1861

AIC 1266

HI-85-40 No. 4

Evaluation of a Simple Technique for Measuring Infiltration Rates in Large and Multicelled Buildings Using a Single Tracer Gas

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ABSTRACT

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

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

A previous paper proposed a relatively simple technique to overcome these difficulties. By considering a multicell model, it showed that it was sufficient to seed part of a building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.

The results from two preliminary field tests, designed to evaluate the "simple" technique, are presented here. The first test was carried out in a mechanically ventilated multicelled three-story office block and the second in a naturally ventilated large, single-cell building. The results obtained from these tests are encouraging and give confidence to proceed with the more extensive field tests required to fully validate this technique.

INTRODUCTION

Although most buildings, whether commercial, public, or domestic, rely on natural ventilation, 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. Problems of scale and lack of appropriate techniques have deterred investigations of bigger, multicelled buildings.

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A previous report (Perera 1982) described possible measurement techniques that could be used in multicelled buildings and laid down the theoretical basis underlying the techniques. Subsequently, interzonal airflows in two large buildings were measured (Perera et al. 1983a; Perera et al. 1983b) using multiple tracer gases. However, the cost and complexity of carrying out multiple tracer experiments can be prohibitive, and in many instances, it would be sufficient 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. Considering a single tracer-gas decay technique, the most obvious of these are;

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

A previous paper (Perera and Walker 1984) proposed a relatively simple technique to overcome these difficulties. In that theoretical study, it was shown that it was sufficient to seed part of a building with a single tracer gas in order to measure the whole building infiltration rate to a good approximation. It was also said that, in principle, this technique is applicable to a wide variety of buildings whether they are small or large, single- or multicelled, naturally or mechanically ventilated.

The results from two preliminary field tests, designed to evaluate the "simple" technique, are presented here. The first test was carried out in a mechanically ventilated, multicelled, three-story office block and the second in a large, naturally ventilated, single-celled building. Further field tests to establish this method for naturally ventilated multicelled buildings are proceeding and the results will be presented at a later date.

BASIS OF "SIMPLE" TECHNIQUE

If a tracer gas at an initial concentration level of $\{C(0)\}$, is allowed to decay in a multicelled building, then its subsequent behavior at any later time, t, is governed (Perera 1982) 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.

It can be proved (Lancaster 1969) that there is a unique solution

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

satisfying Equation 1.

Lancaster (1969) further shows 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.

In a well-mixed single cell building, the single eigenvalue solution to the tracer decay equation, Equation 3, represents the air change rate of that building.

The most important question that was considered in Perera and Walker (1984) was, 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 building. In that paper, a two-cell model was considered and an analytical solution obtained. The results showed that if,

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

then the dominant eigenvalue tends towards the total infiltration rate.

It was stated that the conditions required for this to happen may be too restrictive. It was suggested, however, that the two-cell model is an extreme simplification of a multicelled building and that in a real building, two factors help toward the correspondence between the dominant eigenvalue and the whole building infiltration rate, namely;

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

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

In Perera and Walker (1984), the study was extended to a computer simulation of a five zone representation of a full scale building. This was a three-story office block and is one of the buildings in which the field tests, described below, were carried out.

Various combinations of tracer seeding and internal airflow patterns were studied. Of these, the most relevant to this paper is the tracer decay profiles obtained in a seeded zone when only a certain proportion of the building is seeded with the tracer.

Figure 1 shows predicted concentration profiles in the seeded zone when 11%, 16% and 100% of the building was seeded with a tracer at an initial concentration level of 100 parts per million (ppm). Figure 2 shows the same profiles plotted on a semilogarithmic scale and covering the range from 100 ppm to 1 part per billion (ppb).

The manner in which the concentration profiles are affected by factors such as enhanced internal mixing, stagnant zones, or over-ventilated spaces was also studied. From all these, the following conclusions were drawn:

1. All concentration profiles contain information regarding the eigenvalues characterizing the building regardless of the position of tracer seeding or the extent to which the building is seeded.
2. All profiles consist of a transition period and a steady dominant period.

3. 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.

4. After the transition period, the dominant period occurs during which the tracer decays at a constant rate. This rate, if measurable, characterizes the building.

The most important conclusion to come out from the study of Perera and Walker (1984) was that, in a well-connected building, this final decay rate approximates towards both the dominant eigenvalue as well as to the total infiltration rate of the building, or at least to the infiltration rate of some significant portion of the building. To measure the dominant decay rate, it was suggested that the experimental procedure should make use of the following points:

1. Measurements should be localised to the zone of seeding, thereby ensuring that air samples can be obtained relatively easily.

2. 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.

3. Monitoring in the dominant period will usually require a tracer gas capable of being detected at very low concentrations and over a wide dynamic range. For example, sulphur hexafluoride, SF6, could be used and detected at ppb levels using an electon-capture detector coupled to a gas chromatograph.

MEASUREMENTS IN A MULTICELLED OFFICE BUILDING

The following describes a preliminary test in which part of a building was seeded with one tracer gas, while a second tracer gas was dispersed throughout the whole building. In this way,the long-term decay rates at a common location, for the two seeding strategies, were measured and compared. This showed that the long-term decay rate of the "partially seeded" tracer corresponds to the overall ventilation rate.

Building

The building (Figure 3) used for the test is a mechanically ventilated, three-story "low energy" office building (Price 1982) located on site at the Building Research Station at Garston. It is rectangular in plan (60 m x 12 m), and each floor has a nominal volume of 1762 m^3.

The air-handling unit in this building connects directly only to the rooms whereas the corridors and stairwells are not directly ventilated in this way. During the test, the doors were positioned "as under occupation", i.e. the test was performed during a normal working day, and some doors were wedged open by occupants while others were closed. All fire doors, which separate stairwells and corridor sections, were kept closed. Therefore, while the air within the building was expected to exhibit good mixing, perfect mixing was not expected.

This view of a good, but not perfectly mixed, building is justified with reference to the result (Figures 4.a. and 4.b.) of a test in which the whole building was seeded via the air-handling system. During the test, the weather station at Heathrow was measuring an average wind speed of 4.6 m/s blowing from 35 degrees. The external temperature at Garston was 6 °C while the internal temperature in the office building was maintained at 20 °C.

With the air-handling unit on, air samples were taken at several locations on a single floor level, using an automated system connected to an infrared analyzer. All internal doors were closed. Four important observations can be made:

1. The concentration levels in the rooms, corridor and stairwell were not the same.
2. The decay rates in the rooms and in the corridor were the same in the long-term.
3. There were distinct initial decay rates. This is more easily seen where additional data points have been plotted for two of the sample locations (Figure 4.b.).
4. The slower long-term decay rate in the stairwell represents an "under ventilated", or relatively stagnant zone.

None of these phenomena would be expected to occur if the mixing were perfect within the building. It was therefore decided that, even though the building was mechanically ventilated, the building exhibited sufficient departures from the concept of a "perfectly mixed" building for the "simple" technique to be evaluated.

Tracer gases and injection strategy

For the purposes of distributing tracer gas, it is possible to divide the building on the basis of horizontal or vertical zones and select individual regions for seeding by an appropriate choice of the installed tubing system.

SF6 and bromotrifluoromethane (CBrF3) were choosen as tracers for this test because both can be detected down to ppb levels. During the test, the whole building was seeded with CBrF3 and the second (i.e., top) floor was seeded with SF6 to initial concentrations of 25 ppm.

Tracer sampling and analysis

The sampling point was located at a few metres east of center, along the second floor corridor. Samples were taken at hourly intervals.

Air samples were collected in 5-litre polyvinylfluoride sample bags, which had previously been flushed out several times with nitrogen. During sampling, the bags took approximately 30 seconds to fill using a diaphragm pump. An infrared analyzer was also used to take continuous measurements of SF6 concentration in the range 0 to 50 ppm.

The infrared analyzer was calibrated before and after the test using "zero" gas (nitrogen) and "span" gas (specified to 0.1% tolerance) with the span gas choosen to give a reading approximately 75% of full scale (50 ppm). The accuracy of analysis is estimated as approximately 1% of full scale (i.e., - 1/2 ppm).

The measurements were extended over a long period (seven hours) until both tracers reached ppb concentration levels. The collected bag samples were analyzed off-line using a gas chromatograph with an electron-capture detector.

A stainless steel column, packed with an ethylvinyl benzene divinyl benzene copolymer, was used. The column and detector were both operated at a temperature of 100°C. Argon with 5% methane was used as the carrier gas flowing at a rate of 30 ml/min. Under these conditions, the retention times of SF6 and CBrF3 were 0.88 and 1.98 minutes respectively.

Samples were injected into the gas chromatograph through a 2 ml sample loop of the "gas sampling valve". With this arrangement, SF6 was measurable over the range 1 to 100 ppb, while CBrF3 was measurable over the 10 to 400 ppb range.

Bags containing the lowest concentrations, and lying within the above measurable ranges, were injected directly into the chromatograph with a 100 ml glass syringe. Samples at higher concentrations were first diluted by a known amount with outside air before they were analyzed.

During analysis of the bag samples, several calibration checks were made on the gas chromatograph. For SF6, standards were made by volumetric dilution of span gas (approximately 40ppm) with air while, for CBrF3, the required standards were made by diluting the neat tracer with air through an additional stage of dilution. Measurements made by taking gas from the same sample bag were repeatable to within 5%. It is possible that systematic errors may also be involved in making calibration standards, and also in the dilution of bag samples. These are more difficult to quantify but are estimated to be of the same order.

Additional precautions for "bag" sampling

The following precautions were taken so as to reduce possible adsorption (and absorbtion) effects on the stored tracer gas samples:

1. The bags were repeatedly flushed (at least three times) with nitrogen, and stored inflated, prior to the test.
2. When tracer concentrations were expected to be less than a few ppm, the appropriate sample bags were flushed several more times before samples were taken.
3. Before each sample was taken, the air was flushed through twice through the bag.

The bag samples were analyzed within a few days of the end of the test. Over this period of time, there are no indications that either CBrF3 or SF6 samples would significantly deteriorate over this period. In separate tests (not as yet reported), no deterioration of SF6 samples at ppb levels have been observed.

To minimise the risk of adsorption of the tracers on nylon sampling tubing, the following precautions were taken:

1. The bags were filled at a nominal sample rate of 1.3 litres per minute through a connecting tube of less than three metres.
2. On flushing the bags, immediately before a sample was taken, the tubing was also flushed through twice with the "sample" air.

It was therefore considered that these two factors, together with the 5-litre bag sample size, would not produce any significant absorption (adsorption) effect due to the tubing.

Results and discussion

The decay in concentrations of the two tracer gases is plotted on a semilog scale in Figure 5. The on-line ppm measurements made by the infrared analyzer are included with the gas chromatography measurements. The weather conditions during this test are tabulated in Table 1.

The initial infrared measurements of the SF6 decay are shown in Figure 6. The transition to the dominant decay is emphasised by the "knee" at around 1020 hours, approximately 40 minutes after the injection of the tracer was completed. Inspecting the SF6 bag analyzes, it is suggested that this is more or less complete by 1115 hours.

The decay rates of CBrF3 and SF6 over the subsequent period 1100 to 1230 hours are 0.81 and 0.74 /h respectively. There is apparently a slight disturbance in the concentration profiles of both gases after this time, and which broadly corresponds with the lunchtime period. Disregarding this period, the decay rates between 1330 to 1600 hours are 0.88 and 0.82 /h for CBrF3 and SF6 respectively. After this time, there is an apparent change in the concentration profiles of both gases, but it is not possible to say whether this is real since only two data points are involved.

It is difficult to decide whether the lower decay rates observed from the SF6 trace arises from the calibration and analysis procedures or is real. Other researchers (Grimsrud et al. 1980; Shaw 1984) attempted comparisons of decay rates of different tracer gases. They have seen that rates calculated from SF6 may be consistently either higher or lower by about 10% as compared with other gases. This may have some bearing on the results presented here.

It should be noted that these rates reflect the infiltration rate for those relevant time periods over which weather conditions can be regarded as remaining approximately constant.

In the earlier example (Figure 4), the overall decay rate of tracer seeded throughout the building show a rate around 0.86 /h after an initial "settling" period of about 40 minutes. This value is not inconsistent with the range of values quoted above.

These results are very encouraging. They show that, by only partially seeding the building, the dominant decay rate as observed agrees reasonably well with that obtained with the tracer seeded throughout the whole building.

MEASUREMENTS IN A LARGE, SINGLE CELLED INDUSTRIAL BUILDING.

Although the technique was developed to enable useful measurements to be made in multicelled buildings, the approach is expected to be valid in a wide variety of buildings, including large, single-celled, naturally ventilated spaces. Such buildings can be regarded as made up of many (poorly-defined) zones.

Concern has been expressed that measurements using tracer gas in such buildings would be very difficult, particularly in dispersing (i.e., seeding) the tracer and in maintaining good mixing with the internal air.

The following test was proposed in order to show that it should be possible to obtain the overall infiltration rate of such a building by seeding only part of the building, making no attempt to artificially mix the tracer, and taking measurements at any convenient location.

For this field measurement, a naturally ventilated large "hangar" type industrial building was partially seeded with a tracer gas. The initial decay in concentration was monitored at 12 locations using an automated system, while longer-term measurements were made using the bag sampling technique.

Building

The building (Figure 7) houses a wind tunnel facility. The building is rectangular (30 x 12.5 m) in plan and has a pitched roof. The ridge of the roof is aligned north-south. The roof slopes down from the 10.4 m high ridge to the 7.6 m high eave. The wall then drops down to a 3 m high small, single-story slab structure, which is 4.8 m wide. A second separate, but identical, hangar building adjoins the east face of the test building.

Figure 8 shows the locations of the measuring points. Points 1 to 6 were located around the wind tunnel at a height of 2.2 m each while, immediately above these points, measuring points 7 to 12 were located at a height of 6.6 m.

Tracer injection and sampling strategy

SF6 gas was released from a gas bottle positioned at ground level at a point approximately one metre to the west of center of the building. The gas was released until a target concentration of approximately 200 ppm was measured at location No. 4 in the distant corner.

An automated system was used to sample from all 12 measuring locations. The automated system consisted of a microcomputer controlling a rotary sample valve. This was used to direct the air samples to two infrared gas analyzers from each of the 12 locations in sequence. The two SF6 analyzers, with ranges of 50 and 200 ppm full scale respectively, were connected in parallel so as to maintain accuracy of measurement over the full 200 ppm range.

Bag samples were taken near measuring point No. 3 at half-hour intervals. With this technique, measurements were possible over an extended period of seven hours. At the end of this time, SF6 concentrations were down to a few ppb. The bag contents were analyzed off-line, using the gas chromatograph as described above.

The calibration procedures and the estimated accuracy of analysis for both infrared and gas chromatography measurements were the same as described for the "office" measurements.

Results and discussion

Figures 9.a. and 9.b. show, in a semilogarithmic form, the ppm infrared measurements made at the 12 locations. The measurements at sample location No. 3 are reproduced in Figure 10, together with the bag sample analyzes corresponding to the same location.

Figure 10 shows the tracer concentrations had adopted a steady relationship with respect to each other by approximately 1150 hours. The curves then begin to fall off at a steady rate which is approximately the same at all locations (Table 2). Note that perfect mixing would require concentrations at all points to be equal almost instantaneously.

The above observations, namely that an equilibrium has been achieved between the concentrations at all locations, and that a common decay rate is exhibited, lead to the conclusion that the dominant decay rate has been achieved, and that this is the overall ventilation (infiltration) rate.

The bag sample analyzes indicate that this rate continues until about 1500 hours. The average decay rate over the period 1315 hours to 1515 hours is 1.8 /h. There is then a fairly abrupt change to a slower decay rate, averaging 0.59 /h thereafter.

The abrupt change in decay rate corresponds, at 1500 hours, to a general reversal in the mean wind direction (Table 3) at Garston. Before this, a light wind was blowing from the south-west towards the exposed west face of the building. After 1500 hours, the wind veered through 180° and blew from the north-east. During this period, the test building was sheltered by the ajoining "hangar" building on its eastern side.

FINAL DISCUSSION AND CONCLUSIONS

Two preliminary field tests were carried out as part of a program of work designed to evaluate the "simple" technique. Each of these tests was designed to study different aspects of the technique.

In both experiments, the following propositions of the "simple" technique were tested:

1. It is necessary only to seed part of a well-connected building.
2. A dominant decay rate can be measured at all locations (within a significant portion of the building).
3. The dominant decay rate approximates closely to the infiltration rate.

The two experiments employed two subtly different approaches. For the test in the office building two tracer gases were used with SF6 seeding just part of the building while the CBrF3 was dispersed throughout the whole building. Coupled with prior knowledge of the mixing characteristics, the decay rate of CBrF3 was taken to represent the overall infiltration rate. This rate was compared with that of SF6 at the same location. Following a transition period, which is highlighted by the infrared measurements, the decay rate of the partially seeded tracer was shown to approximate to the overall building ventilation rate.

In the test in the hangar building, a different indicator of overall ventilation rate was used. Rather than using a second tracer and comparing measurements at a single location, measurements were taken throughout the space. In this way it was shown that by only partially seeding the building, an equilibrium was subsequently achieved between the concentrations at all locations and that a common decay rate was exhibited. It was concluded that the dominant decay rate had been achieved, and that this was the overall ventilation rate.

In addition, these two field measurements showed that the tracers used should be measurable at very low concentrations over a wide dynamic range. This was shown to be true for the tracers, SF6 and CBrF3, used in these two tests. The use of off-line bag sampling, as opposed to on-line measurements, was also demonstrated.

To sum up, the results obtained from these tests are encouraging and give confidence to proceed with the more extensive field tests required to fully validate this technique.

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ACKNOWLEDGMENTS

The work described has been carried out as part of the research program of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

TABLE 1

Weather Conditions at Garston on 10-Dec-84 during Test in the Office Building

Time	Temperature		Wind	
(GMT)	Internal	External (degC)	Speed (m/s)	Direction (degN)
0800	20.	2.1	1.2	186
0900	20.	2.9	1.5	205
1000	20.	3.2	1.4	228
1100	20.	4.3	2.2	250
1200	20.	4.6	1.8	232
1300	20.	5.3	1.4	232
1400	20.	6.1	1.5	251
1500	20.	6.0	1.7	232
1600	20.	5.4	1.8	256
1700	20.	4.7	1.5	232

(Note Wind speeds were monitored at a height of 10 m at a nearby open location)

TABLE 2

Decay Rates at all Twelve Locations during Test in the "Hangar" Building over the Period 1200 to 1320 GMT

Sample location	Plot symbol	Decay rate (per hour)
1	○	1.62
2	△	1.68
3	+	1.70
4	□	1.68
5	▽	1.70
6	◇	1.66
7	●	1.67
8	▲	1.75
9	×	1.70
10	■	1.85
11	▼	1.79
12	◆	1.66

TABLE 3

Weather Conditions at Garston on 11-Dec-84 during Test in the "Hangar" Building

Time	Temperature	Wind	
(GMT)	External (degC)	Speed (m/s)	Direction (degN)
0800	-1.6	0.05	228
0900	-1.8	0.03	228
1000	-1.1	0.36	228
1100	-0.2	0.04	228
1200	0.6	0.68	209
1300	1.5	1.21	232
1400	1.8	0.55	140
1500	1.9	0.05	046
1600	1.0	0.24	046
1700	-0.1	0.40	093
1800	-0.3	0.63	070
1900	-0.7	0.26	069

(Note: The internal temperature was estimated to be 13 (+2) degC since the sensor failed)

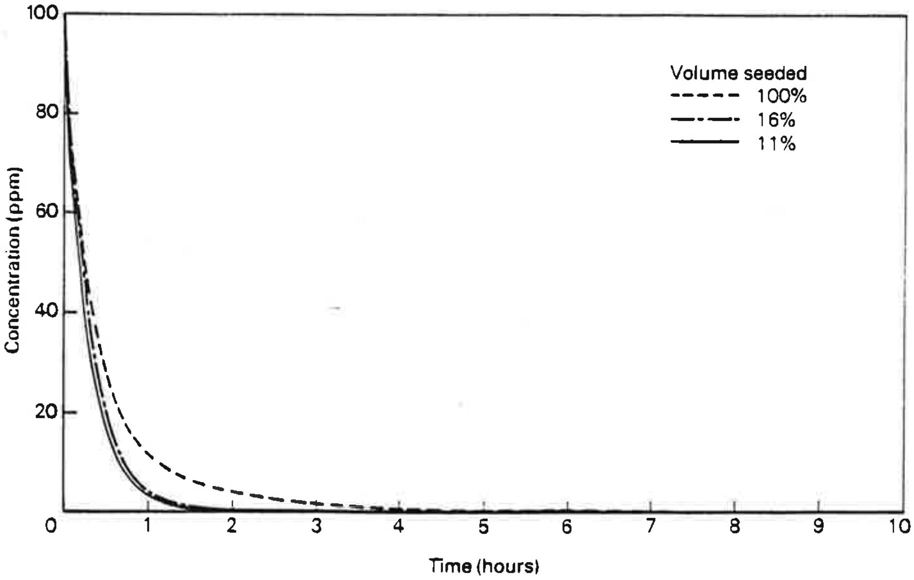

Figure 1. Predicted concentration profiles at a point in the seeded zone for varying amount of building volume seeded with tracer

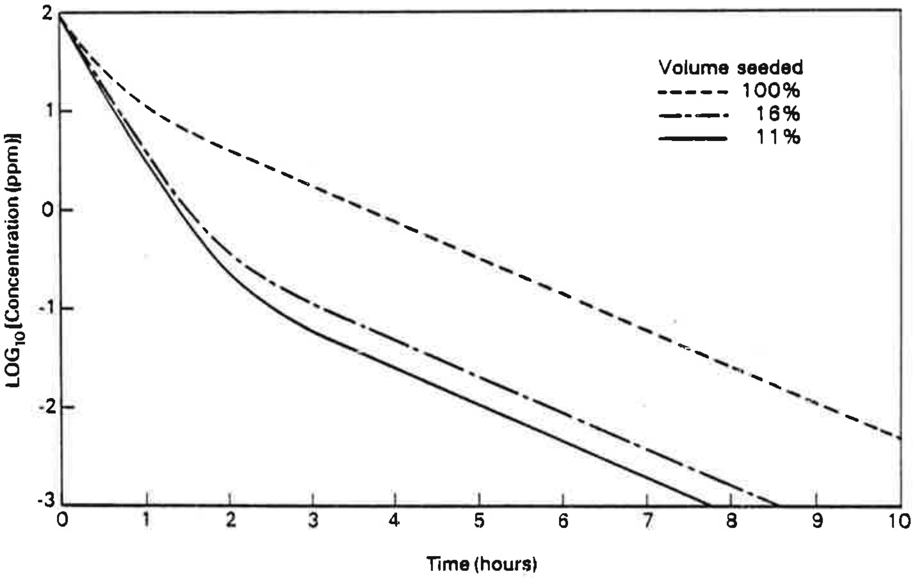

Figure 2. Concentration profiles of Figure 1 plotted in a semi-logarithmic form

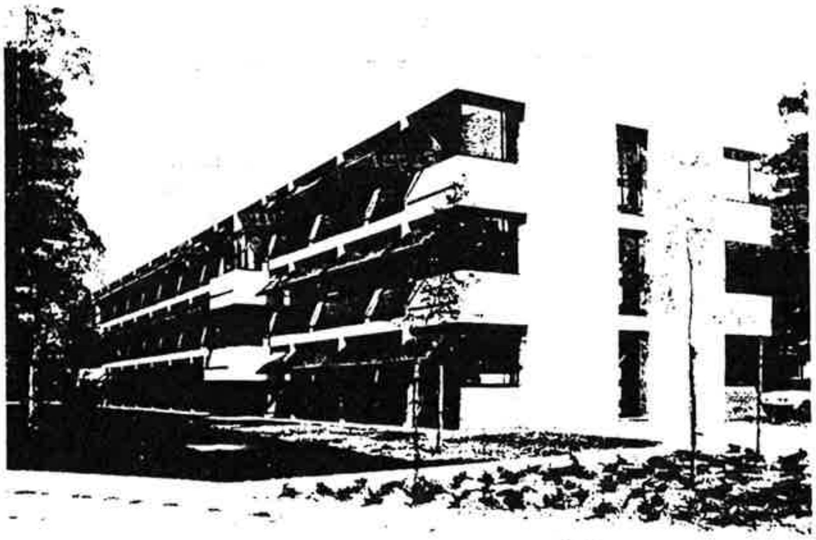

Figure 3. General view of the office building

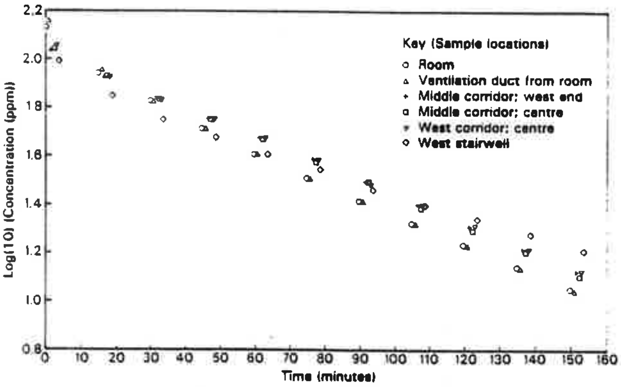

Figure 4a. *Concentration profiles at various second-floor locations obtained by dispersing SF6 throughout the whole building*

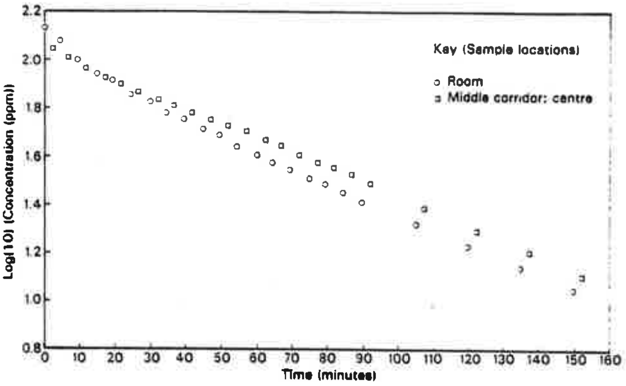

Figure 4b. *Additional data points plotted for two locations during test described in Figure 4a*

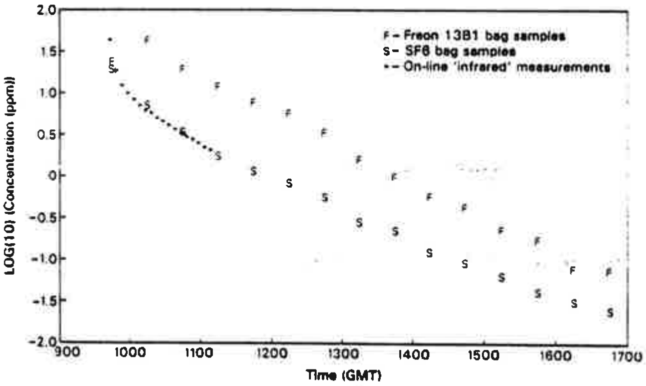

Figure 5. *Concentration profiles for Freon-13B1 (whole building seeded) and SF6 (partially seeded) from bag-sampling*

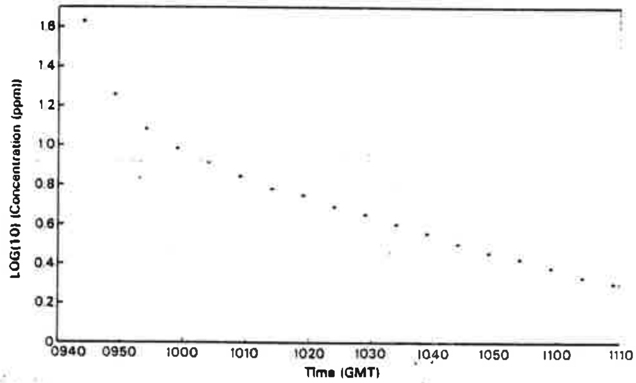

Figure 6. *Concentration profiles for SF6 from 'infrared' measurements over the period 0940 to 1110 GMT*

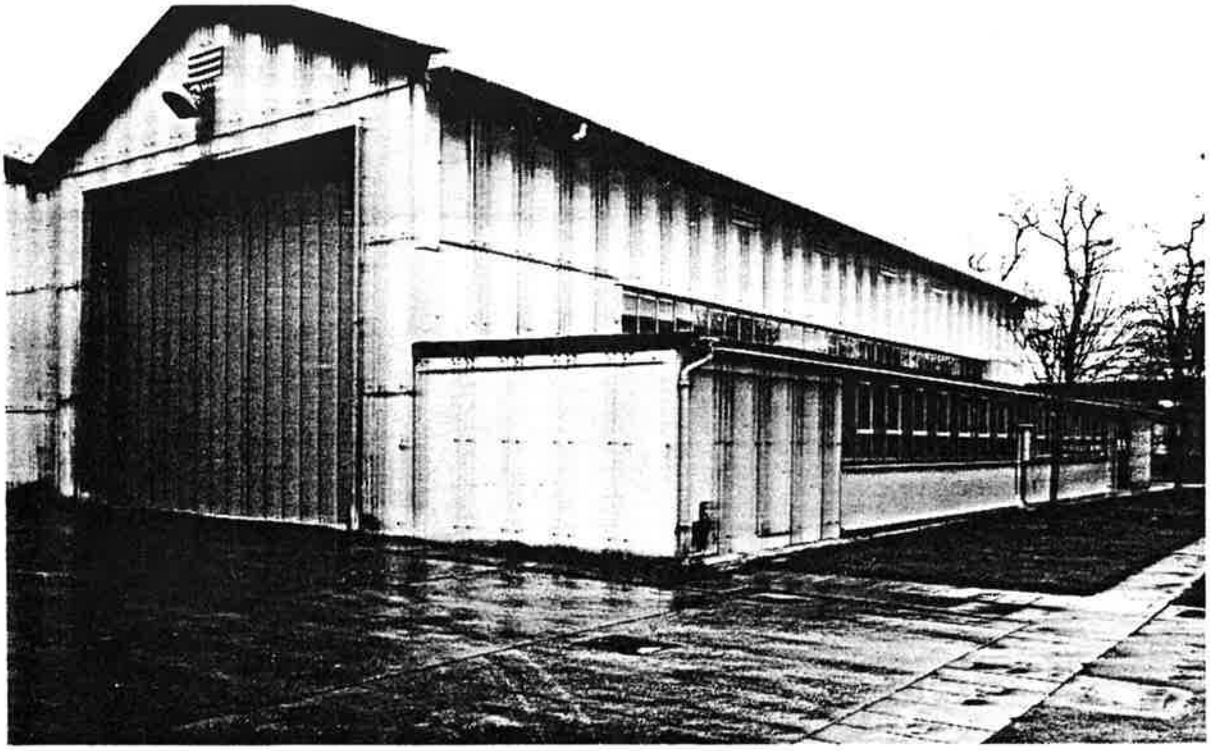

Figure 7. General view of hangar building

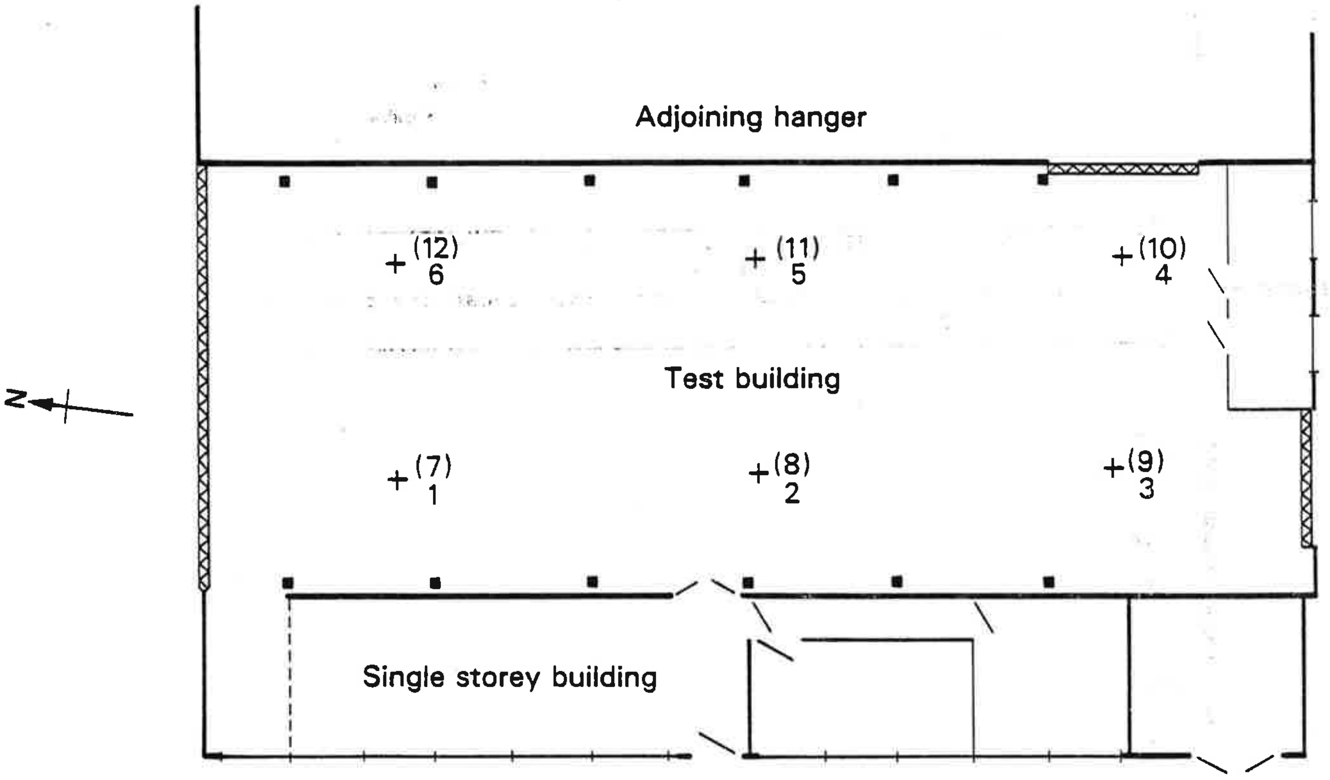

Figure 8. Locations of the measuring points in the naturally ventilated, single-cell industrial building

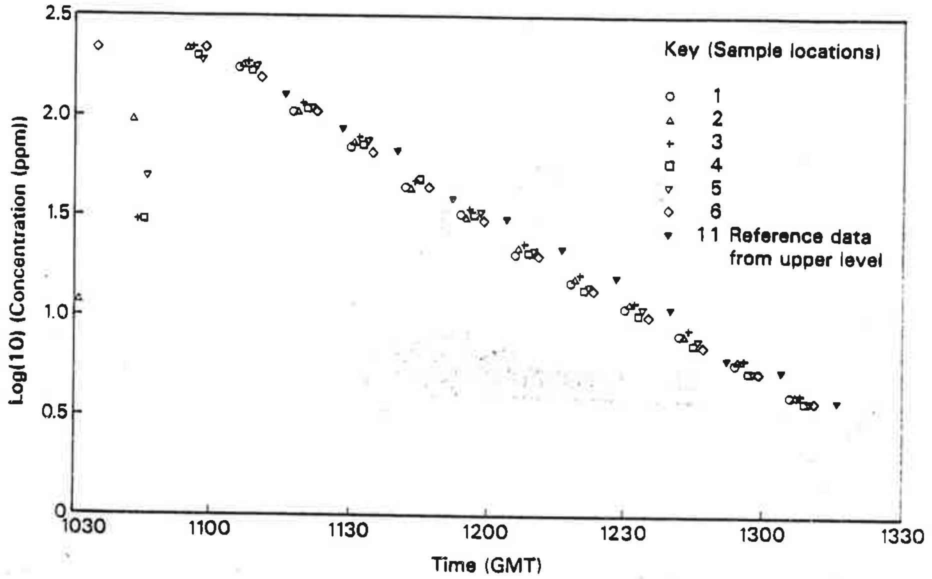

Figure 9a. Automated systems measurements at lower level locations over the period 1030 to 1330 GMT

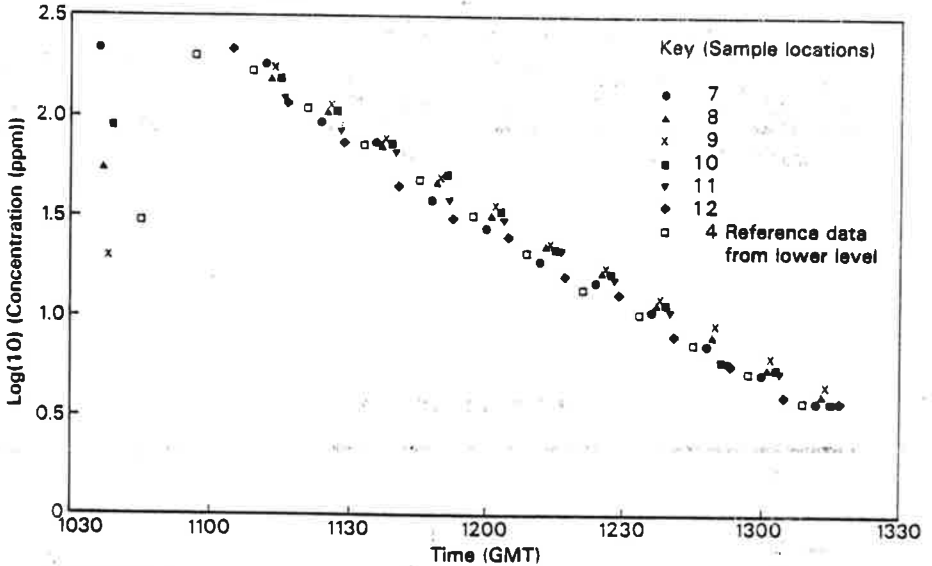

Figure 9b. Automated system measurements at upper level locations over the period 1030 to 1330 GMT

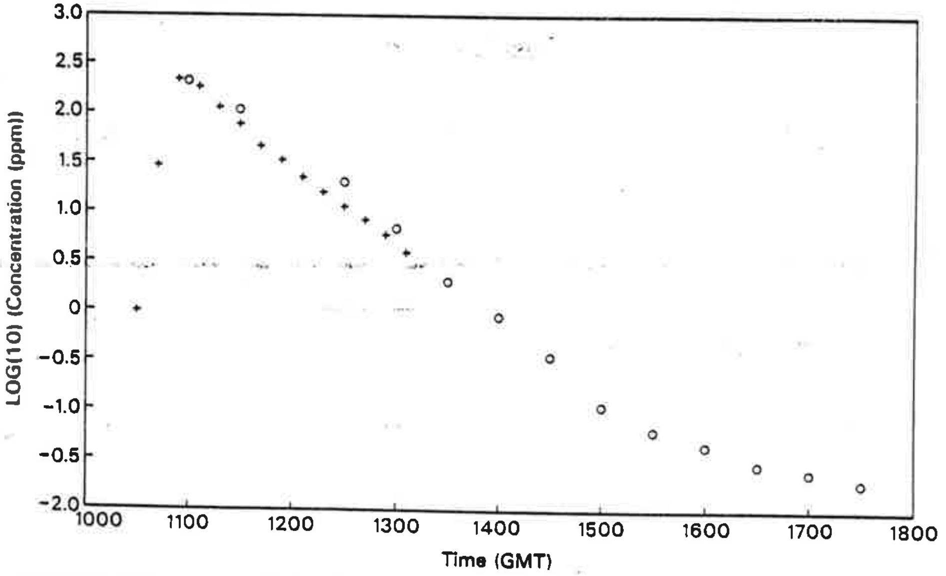

Figure 10. Concentration profile from bag samgles (o) and automated-system measurements (+) at Location No. 3

[illegible]

[illegible]

[illegible]

[illegible]