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INFILTRATION MEASUREMENTS IN NATURALLY VENTILATED, LARGE MULTICELLED BUILDINGS

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ABSTRACT

Large, multicelled and naturally ventilated buildings pose many problems for the measurement of overall infiltration rates using tracer gases. In two previous papers, a simple technique which avoided these problems was proposed. The most salient features of this technique are;

(a) a single tracer gas is used,
(b) measurements need only be carried out in part of the building,
(c) an initially uniform distribution of tracer is not needed, and
(d) artificial mixing of the tracer with the internal air is not essential.

In this paper, the simple technique is explored further by reference to a computer model study as well as by field measurements in two naturally ventilated office buildings.

Results show that using this technique, the overall infiltration rates of large, multicelled and naturally ventilated buildings can be obtained to a good approximation.

INTRODUCTION

Despite the fact that the majority of buildings in countries with temperate climates, such as the United Kingdom, are naturally ventilated, its prediction is one of the most difficult aspects of building design. In recent years, research into air infiltration and ventilation has increased, but mainly with respect to dwellings rather than more complex buildings like offices, especially if they are naturally ventilated. Problems of scale and lack of appropriate techniques have hindered investigations of these bigger, multicelled buildings.

Interzonal air flows in such buildings can be obtained by using multiple tracers gases (refs. 1, 2 and 3), but the cost and complexity of carrying out multiple tracer measurements can be prohibitive. In many instances, it would be beneficial to obtain less comprehensive but nevertheless useful information using a single tracer gas.

Problems arise, however, when conventional single tracer gas decay experiments are attempted in large, multicelled buildings. These have been enumerated in a previous paper (ref 4, 5).

In one of these papers (ref. 4), a relatively simple technique to overcome these problems was proposed. This was formulated by considering an analytical solution to a two-cell building and a computer simulation of airflows in a five-cell representation of an office building. Arising from that study, experimental evaluation of the technique was carried out (ref. 5) in a mechanically-ventilated multicelled office building and in a large single-celled hangar building. The results obtained from these tests were encouraging and gave confidence to proceed with field tests in naturally ventilated buildings.

The first part of this paper describes the results of a computer study carried out on a three-cell model. This is used to determine the applicability of the technique to a building in which the air flow patterns are typical of,

1. buoyancy-induced flow,
2. wind-induced flow, and
3. a combination of both.

In the second part of the paper, results are presented from field measurements of infiltration rates in two naturally-ventilated multicelled office buildings using the simple technique. The paper also discusses the effect on the measured ventilation rate of opening windows, enhancing internal mixing and carrying out tests with partial tracer gas seeding of the building.

'SIMPLE' TECHNIQUE AND MODEL STUDY

The basis of the simple technique lies in a consideration of the solution to the system of ordinary differential equations,

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

governing the dispersion, at time t, of a tracer gas at an initial concentration $\{C(0)\}$ in a multicelled environment. Here, [V] is the cell-volume matrix and [Q] describes the intercell airflows.

It was shown (ref. 4), that if $[V]^{-1}[Q]$ has distinct eigenvalues λ, the solution to this system is given by

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

where [A] is dependent on $\{C(0)\}$ but is independent of time t, and that each element of $\{C(t)\}$ is a linear combination of exponential functions with no polynomial contribution.

For a building with N-cells, there are N eigenvalues the smallest of which dominates at large time, t. If tracer gas is dispersed within the building, then in the long-term, the measured decay rate becomes constant and approximates to the dominant eigenvalue. It was shown (refs. 4 and 5) that, in a well-connected building, this decay rate not only approximates to the dominant eigenvalue but also to the total infiltration rate of the building, or at least to the infiltration rate of the most significant portion of the building.

These conclusions were, however, based on a study [ref. 4] of two models. The first, a two-cell analytical study, gave a set of restricted conditions under which the dominant eigenvalue approximates towards the total ventilation rate. To show that these restricted conditions can be relaxed in the case of a fairer representation of a multicelled building, a five-cell model of a particular office building was considered. This indicated that, provided the cells within the building were well-connected and that there was adequate internal mixing, the dominant eigenvalue did approximate (to within 15%) of the whole-building ventilation rate. That study also indicated that in such a building, it was sufficient to seed part of the building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.

In order to test the general application of the proposed technique, a three-cell model (Fig. 1) with three different airflow patterns has now been considered. This model can be taken to represent a building with three storeys. It is assumed that all internal doors within each storey are kept open so that no individual cell-like structure exists within each floor. This is not an unreasonable assumption as has been shown [ref. 5] previously and is also shown later in this paper. Each storey can then be taken to represent one zone of the building.

The zone volumes were each set arbitrarily to unity and the airflows were selected so that the whole-building ventilation rate was also unity. Three interzonal airflow patterns were set up to represent the action of buoyancy alone, wind alone and a combination of the buoyancy and wind. To investigate the influence of interzonal mixing, 'mixing' airflows (denoted by β) were superimposed on the airflow patterns (Fig. 1). The mixing parameter b was set to 0.1, 1.0 and 3.0 to represent poor mixing, mixing of the same order of magnitude as zone airflow rates and the whole building airflow rates respectively.

Using a computer program (refs. 2, 3 and 4), the three eigenvalues were computed (Table 1) for each case of the airflow model at each of the values for the mixing parameter. The following features can be seen:

1. There is a minimum eigenvalue λ_{min}. This is the eigenvalue which will dominate over the other two eigenvalues, λ_1 and λ_2, in dispersing the tracer in the long term.

2. For the cases when there is wind-induced flows, the dominant eigenvalue is quite close to the whole building ventilation rate. The correspondence gets better as the

internal mixing increases (Fig. 2). When the airflows are induced solely by buoyancy, there is no good correspondence except at high internal mixing. This lack of correspondence has been commented on previously (refs. 4 and 5). All these features are seen by considering the following percentage deviations of the dominant eigenvalue from the total rate;

Case	Mixing parameter, β		
	0.1	1.0	3.0
Buoyancy alone	117	53	26
Buoyancy + wind	24	12	5
Wind alone	33	14	5

3. For this three-zone model, the above Table shows clearly that the simple technique can be used with most confidence when there is some wind induced ventilation. In such instances, the dominant decay rate measured from concentration profiles should be within about 30% of the true total ventilation rate for poor internal mixing and within 15% with reasonable internal mixing. The latter deviation corresponds to that found previously (ref. 4) from a representation of a real building.

4. As the internal mixing increases, the dominant eigenvalue increases slowly towards the whole building ventilation rate of unity. The other two eigenvalues, however, increase rapidly which means that their contribution, and therefore influence, to any tracer gas concentration profile diminishes. The variation of these eigenvalues with increasing internal mixing is shown in Figure 3 for the wind-induced case.

5. Figure 4 shows concentration profiles in each zone for the various cases considered. These have been evaluated with all zones initially seeded to a uniform concentration. It should be noted that the eigenvalues are invariant to any distribution of the initial concentrations. The closeness of the final decay rates of these profiles to the theoretical target rate of -1.0 can be seen quite clearly and gives some perspective the discussions above.

EXPERIMENTAL DETAILS OF FIELD MEASUREMENTS

As already noted, the simple technique is intended to allow a whole building ventilation rate to be measured to a good approximation without either having to,

1. seed the whole building with tracer gas,
2. ensure uniform initial tracer concentration throughout the building, or
3. artificially mix the internal air during the course of a tracer 'decay' experiment.

It was suggested [ref. 4 and 5], however, that the experimental procedure for this technique should make use of the following points:

1. Sampling of tracer to be localised to the zone(s) of seeding.
2. Increasing the volume seeded and opening all internal doors.
3. Using a tracer gas detectable at low concentrations and over a wide measurable range.

Measurements using the simple technique have been carried out in two naturally ventilated multicelled office buildings located at the Building Research Station, Garston, England. Of these, three tests in one building and one in the second building are reported here. Each of these field measurements has been chosen to highlight a different aspect of the simple technique or a particular ventilation condition. During the field measurements described here, the mean wind speed and direction (averaged over 15 minute intervals) and the outside air temperature were monitored at a height of 10 m at a nearby open site (within 50 m of the two buildings). Table 2 gives the weather conditions during the four tests.

Buildings

Building A (Fig. 5) is a conventional two-storey office building with a volume of 2153 m^3. It is rectangular in plan (40 m x 11 m) and each storey is 2.44 m high. A stairwell region located near one end of the building allows access between each storey. Figure 6 shows the plan of each floor.

Building B (Fig. 7) is four-storeys high and has a volume of 4840 m^3. It comprises of several linked structures, each containing a mixture of offices and some laboratory space. On every floor (Fig. 8), 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 that zone.

Tests were carried out when these buildings were unoccupied. Only in Test A1 was the heating in the building turned on. With the exception of Test A3, all windows were kept closed throughout the measurement periods. All internal doors, including fire doors, were kept open. Doors leading to the outside were kept shut.

Tracer gases and injection strategy

Sulphur hexafluoride (SF6) was used throughout all the tests. Previous work (Refs. 2, 3 and 5) has shown this to be one of the best available tracer gases for this kind of application. For Test A1 (described later), bromo-trifluoro-methane (Freon 13B1) was used as a second tracer gas.

In all the experiments, the test zones were seeded by manually discharging the tracers directly from cylinders containing the neat gas.

Tracer sampling and analysis

Figures 6 and 8 show the locations of the sampling points for the two buildings. Samples were taken from each point using 30 m long 6 mm ID nylon tubes. All tubes, from the building under test, were brought back to individual solenoid valves which were under the control of an ITT Director microprocessor unit. Using this unit, every 45 seconds each sample line was connected in turn to a dual-channel SF6/Freon13B1 Leybold-Heraeus infrared gas analyser. To minimise the delay in obtaining a fresh sample at the analyser each time, a 'purge' pump was set to draw on all sample lines continously with the exception of the line currently connected to the analyser (which has its own internal pump). Each line was resampled at five minute intervals. The concentration of the tracer(s) present in each sample was recorded on magnetic cassettes for processing later. The automated system is described more fully in Reference 2.

The infrared analyser was calibrated before and after each test using 'zero' gas (nitrogen) to test for zero-offsets and 'span' gas to test for linearity with the span gas chosen to give a reading approximately 90% of full scale (150 parts per million). The accuracy of analysis is estimated as approximately 1% of full scale (i.e. ±1.5 ppm).

RESULTS FROM MEASUREMENTS IN THE TWO NATURALLY VENTILATED MULTICELLED OFFICES

Three tests, A1, A2 and A3 were carried out in building A with test B1 in building B. Each of these tests lasted between seven and 15 hours.

Effect of partially seeding a building (Test A1)

In addition to using the simple technique to measure the overall infiltration rate of building A, Test A1 was designed to determine the influence (if any) of partially seeding the building on the measured infiltration rate. For this purpose, whilst Freon 13B1 was used to seed the whole of this building, SF6 was used to seed only the corridors in each of the two floors.

During this test, the wind was blowing from the west (Table 2). Before 1800 GMT, the wind speeds were high and between 3.5 to 5 ms^{-1}. After this time, the speed dropped to between 2.5 to 3.5 ms^{-1}. The inside/outside temperature differential was about 11°C.

Figures 9a and 9b show the resulting concentration profiles for Freon-13B1 and SF6 respectively. Before 1800 GMT, the decay rates computed from the whole-building seeded Freon-13B1 was about 0.42 h^{-1} on average. This compares with an average rate of 0.41 h^{-1} computed from the partially-seeded SF6 profiles. Each profile is sufficiently separated from the others in each set to indicate that the internal mixng is not perfect.

With a reduction in the outside wind speed after 1800 GMT, the decay rates as measured in three out of the four upstair sampling points decrease. Both the SF6 and Freon-13B1 profiles show this new decay rate averaged at about 0.21 h^{-1}. The remaining three other decay rates remain unchanged at 0.42 h^{-1}.

It is difficult to explain the two sets of decay rates after 1800 GMT. One hypothesis is that during this time period, the building ventilation is influenced by buoyancy-induced flows. As shown in the model study earlier, this factor, coupled with non-perfect internal mixing can give rise to different rates in different zones of the building.

Effect of increasing internal mixing (Test A2)

Building A was seeded throughout with SF6 for this 12-hour test. Immediately after completing the injection of the tracer gas measurements were started at 0800 GMT. At 1400 GMT, a dozen 'mixing' fan units (placed throughout the building) were switched on so as to enhance the internal mixing. Each of these units consisted of two Vent-Axia fans, facing in opposite directions, and mounted one above the other on a vertical stand.

The enhanced internal mixing does not appear to make any difference to the decay profiles (Fig. 10). This indicates that there is adequate natural mixing within the building .for the dominant decay rate to have reached the overall infiltration rate of the building. This is also indicated by the collapse of the concentration profiles in a floor to one single curve for that floor.

Figure 10 also shows that, even though there are two distinct sets of profiles (one for the ground floor locations and the other for those in the first floor), the profiles are parallel to one another. It is also seen that this dominant region has been set up one hour into the test. The infiltration rates, as measured from the ground and first floor profiles, are 0.30 and 0.28 h^{-1} respectively. These, not surprisingly, are lower than the rates measured in Test A1 when the outside wind speed was higher.

Effect of opening windows (Test A3)

Another 12-hour test, similar to the one above, was carried out to determine the influence of open windows on the ventilation rate of building A.

Figure 11 shows the resulting concentration profiles starting at 0830 GMT. They show the profiles all settling down to a parallel rate of approximately 0.21 h^{-1}. At 1100 GMT, a small louvred window was opened on each of three east-facing upstair rooms. Within 15 minutes, all profiles start to dip to a higher decay rate. In the upstairs region, the rate now is 0.45 h^{-1} whilst on the ground floor the rate is about 0.43 h^{-1}.

Five hours after the windows were opened, the wind speed increased from 1 ms^{-1} to 2.5 ms^{-1} together with an increase in the inside/outside temperature differential from 1.5 to 4.5°C. In a manner similar to that when the windows were opened, the profiles show a response within 30 minutes and all curves (Figure 10) become parallel. The new overall ventilation rate was 0.25 h^{-1}.

Measurement in low wind conditions (Test B1)

Test B1 was carried out in building B on a rather still day when the temperature differential between inside and outside was about 8°C on average. The profiles, obtained in what is probably a mixture of buoyancy and wind induced infiltration, are shown in Figure 12.

The initial portions of the profiles, termed the 'transition' region (ref. 5), have different decay rates. This long transition period is indicative of low internal mixing within the building. After about seven hours into the test, when the external wind speed (Fig. 13) has increased slightly, most of these profiles do become parallel to one another. The resulting decay rate is about 0.28 h^{-1} during this time.

In view of the analysis from the model study concerning results obtained under buoyancy-inducing conditions, it is not possible to say whether this decay rate describes the overall infiltration rate of the building.

DISCUSSION

Two previous papers (refs. 4 and 5) provided the framework for a possible simple technique which could be used to determine the overall infiltration or ventilation rate in naturally ventilated, large multicelled buildings. This paper extends this earlier work by presenting results from field measurements in two naturally ventilated office buildings.

In the first part of this paper, a simplified three-cell model representation of a building has been used to obtain some feel for the types of airflow conditions under which the simple technique could be used effectively. Results showed that, in a tracer 'decay' experiment, provided there was sufficient

1. wind-induced component of infiltration and
2. internal mixing,

then the dominant decay rate approximated towards the overall infiltration of the building.

The main objective of field measurement Test A1, carried out in a two storey naturally ventilated office building, was to show that, even if a building was only partly seeded with a tracer, a whole building infiltration rate can be obtained. By using two tracers, one dispersed throughout the building and the other limited to the corridor areas, this thesis was shown to be correct.

In Test A2, the adequacy of available internal mixing in this office building was examined by artificially enhancing the internal mixing in the middle of a field measurement. No change in the concentration profiles were noticed when 'mixing' fans were switched on and the decay rate remained unchanged. This indicates, that at least for that test, there was adequate internal mixing and therefore the decay rate should correspond closely to the overall infiltration rate.

The influence of changes in the ventilation flows can be sen twice in Test A3. In the first instance, the overall ventilation rate was changed by opening some upstairs windows. In the second occasion, the changes were caused by external weather conditions. On all occasions, it can be seen that all concentration traces show a quick response to these changes and that parallel profiles with a new decay rate are re-established.

What is possibly buoyancy dominated infiltration dominates Test B1. It is seen that a common dominant decay rate is established after about seven hours. It was also stated that, in such circumstances, the approximation of the dominant decay rate as a measure of the overall infiltration should be treated with caution.

CONCLUSIONS

In conclusion, the study has indicated the following features:

1. In general, locations in each floor of a building tend to behave in a similar manner to one another with respect to ventilation into that floor. This means that, provided all internal doors are kept open, each floor can be considered as a single zone of a complex building.
2. Neither uniform seeding nor seeding of the whole building is essential for the correct functioning of the simple technique.

3. Under buoyancy-only conditions, the simplified technique may not provide a dominant decay rate ascribable to the whole building rate.

4. Dominant decay rates respond quickly (within half an hour in these particular tests) to variations in the ventilation of the building caused either by weather conditions or by some other change in ventilation such as opening windows.

To summarise, this study has provided evidence to show that the simple technique can be usefully employed to determine the overall infiltration rates of large and complex buildings. Further work is, however, necessary to fully identify the limitations of this technique and to determine these occasions in which it can be used with confidence.

ACKNOWLEDGEMENTS

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TABLE 1
Eigenvalues obtained from three-cell model study

Case considered	Mixing flow β	Eigenvalues $-\lambda_{min}$	$-\lambda_1$	$-\lambda_2$
Buoyancy alone	0.1	2.17	3.73	2.70
	1.0	1.53	7.07	3.60
	3.0	1.26	13.34	5.60
Buoyancy and wind	0.1	0.76	1.11	1.93
	1.0	0.88	2.35	4.18
	3.0	0.95	4.33	10.12
Wind alone	0.1	0.67	1.02	1.71
	1.0	0.86	2.18	3.96
	3.0	0.95	4.14	9.92

TABLE 2
Weather conditions during field measurements

Test code	Wind speed (m/s)	Wind direction (degrees)	Temperature differential (°C)
A1	3.5 - 5.0 (before 1800 GMT) 2.5 - 3.5 (after 1800 GMT)	270	9 to 13
A2	2.5	225	0 to 2
A3	1.0 (until 1600 GMT) 2.5 (after 1600 GMT)	45	1.5 4.5
B1	calm to 1.5	135	6 to 10

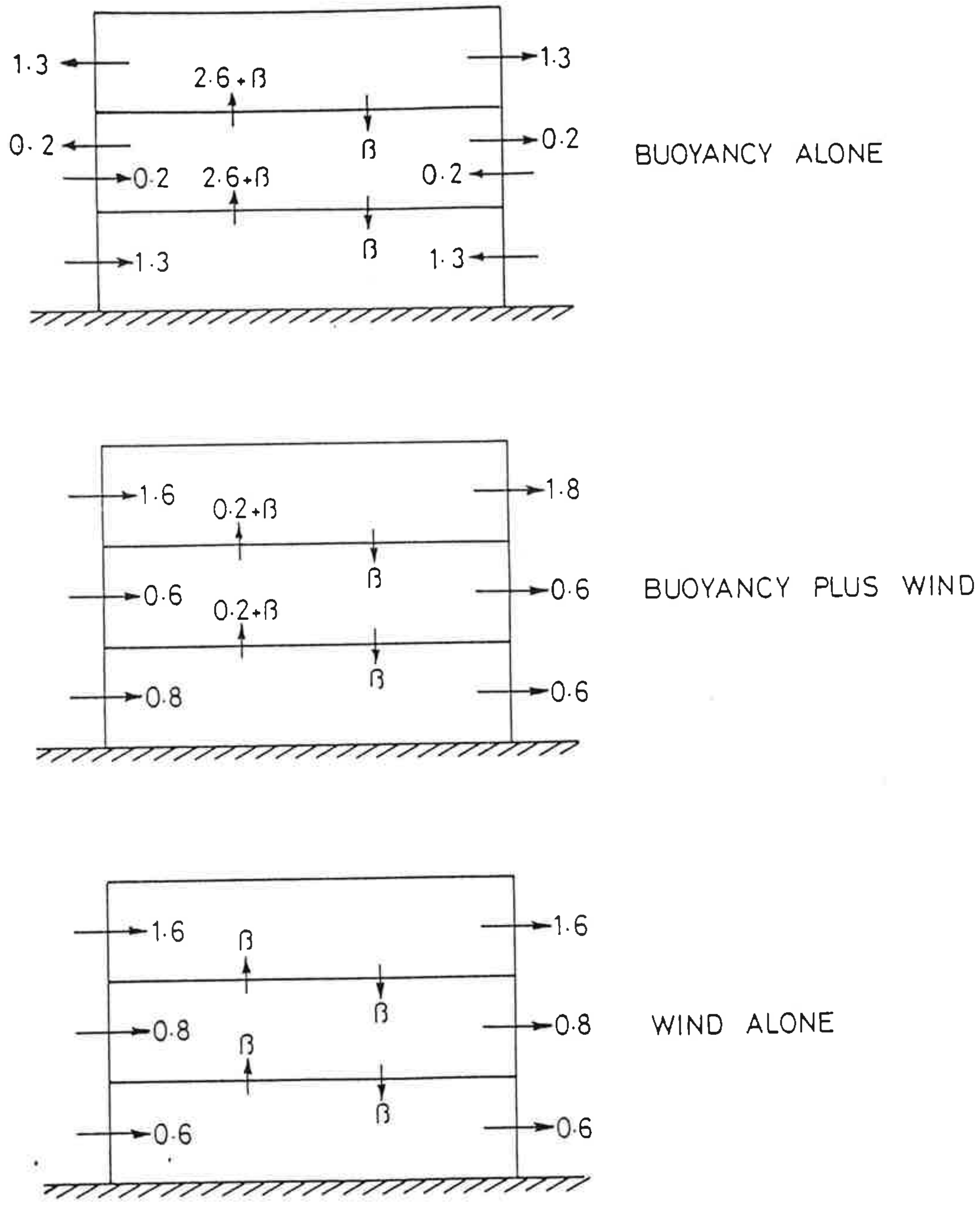

Figure 1 Airflows in the three-cell model

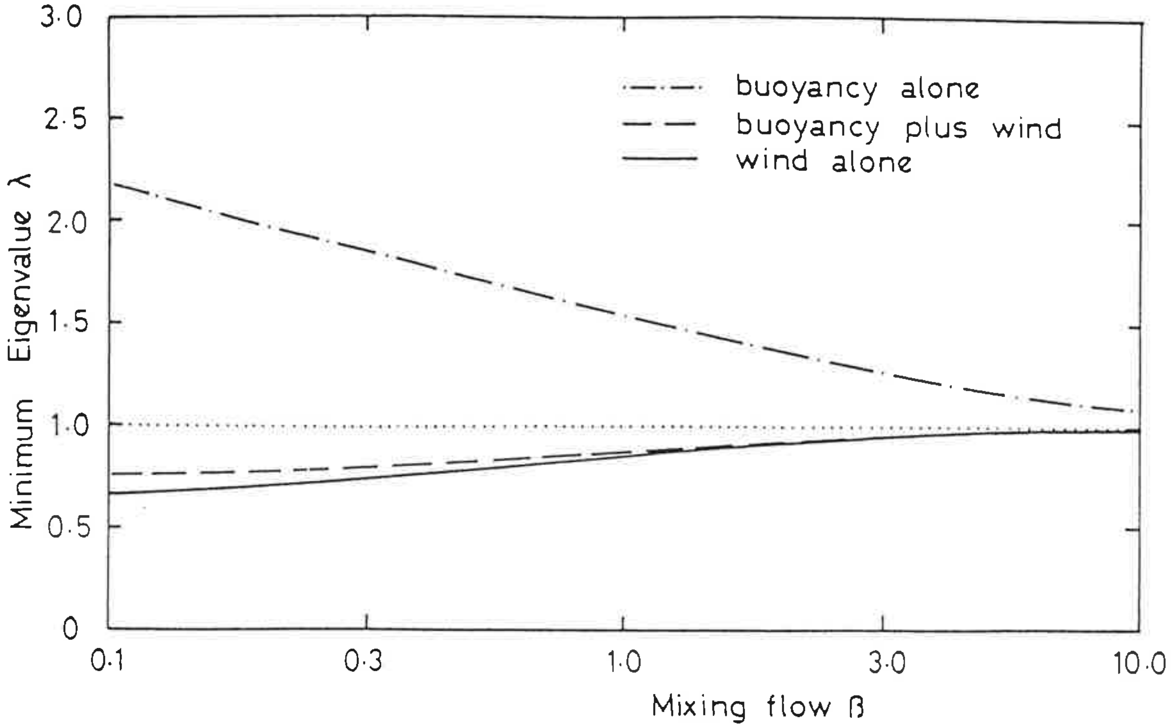

Figure 2 Variation of the dominant eigenvalue with enhanced mixing

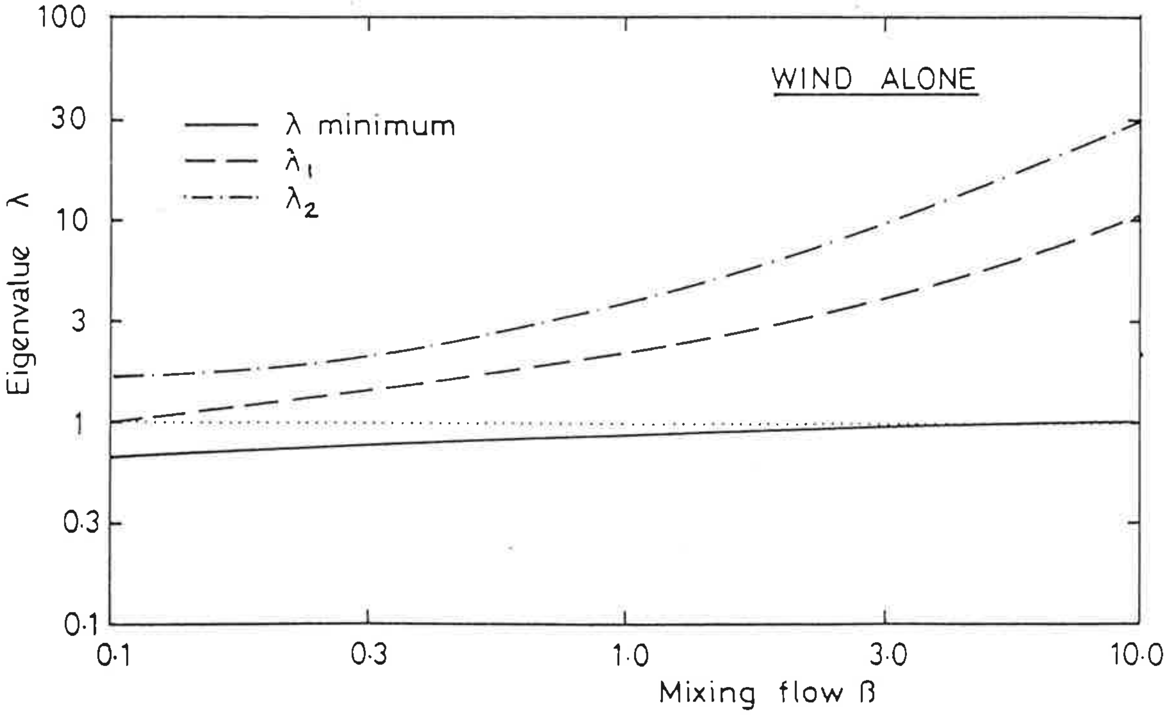

Figure 3 Variations of the three eigenvalues (wind-alone case) with enhanced mixing

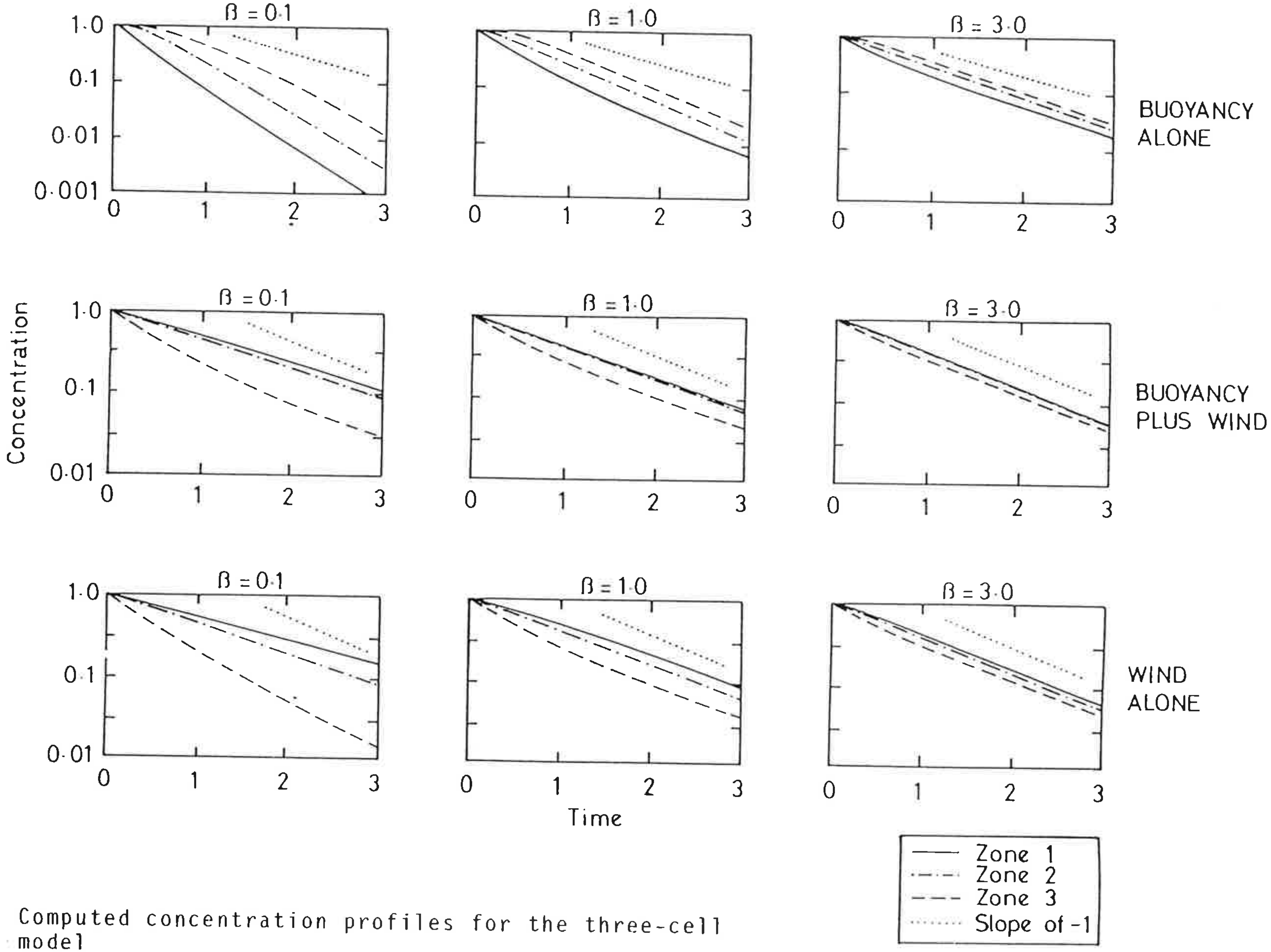

Figure 4 Computed concentration profiles for the three-cell model

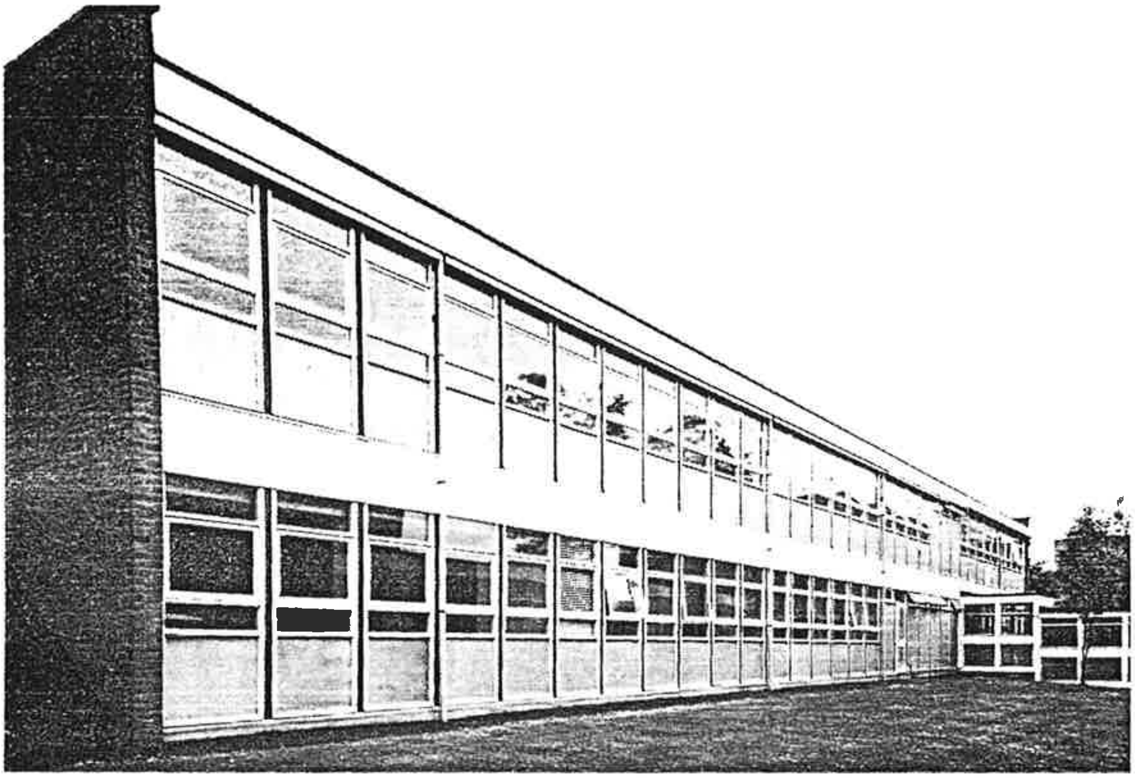
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Figure 5 West face of building A

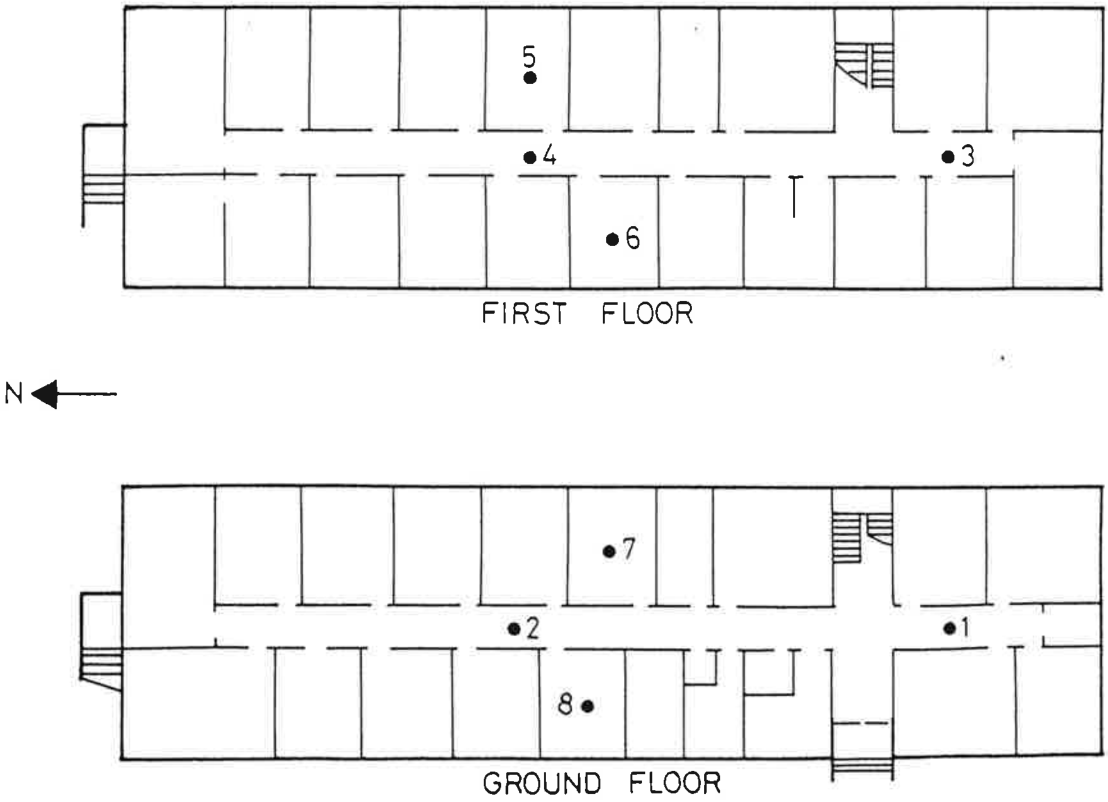

Figure 6 Plan of building A together with locations of sampling points

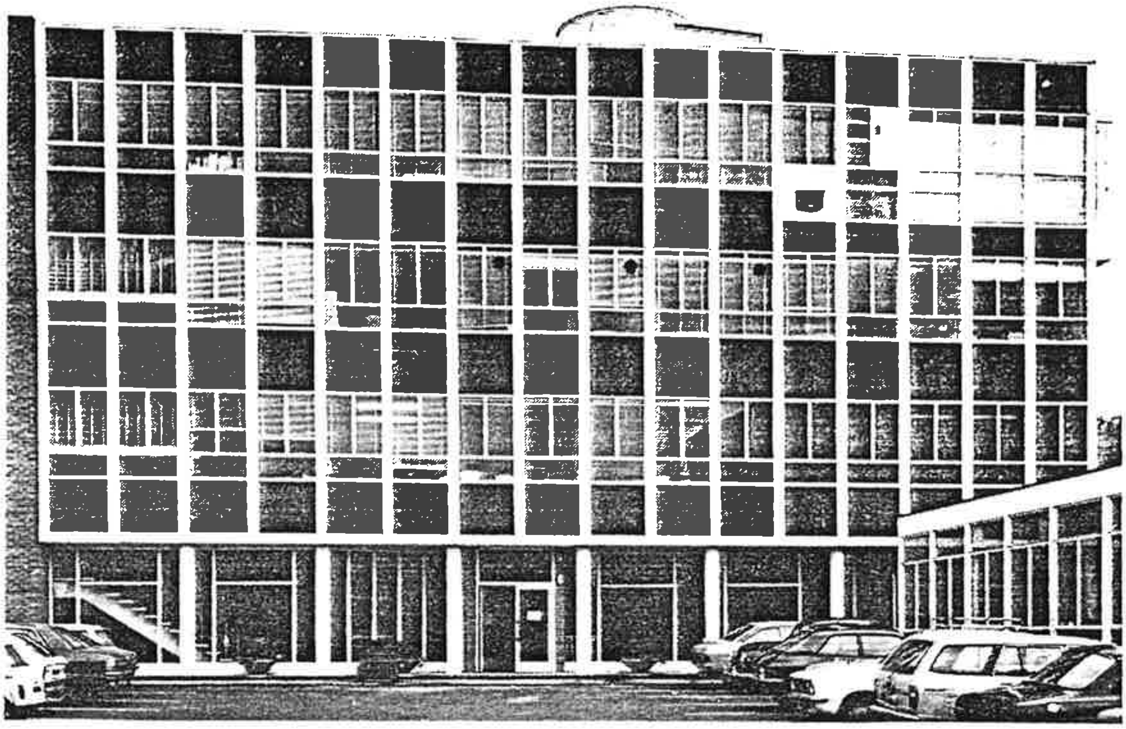

Figure 7 South face of building B

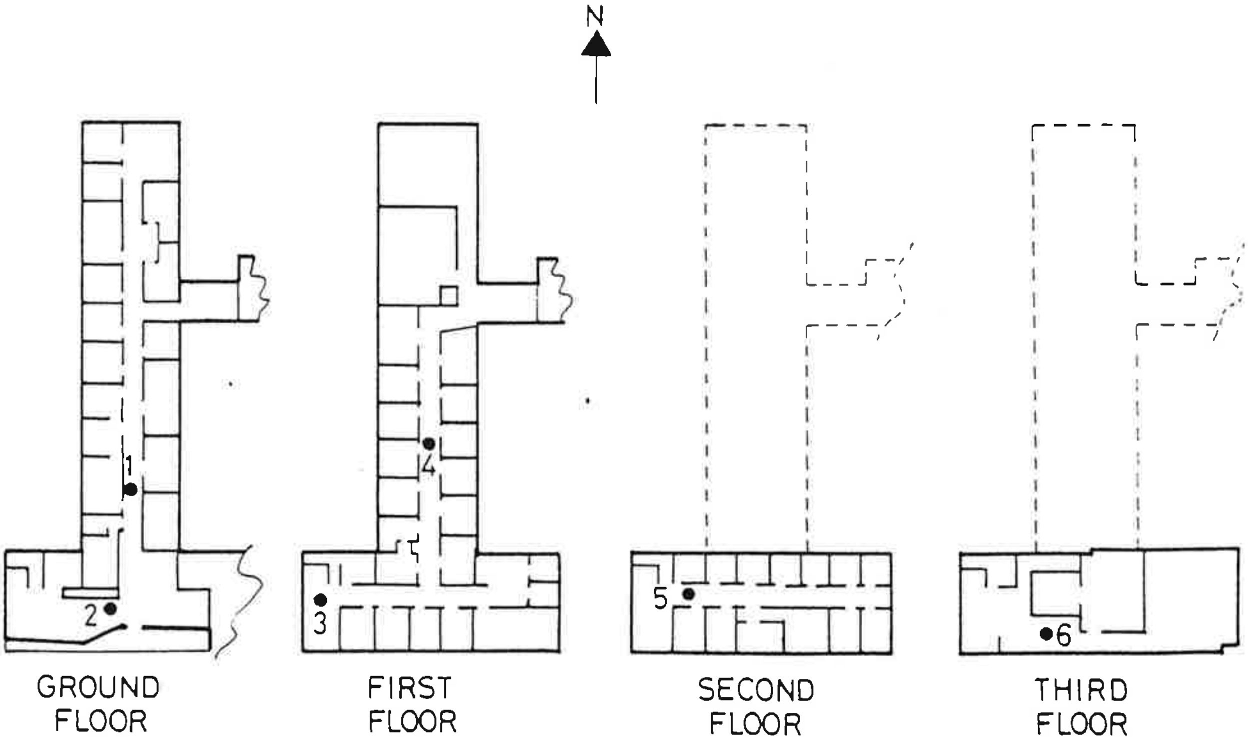

Figure 8 Plan of building B together with locations of sampling points

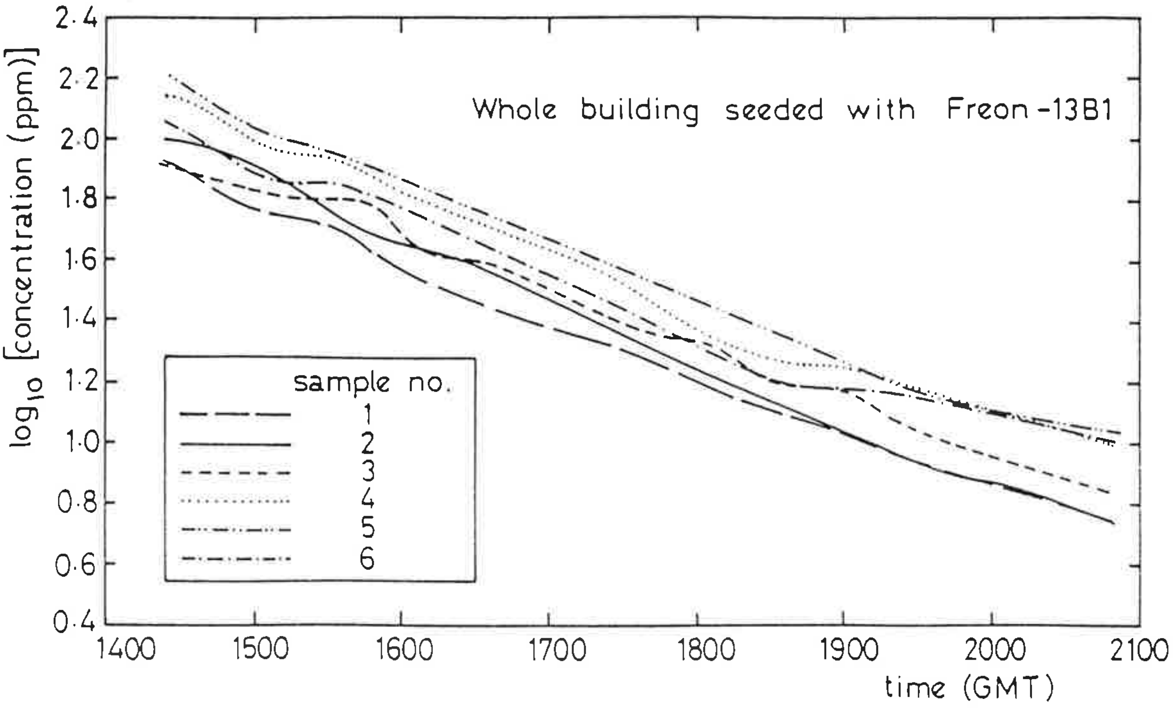

Figure 9.a Freon-13B1 concentration profiles from Test A1

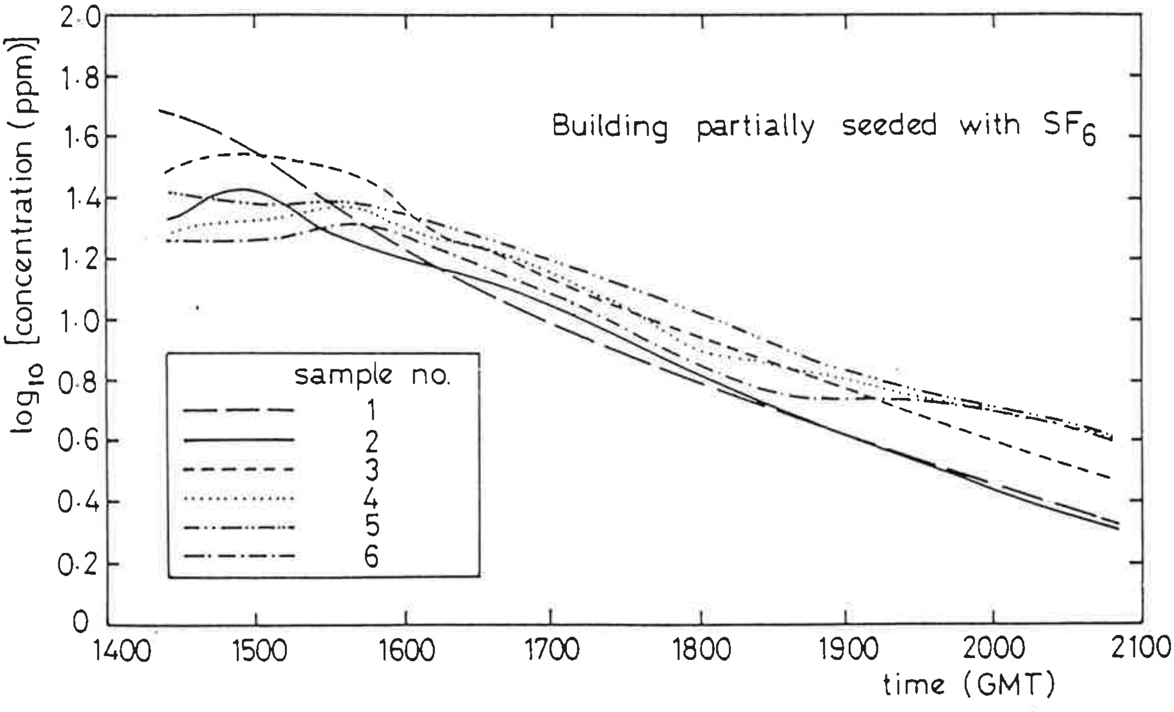

Figure 9.b SF6 concentration profiles from Test A1

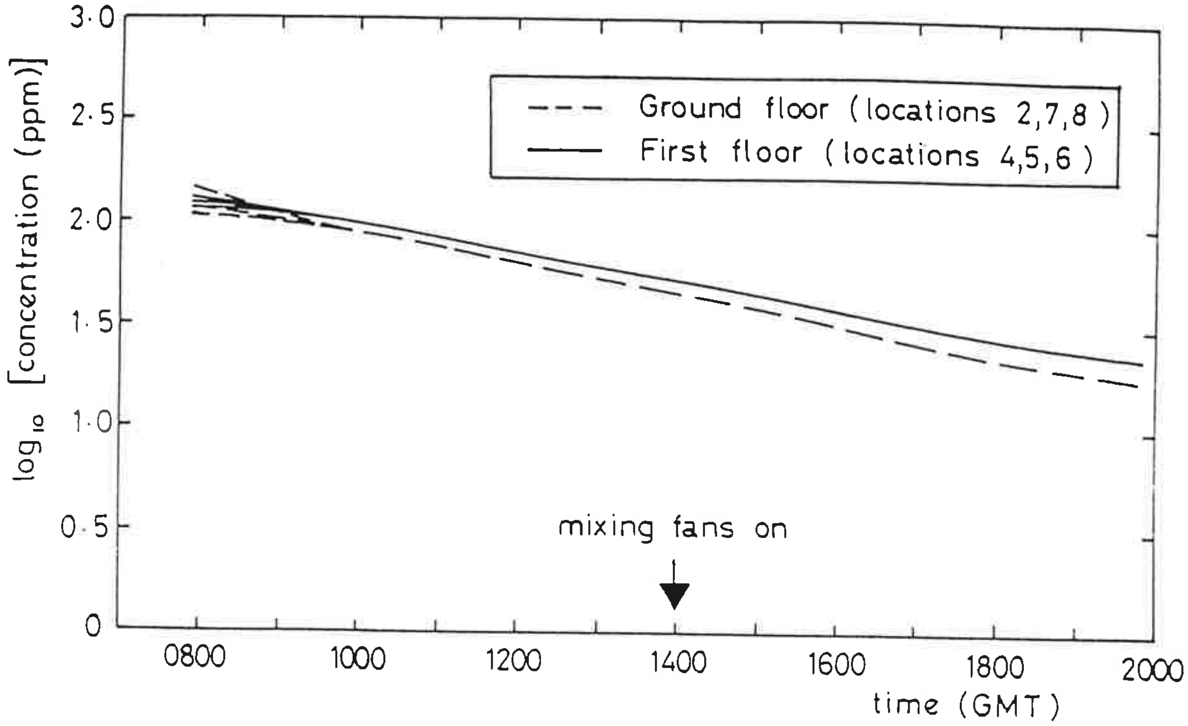

Figure 10 Effect of enhanced internal mixing during Test A2

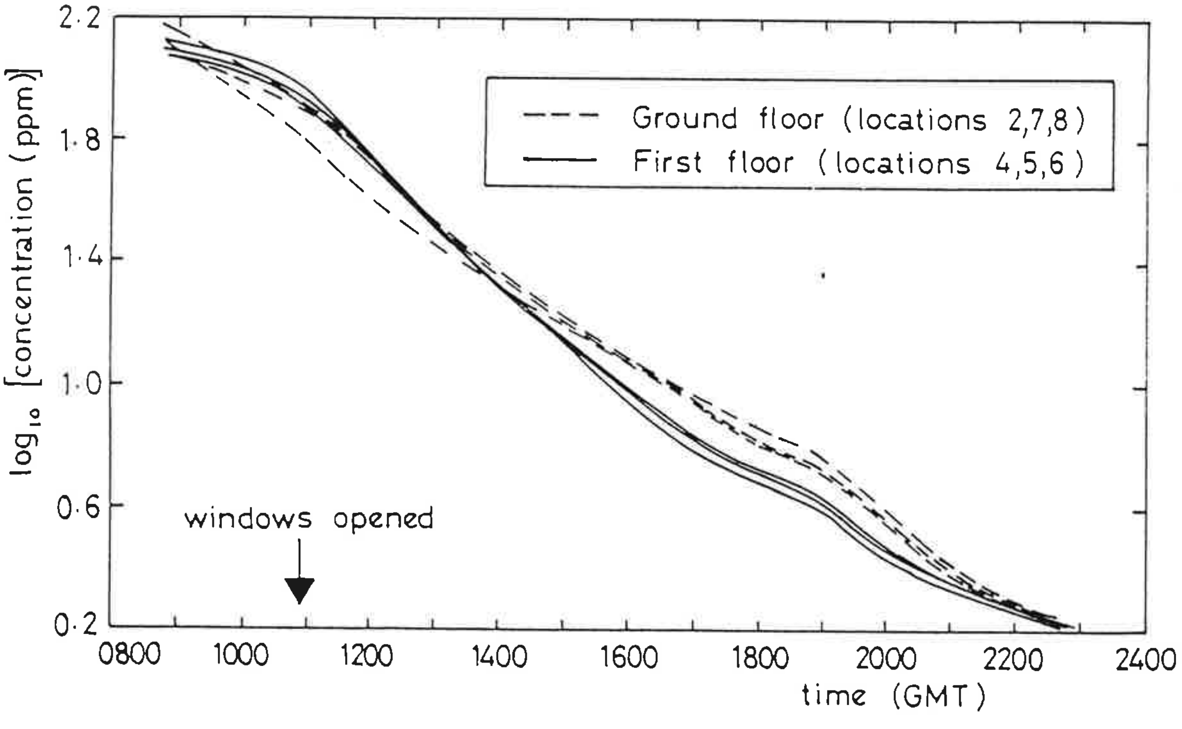

Figure 11 Effect of opening windows during Test A3

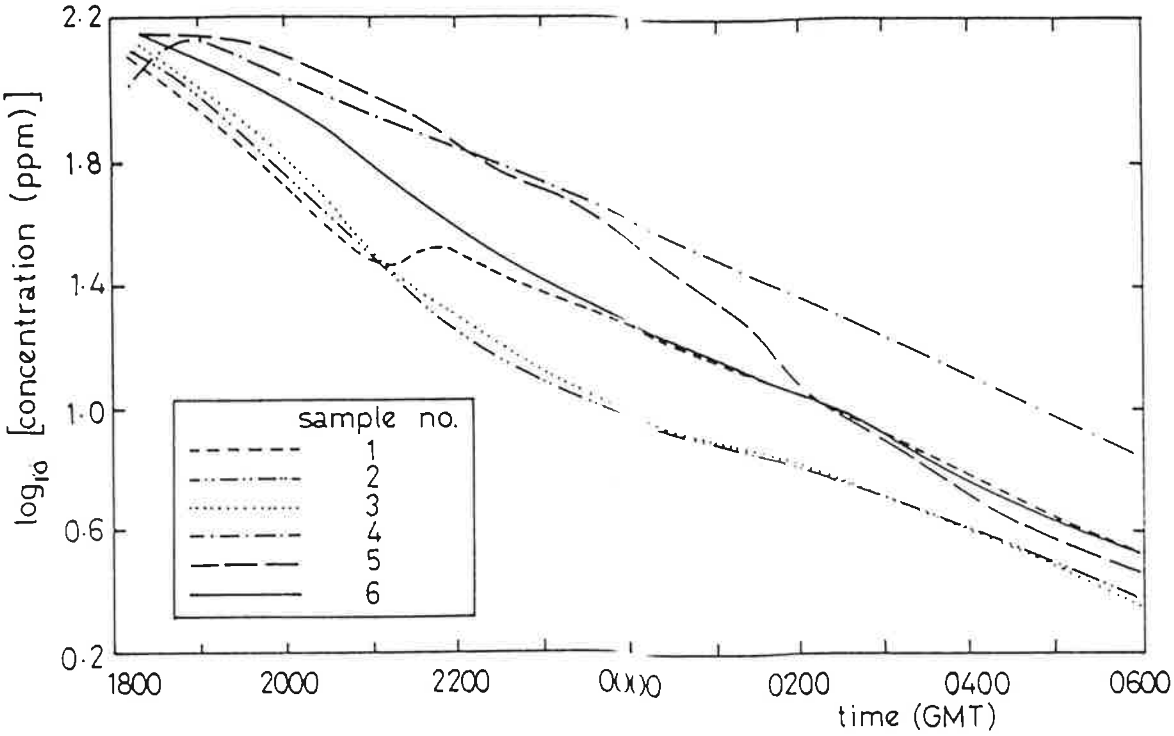

Figure 12 Concentration profiles from Test B1 in building B

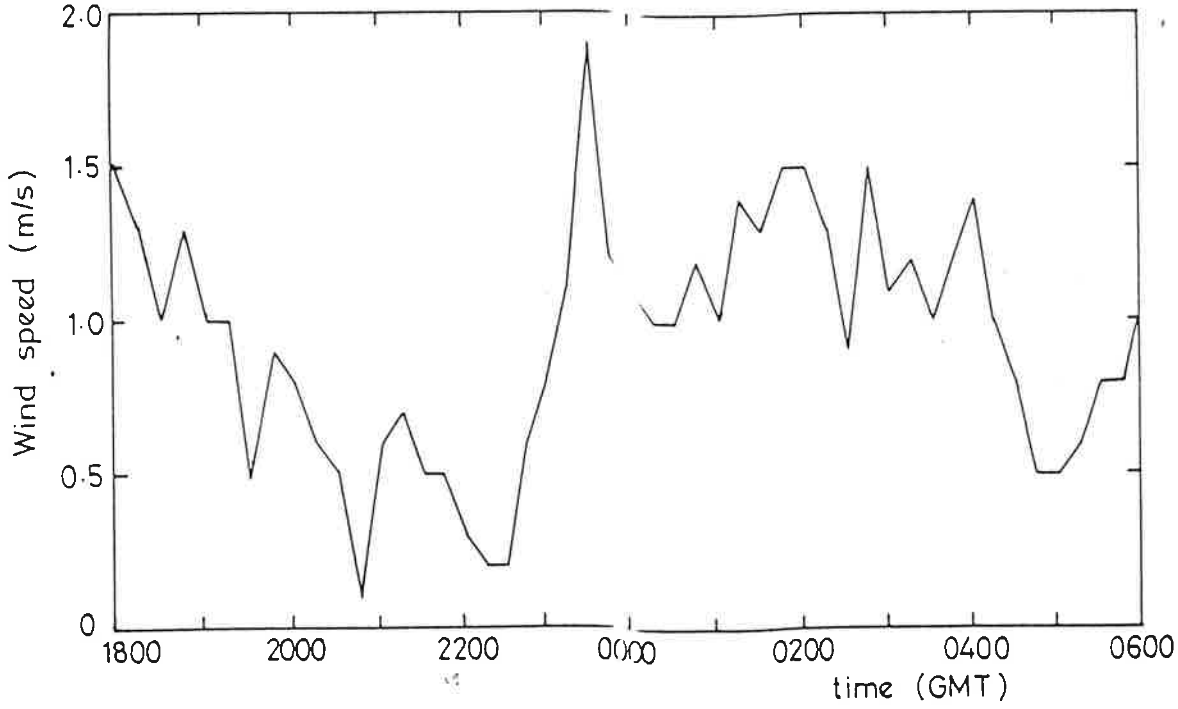

Figure 13 Wind speed record during Test B1