garston. Short descriptions of these buildings are given in this Appendix.

1. BUILDING B9 (PHYSICS BLOCK)

The south face of building B9 is shown in Figure 1 and a site plan showing the location of this building in relation to its surroundings is given in Figure 2.

Building B9 comprises of several linked structures with each containing a mixture of offices and some laboratory space. Fresh air is provided by natural ventilation and, in this connection, side-pivoting metal framed windows are installed throughout.

2. BUILDING B10

This is a naturally ventilated, conventional two-storey office building (Fig 3) with a total volume of 2153 m^3. In each floor, offices are located along either side of a central corridor.

The building is rectangular in plan (40 m x 11 m) and each storey is 2.44 m high. A plan-view (Fig 4) of the building shows that the stairwell, which provides access between each storey, is located near one end of the building.

3. BUILDING B18

The three-storey building B18 (Fig 5) was built as a 'low energy' office. It is rectangular in plan (Fig 2 of Chapter 9), is 60 m long by 12 m wide, and has its major axis aligned east-west. The floor to ceiling height of each storey is 2.6 m. Offices are located on each floor along either side of a central corridor. The total volume of the building is 5286 m^3.

This building incorporates a number of energy saving features. Among these is a mechanical ventilation system which allows a varying amount of fresh air to be taken into the building. This value can be set in a range from nominally zero (full recirculation) to full (no recirculation) fresh air intake depending upon the setting of mechanical dampers at the air handling unit. It is set to 30% fresh air during the heating season.

- Appendix I -

FIGURES

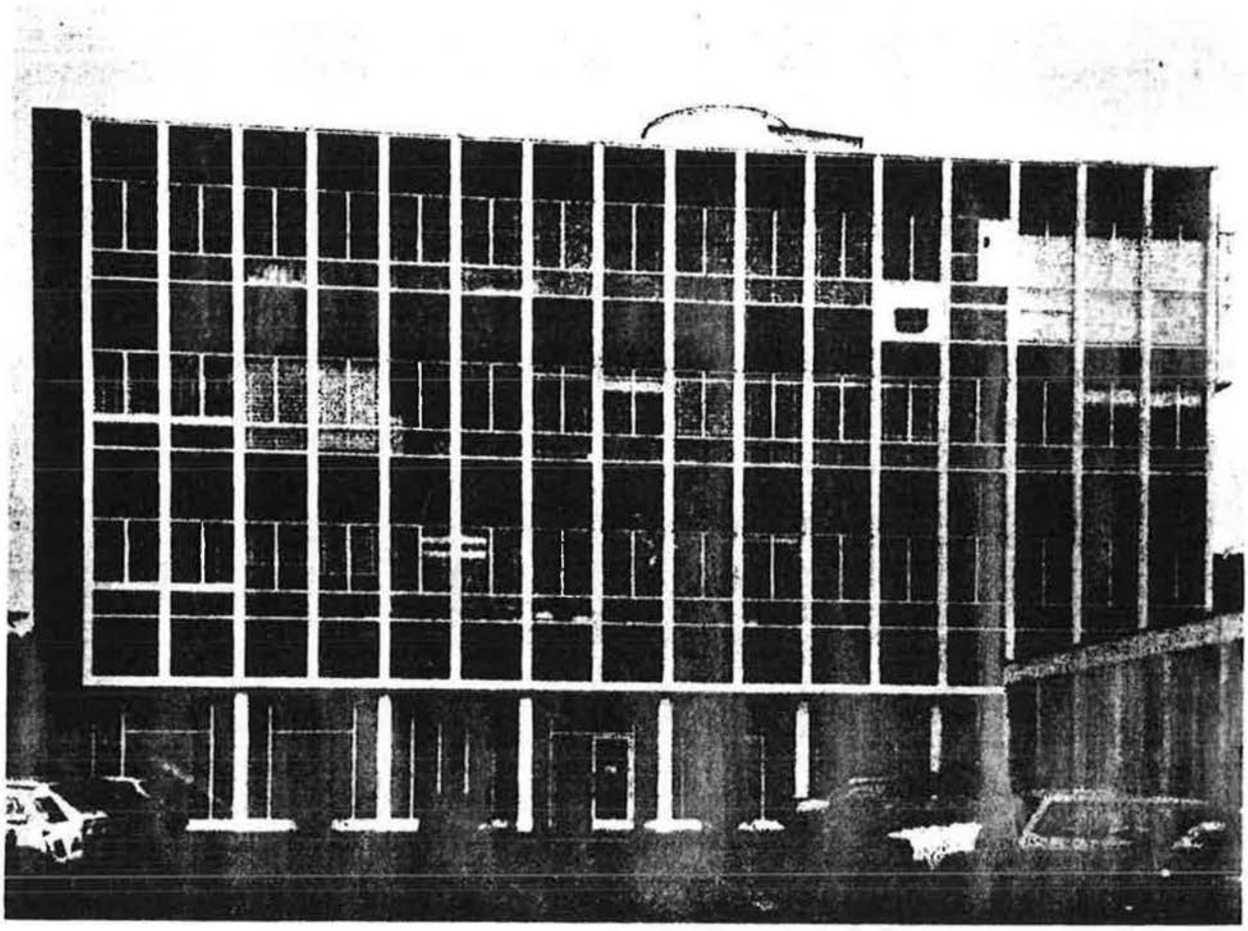

Figure 1 South face of building B9 (Physics block)

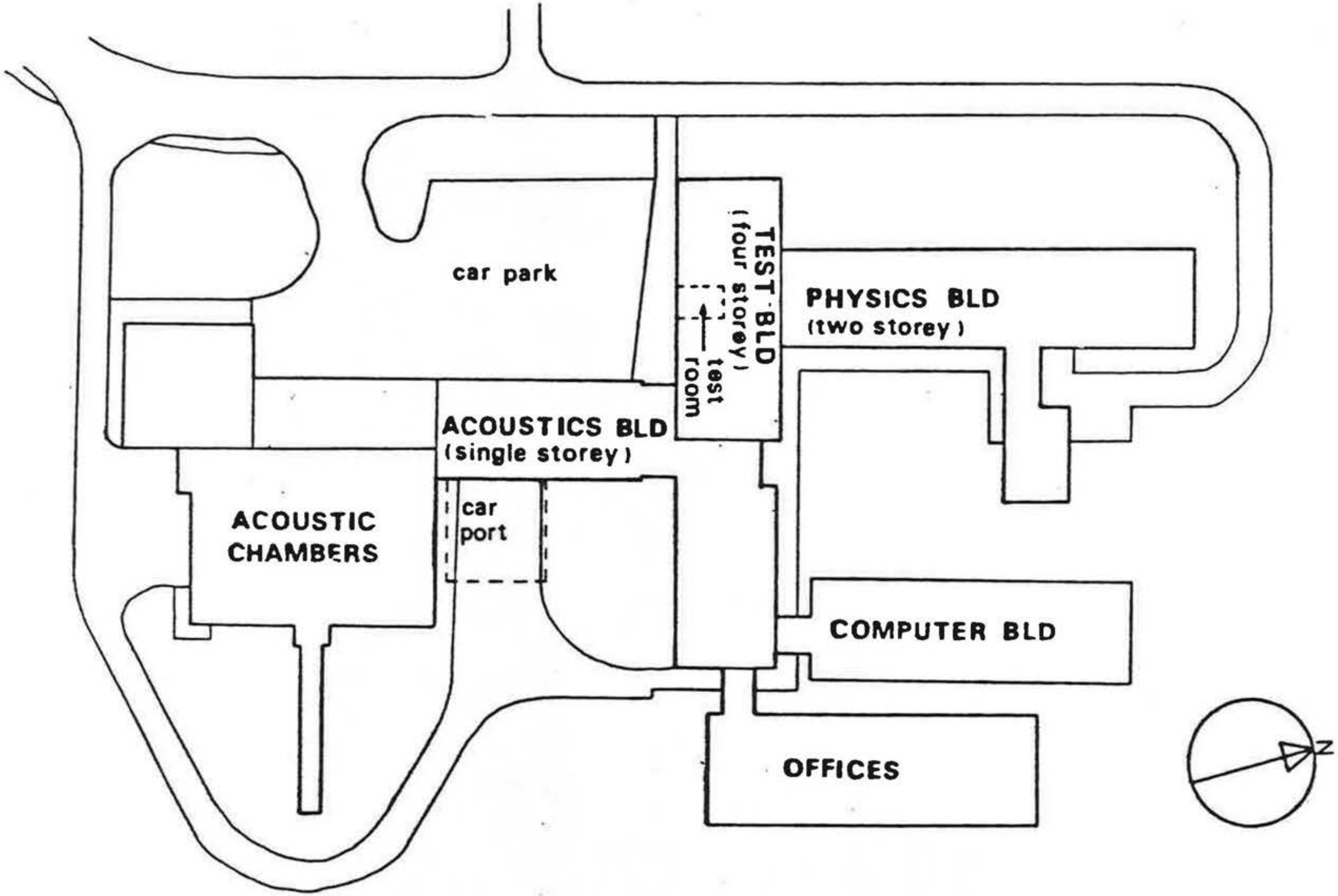

Figure 2 Site plan showing location of building B9

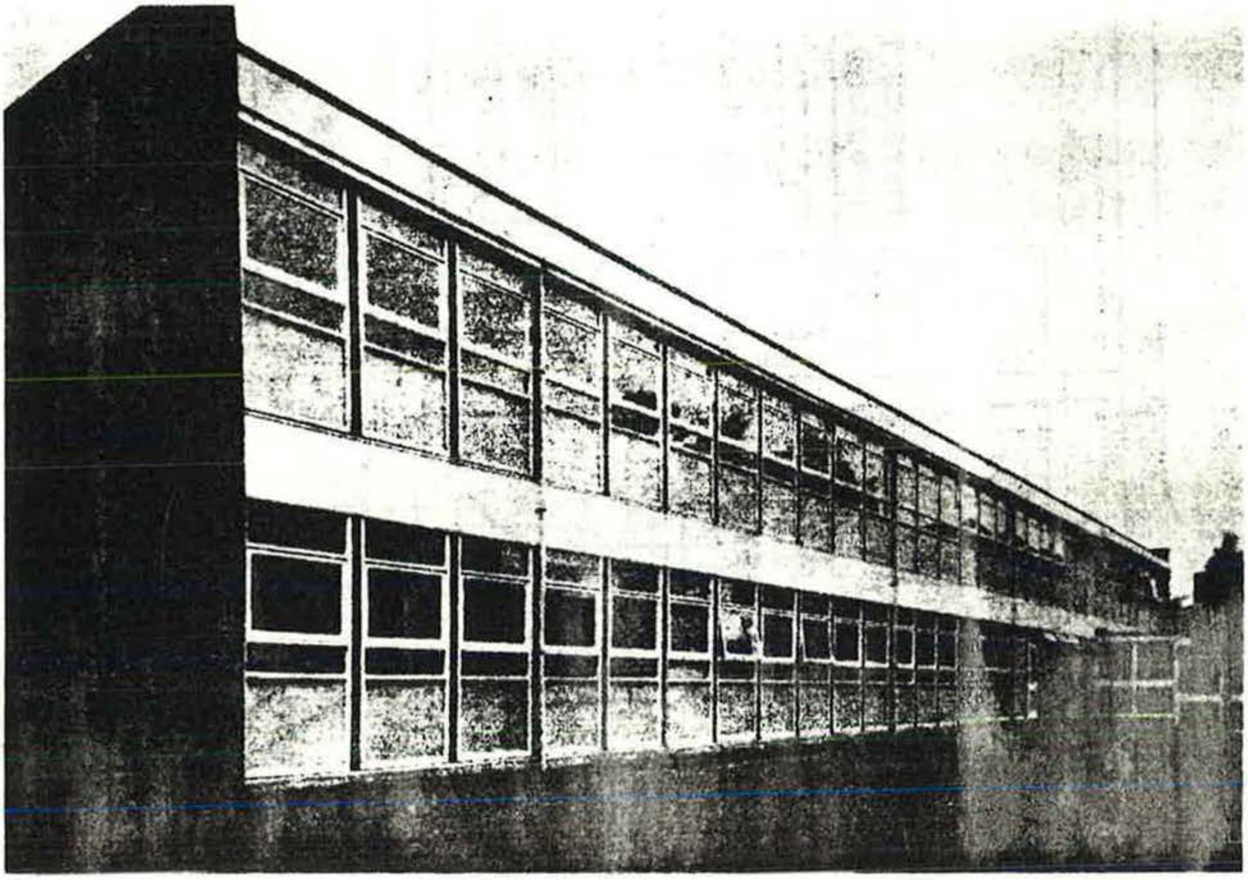

Figure 3 View of the west face of building B10

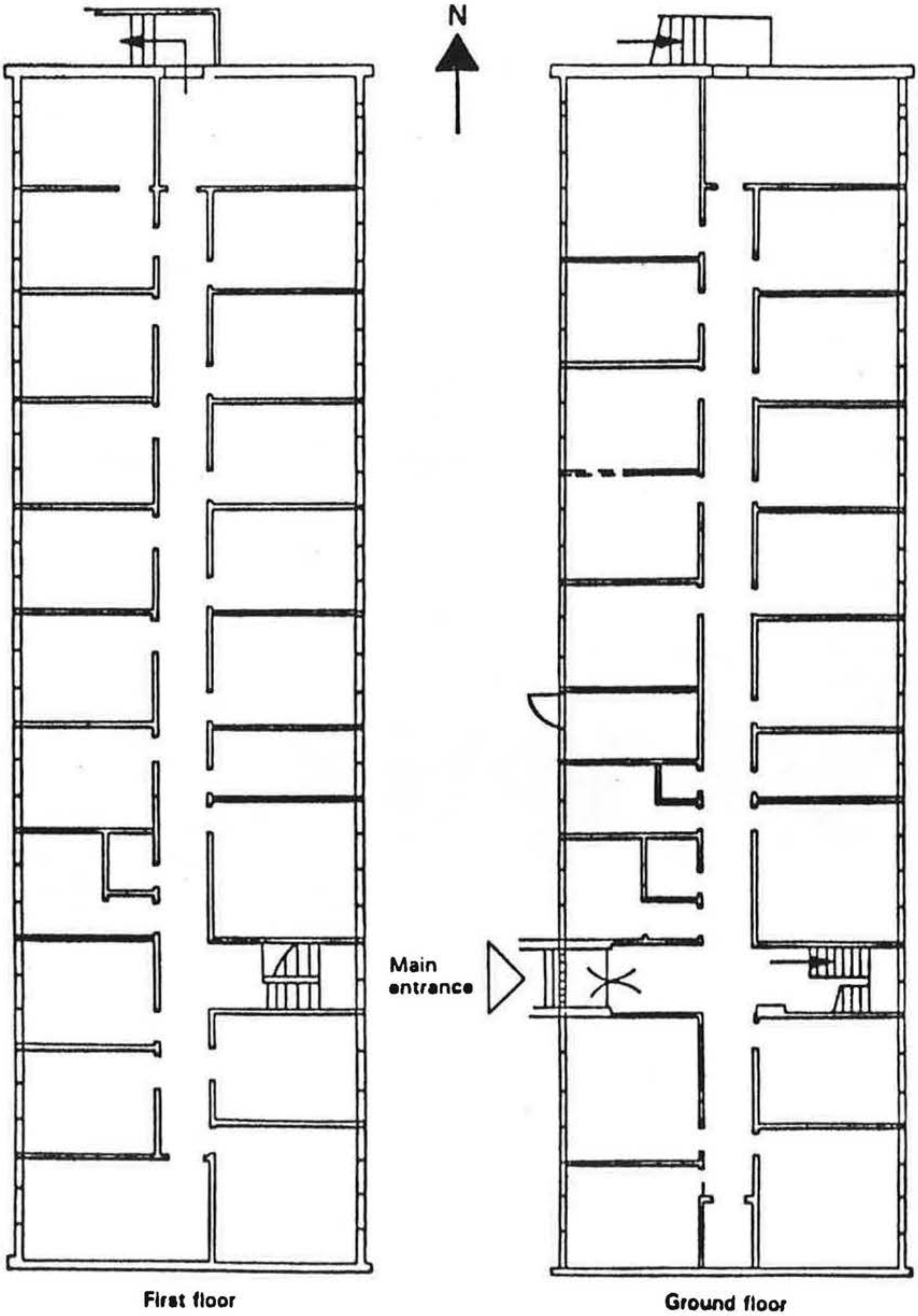

Figure 4 1:200 plan view of building B10

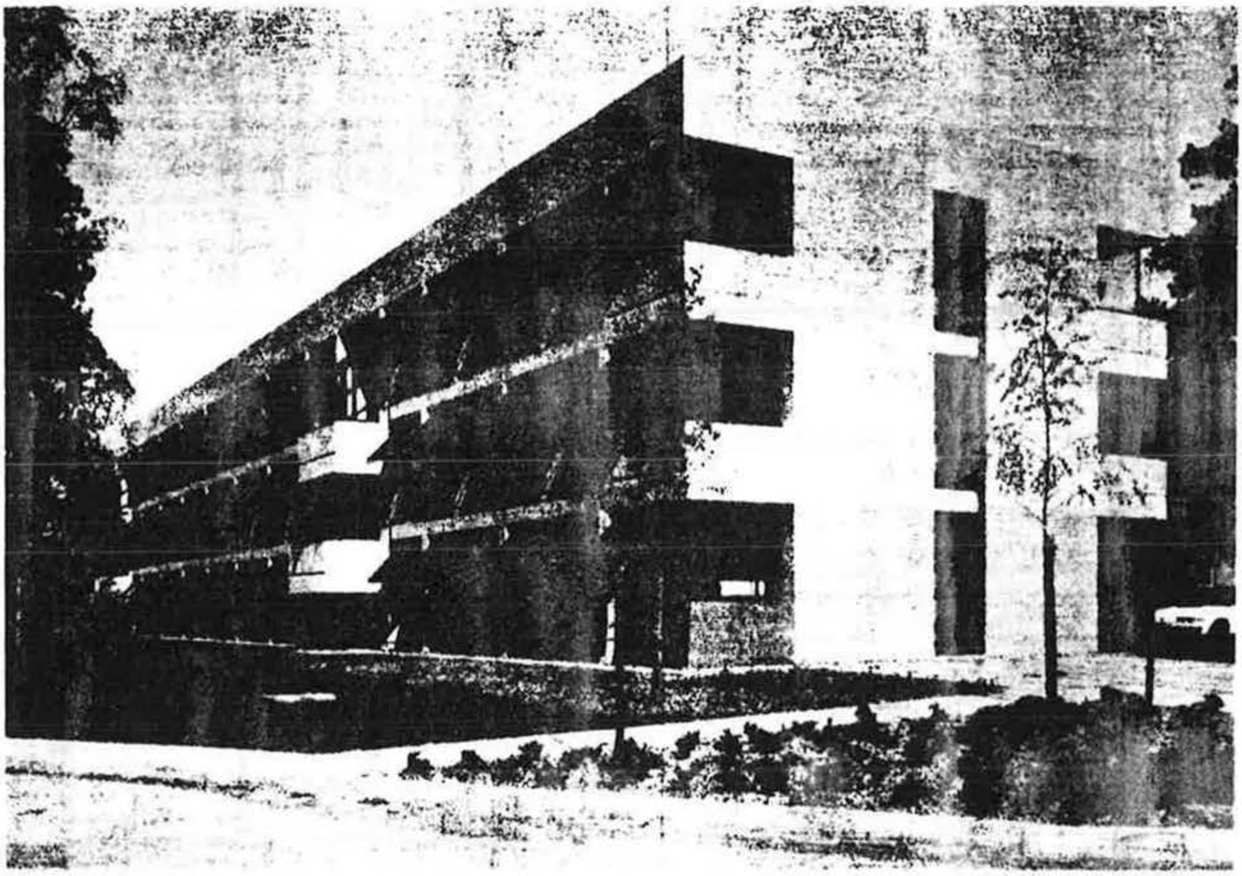

Figure 5 View (looking from the south-east) of building B18 (Low-energy office)

APPENDIX II

EXTERNAL PUBLICATIONS ARISING FROM THIS PROGRAMME OF WORK

1. Perera, M D A E S, Review of techniques for measuring ventilation rates in multicelled buildings, Published in Energy Conservation in Buildings - Heating, Ventilation and Insulation (Ed. Ehringer, H, Hoyaux, G and Zegers, P), Reidl Publishing Co., Dordrecht, (1982).

2. Perera, M D A E S, Walker, R R and Oglesby, O D, Ventilation rates and intercell airflow rates in a naturally ventilated office building, Proceedings of the 4th Air Infiltration Centre Conference, Ulm, Switzerland, (September 1983).

3. Perera, M D A E S, Walker, R R and Trim, M J B, Measurements of intercell airflows in large buildings using multiple tracer gases, Published in Energy Savings in Buildings - Results of the European Communities Energy R and D Demonstration Programmes '1979 - 1983' (Ed. Ehringer, H and Zito, U), Reidl Publishing Co., Dordrecht, (1983).

4. Breum, N O and Perera, M D A E S, Ventilation measurement using spot sampling of sulphur hexafluoride on a solid adsorbent, Building and Environment, Vol 19(3), pp 175-178, (1984).

5. Perera, M D A E S and Walker, R R, Strategy for measuring infiltration rates in large, multicelled and naturally ventilated buildings using a single tracer gas, Building Services Engineering, Research and Technology Journal, Vol 6(2), pp 82-88, (1985).

6. Walker, R R, Perera, M D A E S, Hathaway, M B and Oglesby, O D, Evaluation of a simple technique for measuring infiltration rates in large and multicelled buildings using a single tracer gas, Presented at the ASHRAE Symposium on Multi-Cell Infiltration held in Hawaii, (June 1985).