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Summary Indoor air quality was monitored at two schools in Essex, UK (located on the same site) during the week 3–7 November 1997. The objective was to determine whether the ventilation rates within the buildings were adequate to provide acceptable air quality to the occupants. Airborne carbon dioxide concentration was determined using continuous infrared detectors. A class base in each school was monitored for a two-day period. Occupancy patterns and window/door opening were observed during the first day of each period. Air temperature was also recorded. Indoor carbon dioxide levels exceeded those recommended for acceptable indoor air quality for a large proportion of the occupied period. Fresh air ventilation rates were below recommended guidelines.

Air quality and ventilation rates in school classrooms I: Air quality monitoring

Andrew B Lugg MSc and **William J Batty** MSc PhD
Applied Energy and Optical Diagnostics Group, School of Mechanical Engineering, Cranfield University, Bedford, Bedfordshire MK43 0AL, UK

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1 Introduction

Building designers aim to create buildings which provide high-quality and energy-efficient internal environments. Failure to attain these objectives can lead to poor quality internal environments in which the productivity of the building occupants is reduced and the building underperforms. In more extreme cases the ill health of building occupants both in the short and long terms may result.

Extensive research has been carried out into thermal comfort within the internal environment(1). More recently, air quality is receiving greater recognition as one of the important contributors to overall indoor environmental quality and comfort.

A range of guidelines have been in place for a number of years regarding indoor air quality. Those of the Chartered Institution of Building Services Engineers(2) (CIBSE) recommend a minimum fresh air supply rate of 8 l s^{-1} p^{-1} (litres per second per person) for non-smoking adults in offices and 8.3 l s^{-1} p^{-1} for occupants of schools. The UK Department for Education and Employment(3) (DfEE) recommends a minimum background fresh air supply rate of 3 l s^{-1} p^{-1} for all areas of schools. The DfEE guidelines further recommend that 'all teaching accommodation, medical examination or treatment rooms, sick rooms, isolation rooms, sleeping and living accommodation shall also be capable of being ventilated at a minimum rate of 8 litres of fresh air per second for each of the usual number of people in those areas when such areas are occupied'. The American Society of Heating, Refrigerating and Air-Conditioning Engineers(4) (ASHRAE) recommends fresh air supply rates of 10 l s^{-1} p^{-1} and 8 l s^{-1} p–1 for general office accommodation and school classrooms respectively.

The terms 'fresh air' or 'outdoor air' are used within these standards and guidelines as a basis for prescribing ventilation rates. However, caution should be taken with regard to the quality of outdoor or fresh air, as it may not be as 'fresh' as may have been assumed. Therefore, replacing indoor air with air from outdoors may not always provide an adequate solution.

In office and school environments, the supply of adequate fresh air supply rates, and hence perceived acceptable air quality, should be high on the list of priorities. This will help to ensure comfortable working conditions as well as content and productive occupants. In these types of environment no individual pollutant may present in sufficient quantities to cause immediate adverse health effects. However, a mixture of pollutants may combine to cause adverse health effects or irritation to the occupant in both the short and long terms. Further, some pollutants, such as human bioeffluents, or body odour, which have no known adverse health effects, may cause occupants to become irritated or uncomfortable with their indoor environments.

In recent design projects for school buildings, a concern for indoor air quality has caused the authors to question the usefulness of the guidelines quoted in *Building Bulletin 87*(3). As stated previously, these recommend a background fresh air supply rate of 3 l s^{-1} p^{-1} with the *capability* to supply 8 l s^{-1} p^{-1}. The style of the guidelines leaves them open to interpretation, and introduce ambiguity as to exactly what ventilation rates are satisfactory. Further it is stated 'The heating system shall be capable of maintaining the required room air temperature with the minimum background ventilation of 3 litres per second per person when the outside temperature is –1 °C'. This would suggest that heating systems designed to the guidelines would not be capable of maintaining comfort temperatures if adequate ventilation were provided during cold weather. The DfEE guidelines are often misinterpreted to mean that the fresh air ventilation rate of 3 l s^{-1} p^{-1} is adequate in all areas and under all circumstances.

Another problem is that many schools rely upon natural ventilation through the opening of windows. Windows are often not opened during winter months when the outside temperatures are low and it is therefore unlikely that desired fresh air ventilation rates can be achieved.

This report investigates the quality of the indoor air and the associated ventilation rates in two school classrooms in order to ascertain whether air quality guidelines are satisfied. The schools were chosen due to their location near to the site of development of a new school by the same local authority. They were not chosen because they were known to experience particularly good or poor air quality. The monitoring periods were chosen in advance for the convenience of their date; weather conditions were therefore not known in advance. Monitoring was non-disruptive, with staff and students using the building normally.

2 Indoor carbon dioxide concentrations as an indicator of air quality

A practical means of determining indoor air quality is to monitor the carbon dioxide concentration in the air. This is suitable in buildings where humans are the main sources of air pollutants. Humans produce metabolic carbon dioxide as a product of respiration. Hence the concentration in enclosed spaces such as buildings increases when the rate of production is greater than the rate of removal from the space. Other pollutant sources are those from building materials and processes within the enclosed space. However, during this investigation human bioeffluents were the main pollutant source and so carbon dioxide was considered to be the best indicator of pollutant accumulation. Although variations in carbon dioxide concentration are not directly perceived by occupants at the levels usually found in indoor air, they are considered a good indicator of the concentrations of other human pollutants and human bioeffluents which are sensed and considered as a nuisance[5–7].

Where the indoor carbon dioxide concentrations become high it is indicative that the ventilation rates to the space are inadequate to provide the necessary amount of fresh air to remove pollutants produced by humans. Indoor carbon dioxide concentrations and their associated quality ratings cited by various authorities are listed in Table 1.

Table 1 Carbon dioxide concentrations in indoor air and associated quality ratings

CO_2 concentration (ppm)	Recommended air quality rating
300–400	Typical background (atmospheric) concentrations[8]
800	BSRIA control level for acceptable indoor air quality[8]
1000 or less	Concentration of limited or no concern[9] (short-term exposure)
1000	ASHRAE limit to satisfy comfort and odour criteria[4]
≈ 1000	Threshold for 20% percentage people dissatisfied (PPD)[5]
3500	Recommended threshold to avoid adverse health effects[5]
5000	8-hour occupational exposure limit[2, 10]
6600 and above	Concentration of concern[9] (short-term exposures)

It is *not* thought that the carbon dioxide concentrations normally experienced in buildings are harmful to health in the short term. Far higher concentrations are required before they have a metabolic influence on the human body, some examples of which are given in Table 2.

Table 2 Metabolic influences of carbon dioxide[7]

CO_2 concentration (ppm)	Metabolic influence
Less than 8500	None
8500–10 000	Tidal flow of air through lungs increased
34 000+	Respiration becomes more rapid
40 000–45 000	Sweating occurs
50 000	Anxiety induced
500 000	Narcotic use in surgery during 19th century

The percentage of people dissatisfied (PPD), i.e. the percentage of people in a given space who could be expected to be dissatisfied with the environmental conditions in question, increases as the indoor carbon dioxide concentration above ambient increases; see Figure 1.

Figure 1 suggests that for an indoor carbon dioxide concentration of approximately 700 ppm above the outdoor concentration, 20% of the occupants will be dissatisfied with the indoor air quality. This corresponds to an absolute indoor carbon dioxide concentration of 1000 ppm assuming an outdoor concentration of 300 ppm. A maximum 20% PPD for occupants with regard to thermal comfort is the generally accepted level for temperature requirements in occupied buildings. It would therefore seem prudent to adopt a 20% PPD level with regard to indoor air quality.

3 Indoor air quality monitoring in school classrooms

Carbon dioxide concentrations were measured in each of the schools over a period of two days using Horiba (Model APBA-250E) continuous non-dispersive infra-red carbon dioxide monitors. See Table 3 for specifications.

Table 3 Horiba Model APBA-250E non-dispersive infra-red carbon dioxide monitor specifications

Parameter	Specification
Range of measurement	0–3000 ppm
Repeatability	± 1.5% of full scale
Overall accuracy	± 10% of full scale/3 months
Response time	≤ 15 seconds (90% response to change at instrument inlet)
Operating temperature range	5-40°C

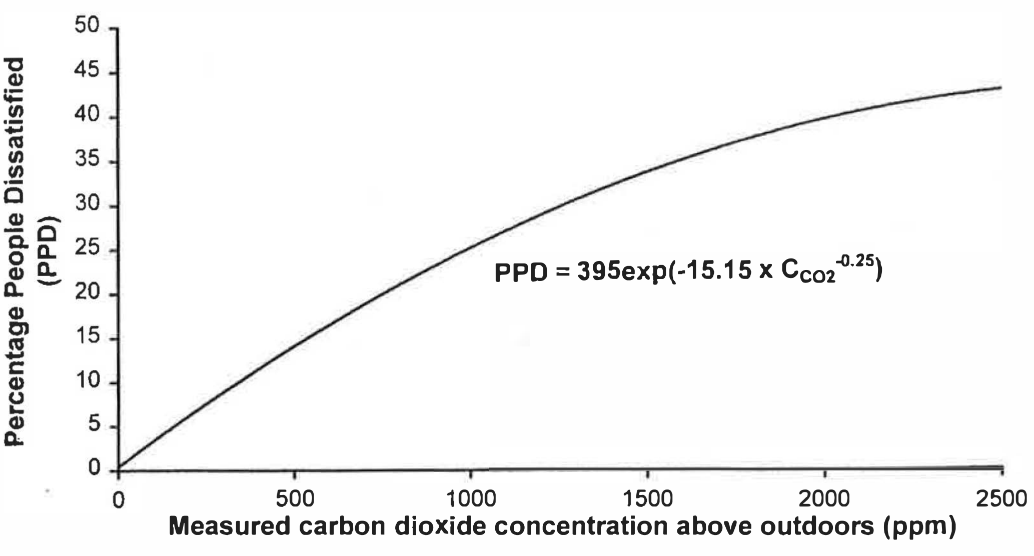

Figure 1 Percentage of people dissatisfied (PPD) as a function of indoor CO_2 concentration[5] (C_{CO2} is the CO_2 concentration in ppm)

The carbon dioxide monitors were calibrated using two calibration points, zero and 2500 ppm, using proprietary calibration gases to the manufacturers' recommendations one day before the monitoring periods.

The monitoring over short time periods (2 days) allowed a 'snapshot' of the air quality conditions occurring within the school classrooms. Thus analysis of airflow between spaces and subjective human responses were not considered during this investigation. The main objective of the monitoring was to assess air quality in densely occupied classrooms in terms of customary evaluation criteria for carbon dioxide, on randomly chosen days, and to indicate the ventilation rates.

On the first monitoring day in each school, details were noted regarding occupancy patterns and the degree to which windows were open. Two carbon dioxide monitors were used in each monitored area in order to give an indication of the air mixing efficiency. For the purposes of this report the schools are referred to as shown in Table 4.

Table 4 School designations and brief descriptions (School 2 is open-plan, therefore air mixing occurs with adjacent class bases.)

School	Pupils	Age range (y)	Construction	Ventilation	Maximum number of pupils in class base
1	Infants	(5–6 years)	Modern—concrete	Natural	60
2	Middle	(8–9 years)	Modern—concrete	Natural	60

Figures 2 to 7 are photographs and schematic plans of Schools 1 and 2.

4 Results of indoor air quality monitoring

4.1 School 1

During the first monitoring day, occupancy patterns were noted. The twin class base was fully occupied except for break periods. Full occupancy of the class base consists of 60 children and 3 to 4 adults. Three of the four windows in the external wall remained open throughout the day. External doors were opened intermittently, mainly during the end of break periods to allow children to re-enter the classroom. The entrance door leading into the classroom from the atrium area was opened intermittently throughout the day, especially during the beginning and end of break periods. No doors remained open for any length of time as they were fitted with self-closing mechanisms. The carbon dioxide concentration and occupancy monitoring results are shown in Figures 8 and 9.

In Figure 9 the carbon dioxide concentration was strongly related to the number of occupants. Carbon dioxide concentrations quickly rise and fall at the beginning and end of occupied periods respectively. However, some discrepancies are apparent in Figure 9. At 16:00 there is a small rise in carbon dioxide concentration without an apparent accompanying rise in occupancy level. This is due to the occupancy pattern being estimated after school hours, and it was assumed that the class bases were unoccupied during this period. According to staff at the school, two or three teachers would normally remain after school hours, leaving work between 16:00 and 17:00. It would seem probable that this unexpected rise in CO_2 concentrations could therefore be attributable to teachers returning to the class base, after a meeting or coffee in the staff room, to prepare for the next day's lessons. Cleaners entering the space during this period are another possible cause. The slowness of the decay in carbon dioxide concentration after 17:00 is due to the windows being shut by the teachers as they leave, and hence lower outside air infiltration rates existing than during the occupied period. The resultant temperature in the school 1 classroom ranged approximately from 20°C to 24°C during the occupied period; see Figure 10.

4.2 School 2

During the first monitoring day, when occupancy patterns were noted, the class base (comprising two classes of 30 pupils maximum each, and 2 to 3 teachers) was occupied except for break periods and one half hour period during the afternoon when one class had a games period outdoors. All windows

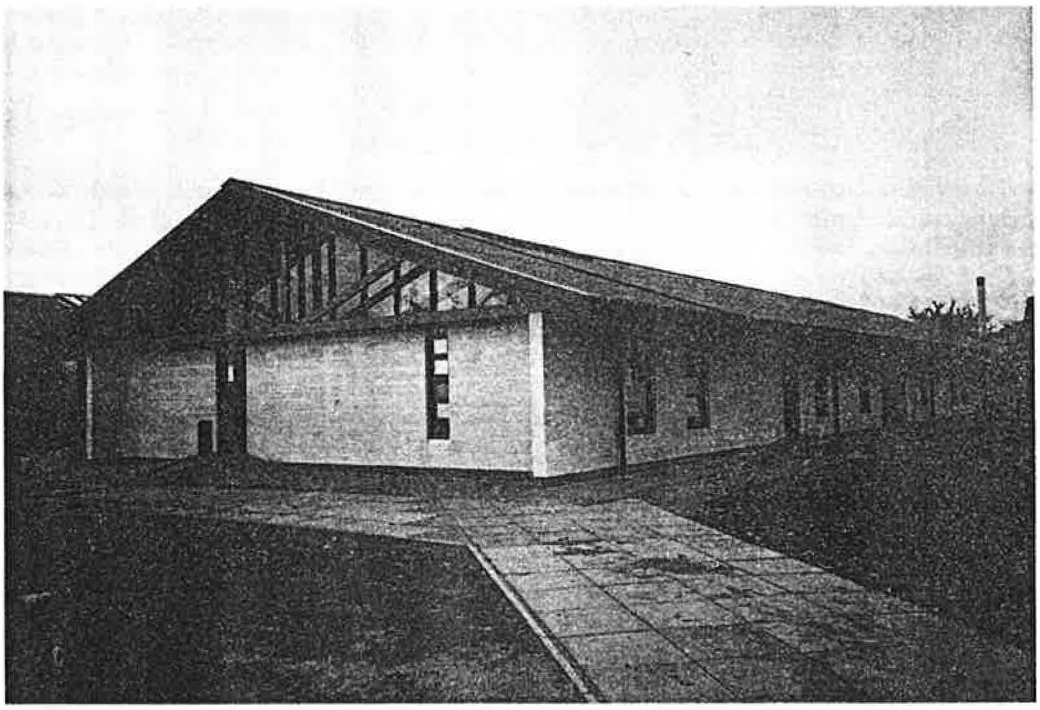

Figure 2 School 1— Outside south-facing elevation

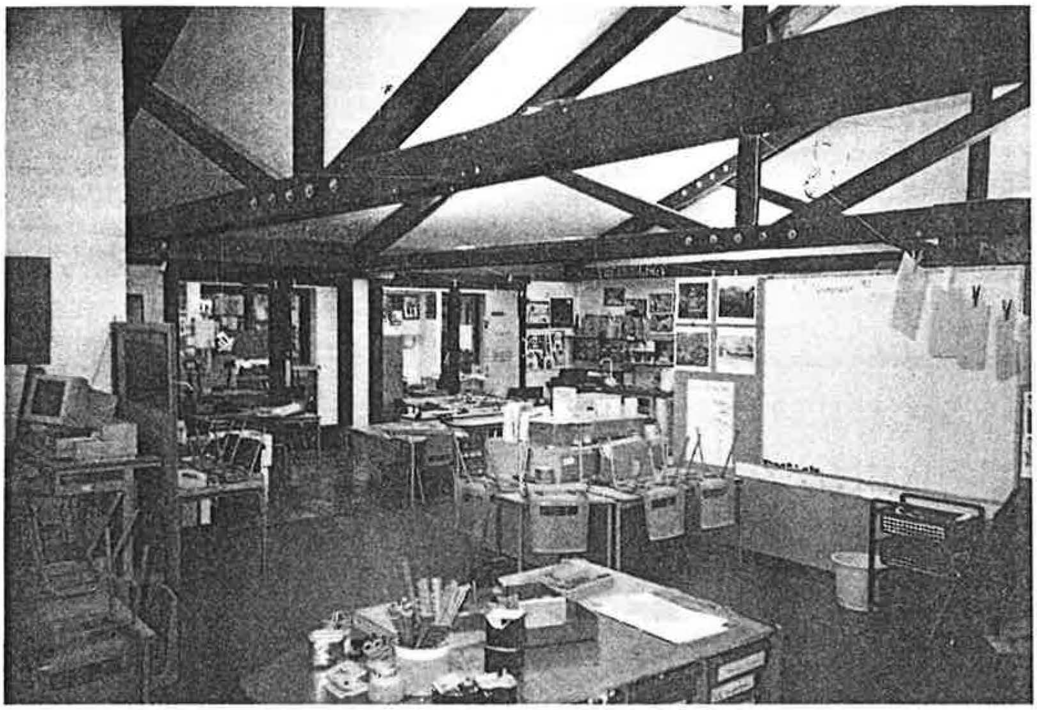

Figure 3 School 1— Monitored twin class base

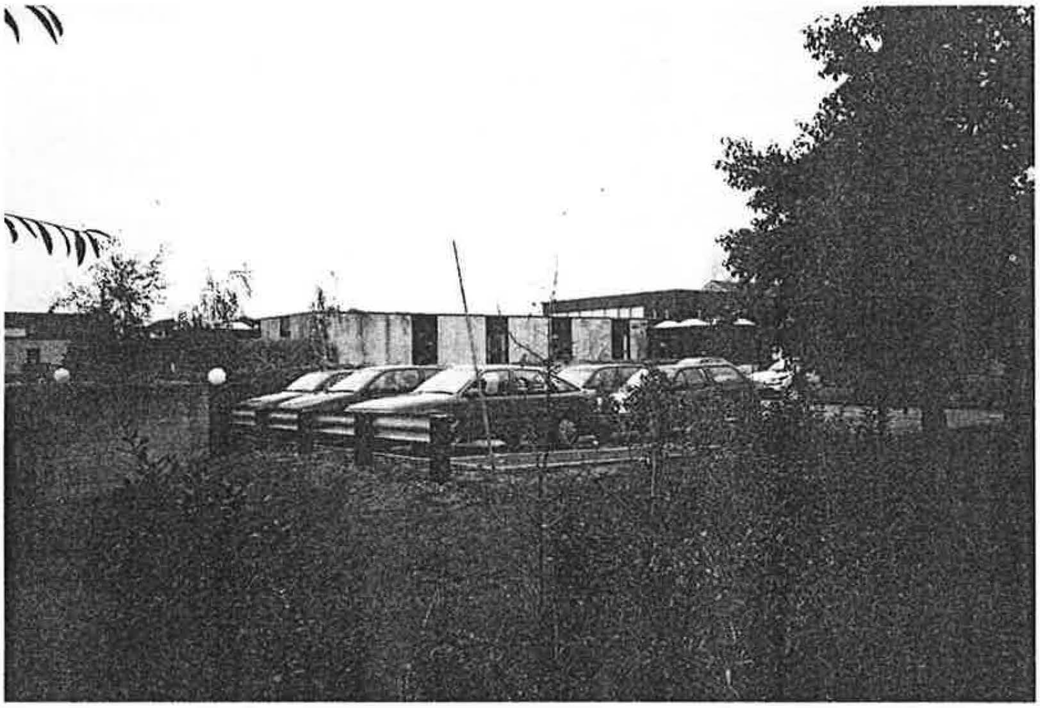

Figure 4 School 2— Outside east-facing elevation

remained fully closed throughout the day except for one window in an adjacent class base which remained approximately 10% open throughout the day. Doors to lobbies leading outdoors were opened intermittently, mainly during the break periods, but did not remain open for any significant length of time, as they were fitted with self-closing mechanisms. Figures 11 and 12 show the monitoring results over the two-day period.

Again, a small discrepancy between what would be expected in terms of carbon dioxide concentrations and the relationship with occupancy pattern can be seen in Figure 12 at approximately 12:45. The carbon dioxide concentration begins to rise before the class base becomes occupied. Examination of the data on occupancy patterns taken during the monitoring period reveals that pupils had began to re-enter the building at the end of the lunch period, but not the class base being monitored for air quality. School 2 is of an open-plan design, which would allow carbon dioxide to disperse to the monitored class base. Careful examination of Figure 12 reveals that the rate of increase in carbon dioxide concentration becomes much greater once the class base becomes occupied (approx. 13:00).

During the two-day monitoring period in school 2 the resultant temperature fluctuated between approximately 22°C and 26.5°C during the occupied periods; see Figure 13.

5 Monitored carbon dioxide concentrations and their implications for indoor air quality

Previously mentioned guidelines state that an absolute indoor carbon dioxide concentration *not* exceeding 1000 ppm is preferable; see Table 1. This would help to ensure that the percentage of people dissatisfied due to poor air quality does

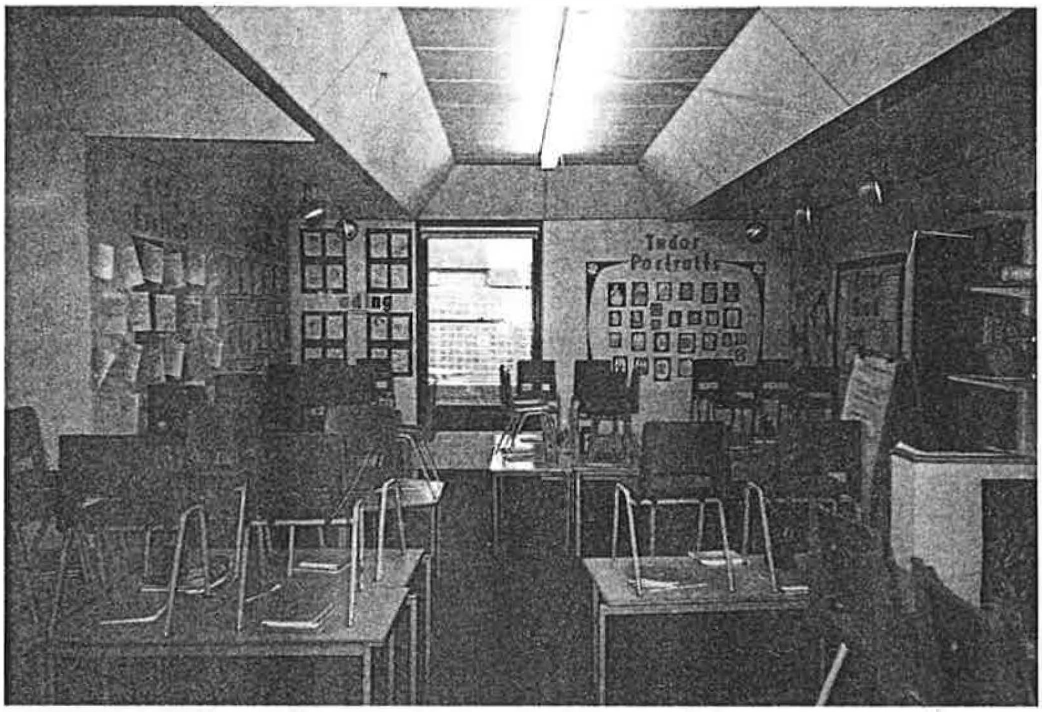

Figure 5 School 2— Area of monitored class base

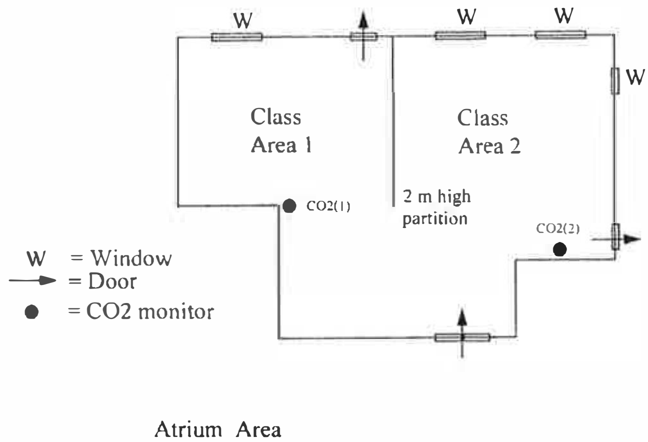

Figure 6 Plan of monitored class base in school 1 (CO2(1) and CO2(2) refer to carbon dioxide monitors 1 and 2 respectively.)

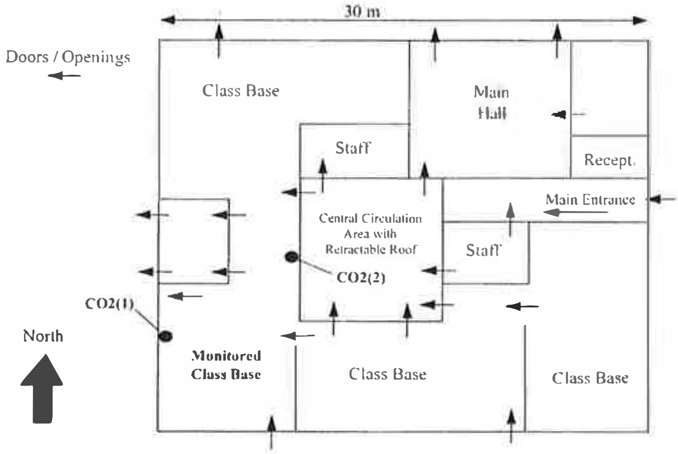

Figure 7 Schematic plan of school 2 showing monitored class base as diagonally hatched (CO2(1) and CO2(2) refer to carbon dioxide monitors 1 and 2 respectively)

not exceed 20%; see Figure 1. However, this should be regarded as an upper limit. BSRIA (see Table 1) consider that concentrations of 800 ppm and below would provide acceptable air quality. It is reasonable that in the absence of alternative recommendations that concentrations of these magnitudes be sought for the majority of the time during occupied periods. Table 5 summarises the monitored results by stating the percentage of the time during occupied periods for which the carbon dioxide concentration exceeds both 1000 ppm and 800 ppm thresholds.

Table 5 Percentage of time that carbon dioxide concentrations exceed the stated limits during the occupied period (09:00 to 15:15)

School	Date	Proporton of time exceeding 1000 ppm (%)	Proportion of time exceeding 800 ppm (%)
1	6/11/97	63	83
1	7/11/97	87	95
2	4/11/97	83	89
2	5/11/97	95	96

Table 5 clearly shows that threshold concentrations for carbon dioxide are exceeded for a large proportion of the occupied period. This is especially true of the 800 ppm threshold value and shows that the air quality in these areas was in general poor.

5.1 School 1

Figures 8 and 9 indicate that the carbon dioxide concentrations in school 1 ranged from 300 ppm after school to a peak of 2100 ppm during the occupied periods. Figures 8 and 11, for schools 1 and 2 respectively, show that the carbon dioxide concentrations in the school 1 class base did not reach such high levels as in the school 2 classrooms. Three of the four windows were open all day, thus providing a relatively high air change rate. Should the outdoor temperature be lower it is probable that these windows would remain closed, thus creating higher indoor carbon dioxide concentrations and hence lower indoor air quality.

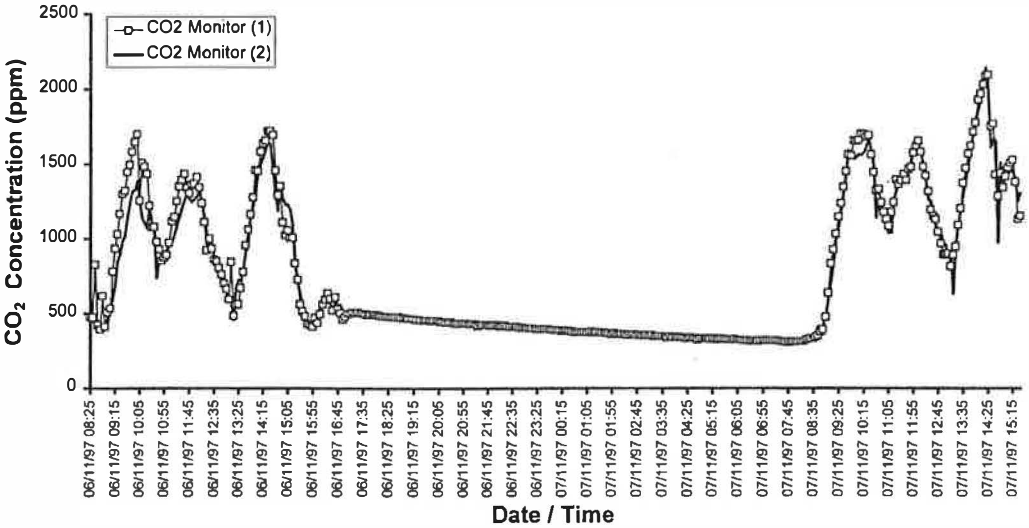

Figure 8 Carbon dioxide concentrations for school 1 over the two-day monitoring period

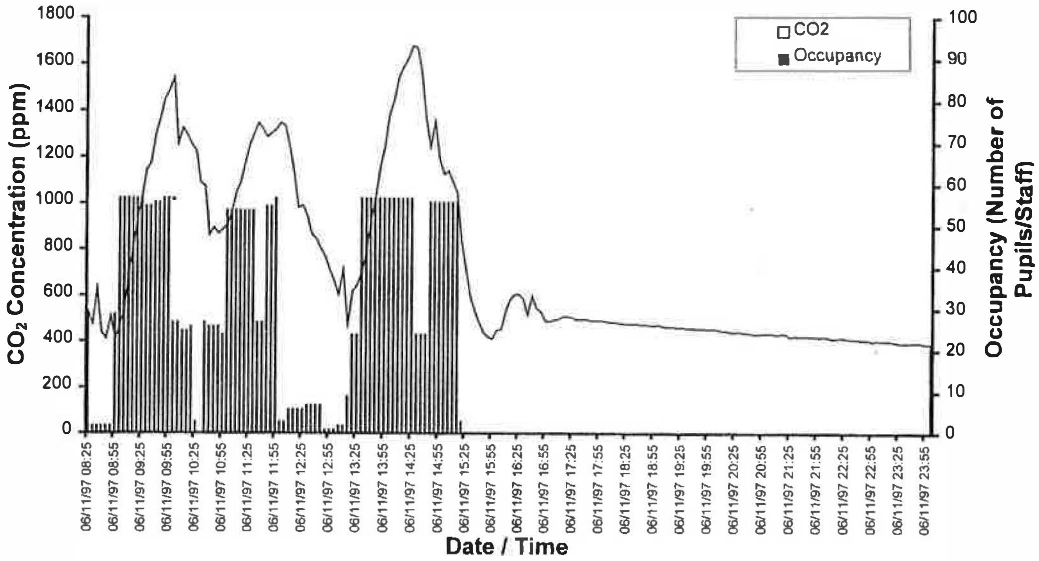

Figure 9 Averaged carbon dioxide concentrations and occupancy patterns during the first day's monitoring for school 1

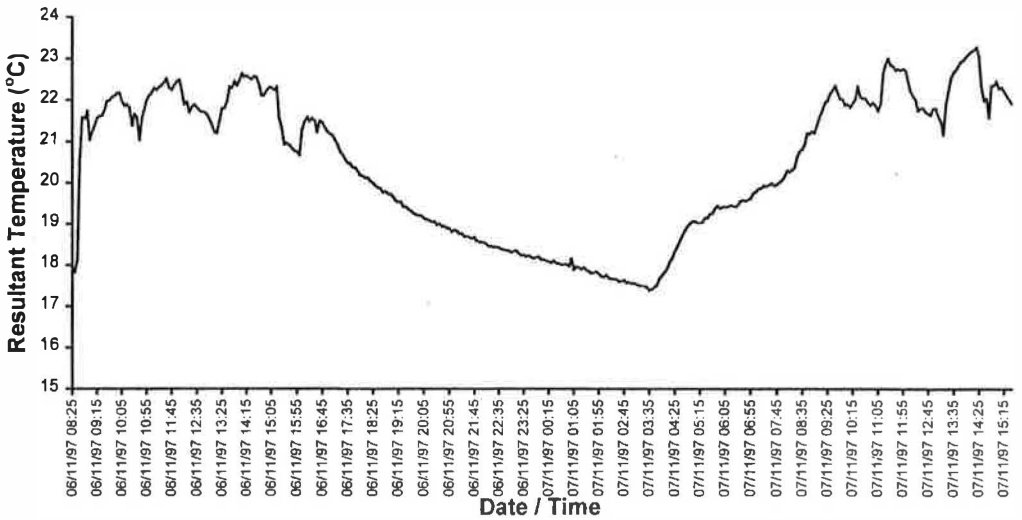

Figure 10 Resultant temperature during the monitoring period for School 1

5.2 School 2

Figures 11 and 12 indicate that the carbon dioxide concentrations in school 2 ranged from 300 ppm after school to a peak of 3500 ppm during the occupied periods. The carbon dioxide concentrations quickly rise above the 1000 ppm threshold soon after the classrooms become occupied at 09:00. They remain above this threshold until the end of each school day, with the exception of the lunch periods, when the concentrations fall to acceptable levels during some of the unoccupied period.

6 Estimation of ventilation rates within the monitored school class bases

Analysis of the carbon dioxide concentration decay rates, after occupation of the class bases ended, were carried out

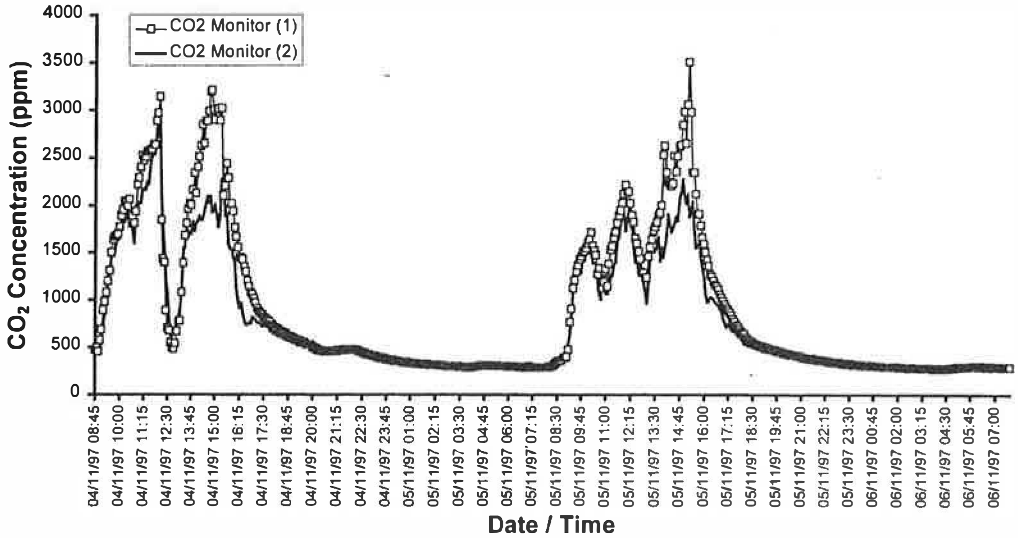

Figure 11 Carbon dioxide concentrations for school 2 during the two-day monitoring period

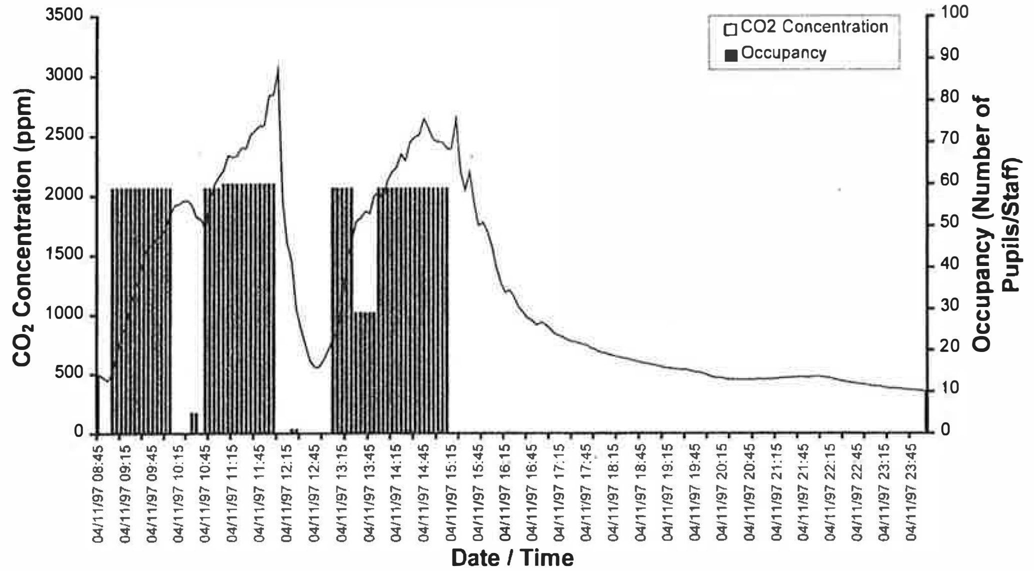

Figure 12 Averaged carbon dioxide concentrations and occupancy patterns for the monitored class areas during the first day's monitoring for school 2

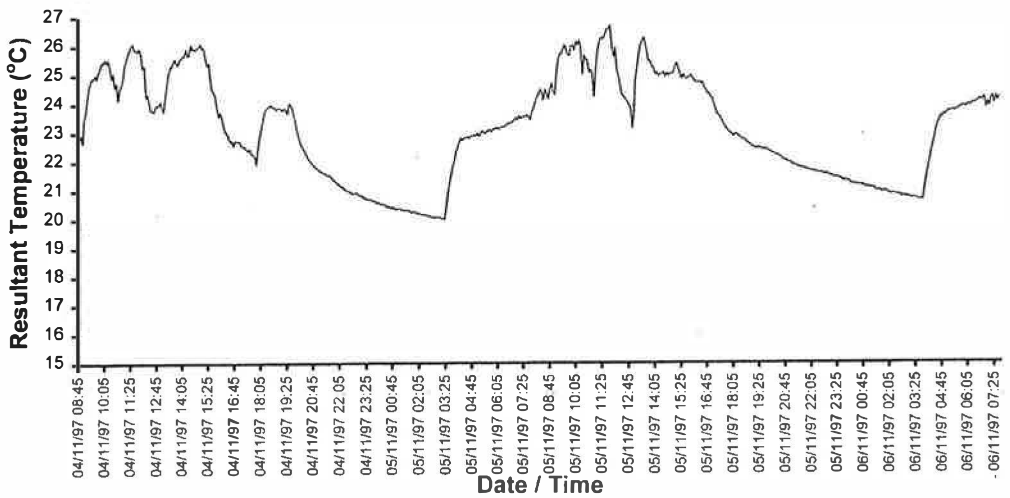

Figure 13 Resultant temperature during the monitoring period for School 2 (location 1, Figure 7)

using a carbon dioxide concentration decay rate method as described in the Appendix. The calculations assume that the air mixes completely within the spaces.

6.1 School 1

The monitored values were analysed immediately after the classroom was vacated at the end of the school day on the first day's monitoring. This suggests that the ventilation rate in the school 1 classroom was in the region of 2.9 ac h^{-1}. It has been assumed that this rate remained relatively uniform throughout the day, as the windows were constantly open at the same position and still, mild weather conditions were experienced. The air change rate would be higher than this at the beginning and end of break periods when the main entrance door from the atrium area, and occasionally, external doors were opened. It has therefore been assumed that the intermittent opening of external doors for very short periods had little overall effect on the fresh air ventilation rate, especially considering the constantly large area of window that remained open. Carbon dioxide concentration decay rates could not be analysed at any other times for the monitored data as the classrooms remained partially occupied.

6.2 School 2

After-school analyses of the decay rates of carbon dioxide concentration for both of the monitored days indicate that the background ventilation rate with all the windows closed was in the range 0.5–1.0 ac h^{-1}. Analysis of the decay rate during lunchtime on day 1 indicates that the air change rate, with frequent opening and closing of external doors due to the pupils leaving and entering the building, rises to between 3 and 3.5 ac h^{-1}. Analysis was not possible for Wednesday lunchtime as the occupancy patterns were unknown for this period. The data analyses for these days indicate that during normal occupancy, when the external doors are opened less frequently, the air change rate lies between 0.5 and 3.5 ac h^{-1}. However, during normal occupied periods, i.e. during lessons, it is probable that the air change rate is closer to that of the time immediately after school, i.e. 0.55–1 ac h^{-1}, due to the window and door openings being similar for these time periods.

Elementary calculations for per capita ventilation rates within the schools based on calculated air change rates are given in Table 6.

Table 6 Per capita fresh air ventilation rates (assumed occupancy 60 students, 2 adults)

School	Day	Time	Calculated air changes per hour	Equivalent per capita fresh air flow ($l\ s^{-1}\ p^{-1}$)
1	1	After school	2.9	4.7
2	1	Lunch	3.0–3.5	5.7–6.7
2	1/2	After school	0.5–1.0	1.0–1.9
2	Estimated for occupied periods		1.0	1.9

Table 6 suggests that the maximum possible fresh air ventilation rate provided during the monitoring period was 6.7 $l\ s^{-1}\ p^{-1}$. However, this occurred during the beginning of the lunch time period in school 2 when the students were leaving the building and ventilation rates were higher than during the occupied period due to frequent door opening. The fresh air ventilation rates determined for the periods just after the end of the school day are more representative of those occurring during occupied periods, as doors remain in the same position, i.e. closed. These values are far lower and indicate that fresh air ventilation rates are significantly less than those required to provide acceptable air quality.

7 Conclusions

The use of continuous CO_2 concentration monitoring in the two monitored class bases, each for a period of two days, provides a snapshot of the air quality provided by means of natural ventilation. Analysis of the CO_2 decay rates allows approximate air change rates to be estimated for the monitoring periods.

Carbon dioxide concentrations recorded at the schools suggest that the indoor air quality experienced by the occupants is consistently below that recognised as acceptable, i.e. > 1000 ppm carbon dioxide concentration, during the occupied periods. The results Table 5 indicate that carbon dioxide concentrations exceeded this threshold for between 63% and 95% of the occupied period. Where 1000 ppm carbon dioxide concentrations are considered to represent a 20% PPD level with respect to the indoor air quality, the monitoring results clearly show that unsatisfactory conditions persist within the schools.

The carbon dioxide concentrations were higher for school 2 than for school 1. However, as the windows remained closed all day during the monitoring period in school 2, these results probably represent the worst case scenario regarding this school. In contrast, school 1 windows remained open throughout the occupied period, mainly due to the classrooms being too warm and stuffy. During colder weather it is probable that these windows would remain shut and carbon dioxide concentrations would at least approach those experienced in school 2.

The calculated fresh air infiltration rates for the schools on a per-capita basis, 1.0–6.7 $l\ s^{-1}\ p^{-1}$, were not capable of providing acceptable air quality when considered in relation to the CO_2 concentrations. Implementation of CIBSE recommendations[2] of 8.3 $l\ s^{-1}\ p^{-1}$ would improve the air quality. However, DfEE recommendations[3] of a minimum background ventilation rate of 3 $l\ s^{-1}\ p^{-1}$ would be inadequate for the schools concerned. The DfEE does recommend[3] that the ventilation system be capable of providing 8 $l\ s^{-1}\ p^{-1}$ in classroom areas. Unfortunately the DfEE guidelines are easily misinterpreted and the lower air change rate is regarded as being able to satisfy air quality requirements of the occupants. The DfEE guidelines need to be clarified in order to eliminate the ambiguity of the recommendations.

The natural fresh air ventilation rates in the monitored schools were found to be inadequate to provide sufficient fresh air to the occupied spaces. This is a problem that may be difficult to overcome using natural ventilation alone, because of the high occupancy densities of school classrooms. Careful consideration needs to be given at the design stage as to whether the necessary ventilation rates can be achieved, or whether mechanical assistance is required in order to provide acceptable air quality.

Appendix: Determination of ventilation rates from transient indoor carbon dioxide concentrations

The air change rate in an internal space can be determined by monitoring and analysing the decay rate of carbon dioxide concentration immediately after the occupants have vacated the space.

List of symbols

- C_0 Initial CO_2 concentration above ambient in the space at start of decay period (ppm), $t = 0$
- C_t CO_2 concentration above ambient after time t (ppm)
- t Time elapsed since start of decay period (s)
- v Volume of the space (m^3)
- x Volume of air leaving the space per second ($m^3\ s^{-1}$)

Procedure

(*a*) Monitor the dynamic carbon dioxide concentration in the space.

(*b*) When the occupants leave note the CO_2 concentration at this time (C_0).

(*c*) Note the CO_2 concentration after a time t (C_t).

(*d*) Use the following equations to calculate the air change rate.

Note: when using metabolic CO_2 as the tracer gas the carbon dioxide concentration in the ambient (i.e. outdoor) air should be subtracted, i.e. use the difference value not the absolute value.

Where the zone internal rate of CO_2 production is zero, the zone concentration will decay to the outdoor concentration according to equation 1[12].

$$C_t = C_0 \exp(-xt/v) \qquad (1)$$

The negative sign indicates that the CO_2 concentration is decaying. Rearranging equation 1:

$$x = (-v/t)\log_e(C_t/C_0) \qquad (2)$$

In equation 2 the negative sign indicates that the air is leaving the space. However, air also enters the space at the same rate. Therefore the negative sign can be removed and equation 2 effectively gives the air change rate.

Acknowledgements

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