INDOOR AIR QUALITY IN NATURALLY VENTILATED BUILDINGS IN URBAN AREAS: CASE STUDIES

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ABSTRACT

With environmental issues (such as high energy costs for air-conditioning and related CO_2 emissions and global warming) in mind, designers are increasingly considering natural ventilation as the primary design option. Naturally ventilated office buildings can typically consume less than half the delivered energy consumed in air-conditioned buildings representing cost-effective energy savings of the order of 20-30%.

In this paper results will be presented of measurements of the internal climate in two naturally ventilated office buildings located near major roads where atmospheric pollution and noise levels are perceived to be high. Results of levels of typical air pollutants such as carbon monoxide, nitrogen dioxide and sulphur dioxide and of noise levels are presented and compared with air quality guidelines and standards. Ventilation rates within the building and external wind speed and direction are also given to allow the pollution measurements to be put into context.

An initial analysis of the ventilation strategies used in mitigating the effect of external pollution is made and initial conclusions drawn for future guidance.

Keywords: Urban areas, external pollution, indoor air quality, natural ventilation

INTRODUCTION

In recent years, increases in pollution emissions resulting from an increase in vehicular traffic have caused great public concern regarding the quality of urban air and its impact on those working in these areas. In buildings this has led to an increase in the installation of mechanical ventilation and air-conditioning systems to 'clean' the incoming air from external urban pollution sources although there is evidence that such systems do not always provide clean fresh air [1, 2]. With environmental issues such as, high energy costs, associated CO_2 emissions and global warming in mind, designers are increasingly being encouraged to consider natural ventilation as the primary design option. Naturally ventilated office buildings can typically consume less than half the energy consumed in air-conditioned buildings, representing cost-effective energy savings of the order of 20-30%.

At present, however, there is little information on or understanding of the interaction between indoor air quality and external pollution levels. As a consequence, no formal guidelines exist on designing for natural ventilation in office buildings in urban areas. The UK Building Research Establishment Ltd (BRE) is thus carrying out building monitoring studies to determine the levels of externally generated air pollutants found in such buildings with a view to developing practical guidance on effective low energy ventilation strategies for buildings in urban areas. As part of this study, two naturally ventilated buildings, in London and Birmingham, have been monitored. Initial findings from this study are reported here.

PREVIOUS STUDIES

Previous studies [2,3,4] have shown that in urban areas, road vehicles are a major source of pollution, in particular of carbon monoxide and nitrogen dioxide. Concentrations of these pollutants are often lower internally than in the external environment although they usually follow outdoor pollutant trends. Other, more localised, pollutant sources such as, boiler flues and cross-contamination between ventilation exhausts and inlets, may account for higher internal concentrations of certain pollutants than those found externally.

Furthermore, studies have also shown that internal-external air quality relationships can be a complex function of several factors which include the combination of external 'local' sources and 'background' pollutant levels and their temporal and spatial variation [5], meteorology and dispersion processes around the building, permeability of the building envelope, indoor pollutant sources, pollution depletion mechanisms and ventilation processes [6]. In urban locations, the surrounding structures, as well as the size, shape and the orientation of the building itself are also important parameters in the building contamination process.

CURRENT STUDY

Description of buildings and ventilation strategies

The indoor air quality in two naturally-ventilated buildings located in major UK urban areas was investigated. Building A is a four-storey traditional 1960's UK building located in the centre of Birmingham on an eight-lane major road (Figure 1). Ventilation is via openable vertical sash windows and background infiltration. The measurements were made continuously over a one week period in February 1996 in a ground floor office with openable windows facing onto the main road on one side and an internal court-yard on the other. External measurements were also carried out outside this office at a height of 5 m. The objective in studying this building was purely to determine its indoor air quality with respect to external pollution levels and the effect of the building fabric in reducing these levels.

Building B, a two-storey modern day-care centre incorporating a specific natural ventilation strategy was completed in 1994 and is located on a busy high street in London (Figure 2). The natural ventilation strategy (Figure 3) was developed using diaphragm cross walls to provide a series of chimneys which allow air to be drawn through the building assisted by wind and buoyancy forces. Diaphragm walls are structural cavities which interjoin two or more cells; here they have been used to merge the air intake and exhaust for a number of rooms. Fresh air for the building comes exclusively from the courtyard side where air pollution and noise levels are believed to be low. It enters through slots in the external ends of the diaphragm walls and is drawn into the rooms located on the high street through low level grilles in the diaphragm wall. Windows on this side are not openable since air pollution and noise levels are believed to be high. Fresh air for rooms on the courtyard side is via trickle ventilators and openable windows. 'Used' air is expelled through grilles at high level in each room and is drawn out at the chimney tops.

Measurements in Building B were carried out continuously over a one week period during March 1997 in four offices: two on the roadside and two on the courtyard side (ground and first floor) and a seminar room. Some external measurements were also taken at a single point at a height of 4m immediately outside office 3 on the roadside. The objective in studying this building was to compare the indoor air quality in rooms facing the roadside with those on the courtyard side to determine the effectiveness of the ventilation strategy in reducing external pollution levels found indoors. The wind speed and direction were obtained from the nearest meteorological site relevant for each building.

The offices in both buildings were in normal use with variable occupancy and normal office activities. Both offices had a no-smoking policy and there were no gas appliances or any other significant internal sources of the measured pollutants. Only metabolic CO_2 was generated internally by the occupants. Monitoring in both buildings was carried out during the winter periods when the windows in the offices were generally closed.

MEASUREMENTS

Measurements of the following were made (Table1):

- carbon monoxide (CO)
- carbon dioxide (CO_2)
- oxides of nitrogen (NO_x)
- sulphur dioxide (SO_2)
- building air change rates

Each building was provided with a set of high quality gas analysers using chemiluminescence (NO_x), fluorescence (SO_2) or photo-acoustic techniques (CO, CO_2, trace gases for air change rates) as appropriate and were capable of detecting the pollutants at the concentrations anticipated. They were calibrated immediately prior to monitoring and their sensitivity, in general, was within 10%. The building air change rates were measured by using the conventional technique of observing the decay of an injected tracer gas (sulphur hexafluoride, SF_6) seeded into the areas of interest.

RESULTS

Building A (Birmingham)

Pollutant concentrations

Figures 4 to 7 show the CO, CO_2, NO_2 and SO_2 concentrations obtained inside Building A in Birmingham. Traffic appeared to be the major source of both CO and NO_2. However, SO_2 concentrations were not so clearly associated with the traffic as can be seen from the low levels which occurred on Saturday evening when the high levels of other pollutants suggest a considerable flow of traffic.

In general, external concentrations of the pollutants were higher than the internal concentrations although the latter followed the outdoor pollutant trends. The high peaks in the external concentrations were not seen in the internal environment indicating the ability of the building to attenuate the external pollutants. The building tended to smooth out the external pollution levels over a period of about an hour.

As expected, internal levels of CO_2 were higher than external levels corresponding to periods when the office was occupied. During unoccupied periods the levels reduced to a background value of about 400 ppm which is in agreement with previous work [4].

For occupants, the period of interest is the occupied day of 08.30 to 17.30 during the working week. Table 2 gives the pollutant concentrations obtained during this period compared with air quality guidelines. The levels of all pollutants monitored are well below the standard guidelines indicating little risk to the occupants of the buildings.

Table 1: Summary of measurements carried out.

Parameter measured	Building A		Building B					
	Internal	External	Internal					External
			Office 1	Office 2	Office 3	Office 4	Seminar room	
CO	✓	✓	✓	✓	✓	✓	✓	✓
CO_2	✓	✓	✓	✓	✓	✓	✓	✓
NO	✓	✓	-	-	-	-	✓	-
NO_2	✓	✓	-	-	-	-	✓	-
SO_2	✓	✓	-	-	-	-	✓	-
T	✓	✓	✓	✓	✓	✓	-	✓
H	✓	-	✓	✓	✓	✓	-	-
Ach^{-1}	✓	-	✓	✓	✓	✓	-	-
Noise	✓	✓	-	-	✓	✓	-	-

Temperature and humidity

Temperature within the office in Building A ranged from 16 to 24°C with external temperatures ranging from -3 to 13°C. Internal humidity levels varied between 17 to 34 % which are lower than the recommended values of between 40 and 70% quoted in CIBSE Guide A [7].

Air change rates

Average air change rates obtained for the office in Building A ranged between 0.8 to 1.6 ach^{-1}. This corresponds to a ventilation rate in the office of between $14ls^{-1}$ to $28ls^{-1}$ per person over the monitoring period. This is a little high when compared with a recommended value of 10 ls^{-1} per person [8].

Wind speed and direction

Over the period of the tests, wind speeds were recorded at the nearby Meteorogical site as being higher than normal, ranging from 5 to 10 ms^{-1} with gusts of about three times the mean wind speed.
Some initial analysis showed no simple relationship of the wind speed or direction with the concentrations of the pollutants measured.

Noise

External noise measurements outside Building A showed a clear cyclic variation in noise levels from day to day. External noise levels of around 80dBA and internal levels of around 30dB(A) were obtained. These are in reasonable agreement with acceptable values of about 45-50 dBA for offices [9, 10, 11].

Table 2: Measured mean concentrations inside the buildings for the working week compared with Air Quality Guidelines.

Parameter measured	Building A	Building B					Air quality standards	
		Office 1	Office 2	Office 3	Office 3	Seminar room	WHO	EC
CO	1.7	0.4	0.4	0.4	0.4	-	10	-
CO_2	650	425	440	405	395	-	-	-
NO	97	-	-	-	-	27	-	-
NO_2	28	-	-	-	-	22	80	105
SO_2	4	-	-	-	-	1.7	122	94

Building B (London)

Pollutant concentrations

Figure 8 shows an example of the typical concentrations obtained for CO in all the four offices monitored in Building B in London. Again traffic appeared to be the major source of CO. As expected, all the offices showed very similar contaminant levels because of the common air intake from the courtyard side of the building. Low external CO levels measured over the weekend period indicate little vehicular activity in comparison with the working week. During certain periods of the working week, relatively high CO concentration peaks occurred externally reaching levels of about 12 ppm. Comparison of the contaminant levels measured inside the offices with external measurements taken at a single point on the roadside indicate that these high contaminant peaks were reduced considerably and did not occur inside any of the offices monitored. Even office 3, outside of which the external measurements were carried out, does not show these peaks, indicating little pollutant infiltration through the fabric of the building. It is clear that by using supply air from the courtyard side the high concentration peaks of CO (12ppm) in the external environment appear to have been reduced to values around a mean of about 0.4 ppm inside the building. This is well below recommended air quality guidelines as given in Table 2.

CO_2 results for office 1 are shown in Figure 9. These are typical of levels obtained in all the offices monitored. As expected, the high concentrations (with peaks of about 1100 ppm) correspond to periods during the working week when the office was occupied. Again levels reduced to a background of about 400 ppm during the weekend and at night. In general the occupancy in each room was variable on each day and this is shown by the varying degree of CO_2 levels. A background value of about 400ppm is also seen in the external environment where there are no known sources and is in agreement with results obtained in Building A in Birmingham and previous work [4].

The measurements of nitrogen dioxide (NO_2) and nitric oxide (NO) are shown in Figure 10. Due to practical constraints only internal measurements were made and it is not therefore possible to make any comparison with concurrent external concentrations. However, comparison of hourly concentration means of these pollutants with standard air quality guidelines (Table 2) shows that levels were low in the building. In general, NO_2 is a product of a variety of combustion processes including traffic. However, there were no other known sources of NO_2 in the area apart from the road traffic on the High Street. It can therefore be assumed that the low levels measured in the building indicate that air intake from the courtyard side away from the road traffic gave acceptable concentrations.

Internal levels of SO_2 (Figure 11) were also below recommended air quality guidelines. This is as expected, since in general, external trends of SO_2 concentrations in London show that background levels have decreased by almost 60% since 1970 and by 45% since 1980 [12]. This is largely attributable to the relocation of power stations away from city and urban areas and the growing use of natural gas and lower sulphur content fuel oils in combustion plant.

Temperature and humidity
The issue of overheating arises in the summer months. However, the monitoring in Building B was carried out during a relatively warm winter period (March 1997) with external temperatures reaching values of about 16°C. In the four offices monitored, mean internal daily temperatures varied between 17.5 - 21°C and at night between 16 - 19°C. This is in good agreement with an average internal winter temperature of 18°C for which the offices in the building were designed.

Relative humidity levels varied between about 40 and 60% in the offices monitored which is in agreement with the general levels quoted in the CIBSE Guide A.

Ventilation rates
During the monitoring period (in winter) air change rates of between 1 and 2 ach^{-1} were measured in the offices. This corresponds to ventilation rates in the four offices of between $8ls^{-1}$ and $20ls^{-1}$ per person over the monitoring period. Again, this is in reasonable agreement with an average design value for the building of $12ls^{-1}$ per person and a recommended value of 10 ls^{-1} per person.

CO_2 is a surrogate indicator of indoor air quality. In general, a ventilation rate of 8 ls^{-1} per person is recommended to achieve levels of <800ppm. However in this case, levels were reduced to a background value of about 400ppm in a very short time period after the occupants left the offices at the end of the day.

Thus, from the results of the CO_2 and temperature measurements, it is apparent that the air change rates that were reached during the monitoring period were successful in removing metabolic CO_2 from the offices and in keeping temperatures in the offices to values for which they were designed.

Wind speed and direction
Wind speeds varied between 1 and 9 ms^{-1} over the monitoring period. Again initial analysis of wind speed and direction showed no simple relationship with the internal and external CO concentrations measured.

Noise Levels
Noise measurements taken for an earlier monitoring period in October 1996 gave average external noise levels of 75dBA. It was found that, in general, average noise levels were lower in office 4 (courtyard side) at 40dBA than in office 3 (roadside) at 50dBA and higher during peak periods of traffic. Again these are in reasonable agreement with acceptable values of about 45-50 dBA for offices.

CONCLUSIONS

From the measurements made in the study of the two buildings a number of conclusions can be drawn about the attenuating capability of the fabric of the buildings and the comparison of the internal measured concentrations with existing air quality guidelines.

1. In both buildings the concentrations of the external pollutants were attenuated by the building fabric and the transient peak concentrations measured externally reduced considerably.

2. In Building A, the peak concentrations measured externally were approximately halved in value. However, in Building B the peak concentrations obtained externally were reduced by a factor of

about 30. Therefore comparison of the two ventilation strategies in the two buildings has shown that 'fresh' air intake from the courtyard side away from the traffic has been successful in giving a greater damping effect of the high concentration peaks which occurred in the external measurements on the roadside.

3. The indoor air quality in both buildings, over the monitored period, did not exceed any of the main health standards.

Ventilation measurements showed adequate air change rates for the removal of metabolic CO_2 in both buildings and keeping temperatures down within acceptable values for the winter monitoring periods. Noise levels were also found to be acceptable.

From these two short winter monitoring periods, it can be concluded that natural ventilation is possible in urban locations where external traffic pollution is perceived to be high. However, considerable work in understanding the interactions between the indoor and external environment all year round together with all the associated parameters still needs to be carried out before guidance can be given on effectively ventilating buildings located in urban areas.

Ongoing research at BRE is addressing the complex behaviour of external pollutant sources and flows, dispersion of these and their interactions with the cities' infrastructure and their subsequent effect on the internal environment of buildings with a view to providing the required guidance. As part of this study, monitoring is currently being carried out in Building B during the summer period when occupants are likely to open the windows to cool down the building.

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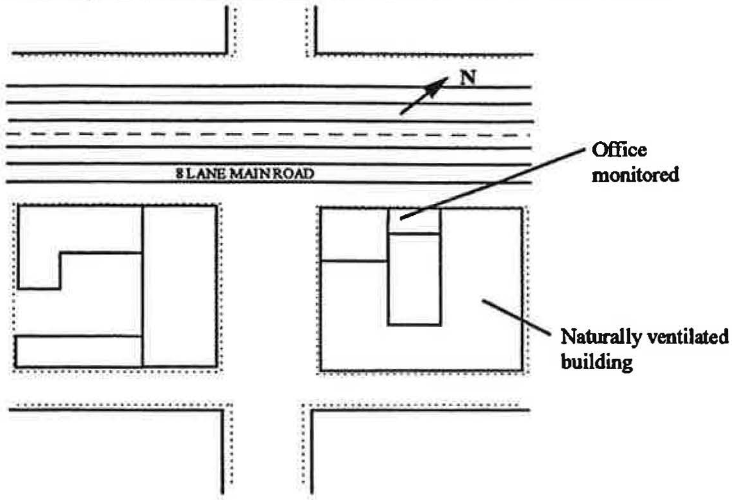

Figure 1: Plan view of Building A, Birmingham, February 1996

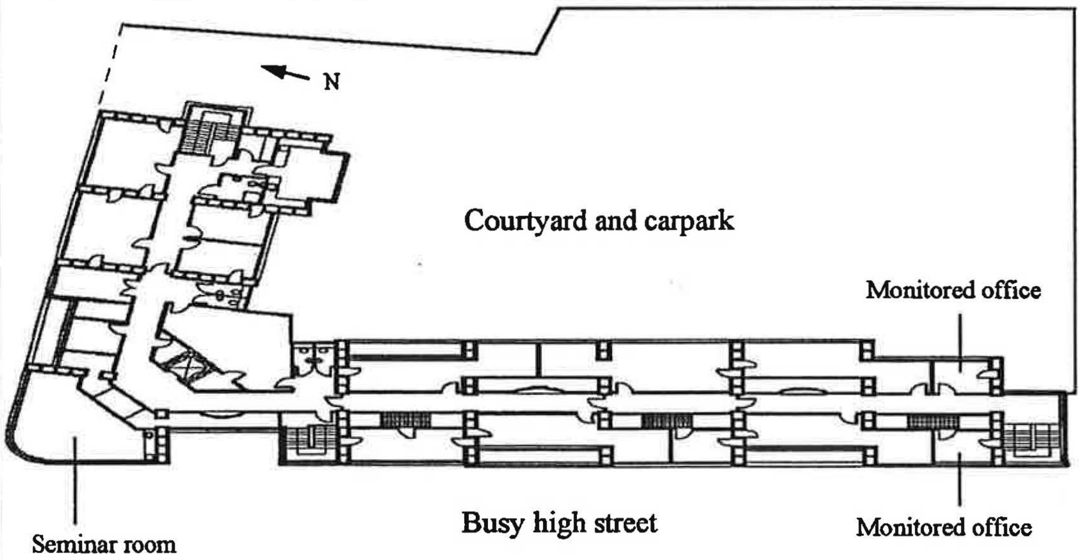

Figure 2: Plan view of building B

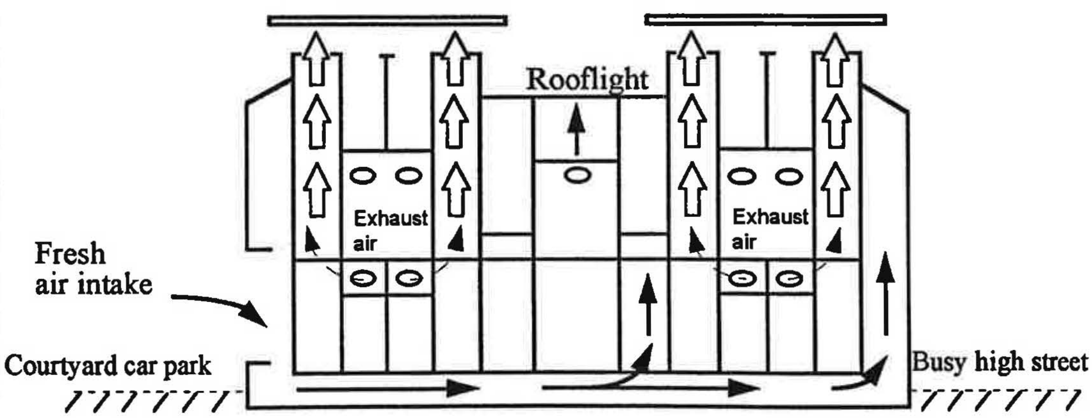

Figure 3: Natural ventilation strategy, Building B

Figure 4: Carbon monoxide concentrations (ppb), Building A (Birmingham, February 1996)

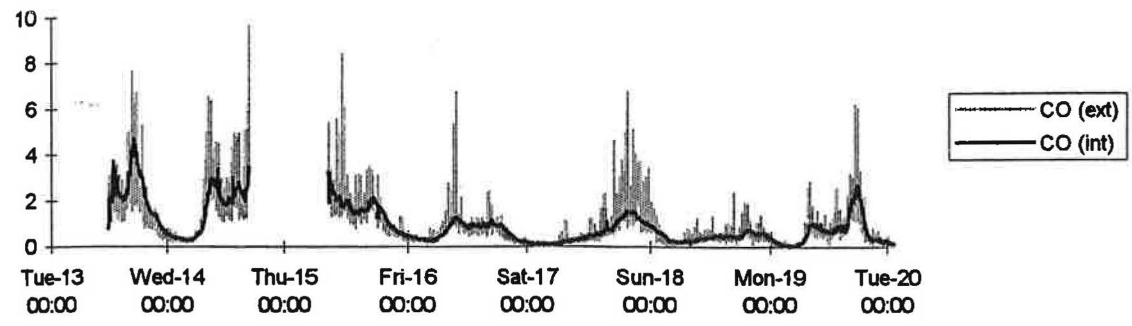

Figure 5: Carbon dioxide concentrations (ppm), Building A (Birmingham, February 1996)

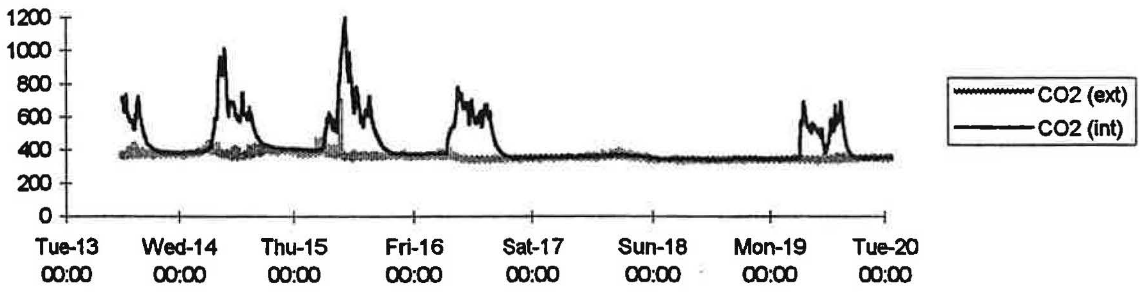

Figure 6: Nitrogen dioxide concentrations (ppb), Building A (Birmingham, February 1996)

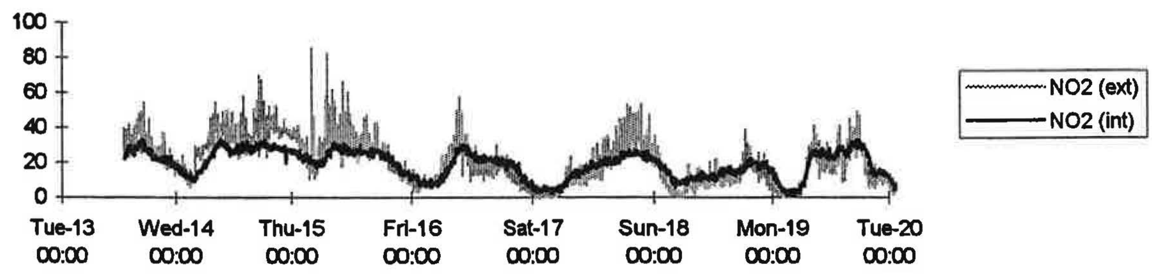

Figure 7: Sulphur dioxide concentrations (ppb), Building A (Birmingham, February 1996)

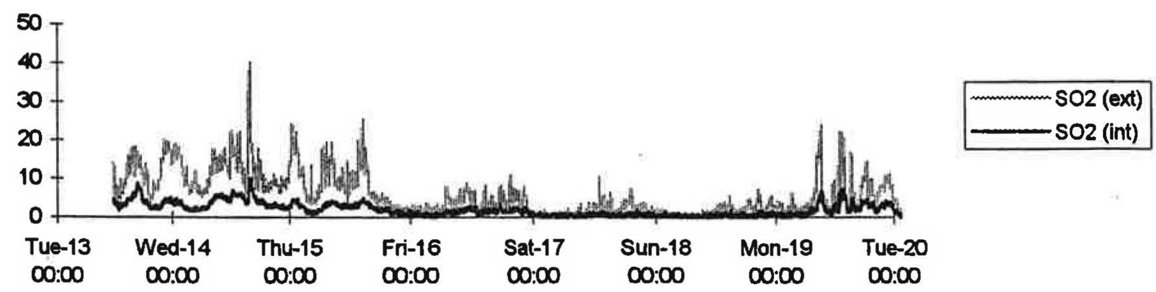

Figure 8: Carbon monoxide concentrations (ppb), Building B (London, March 1997)

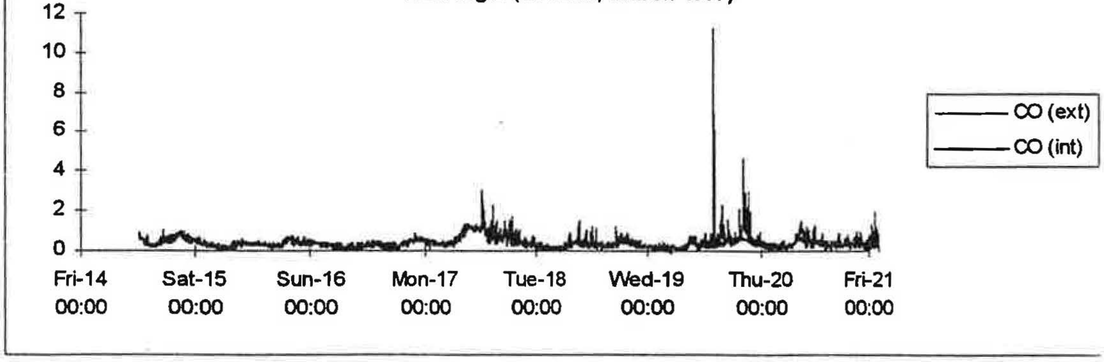

Figure 9: Carbon dioxide concentrations (ppm), Building B (London, March 1997)

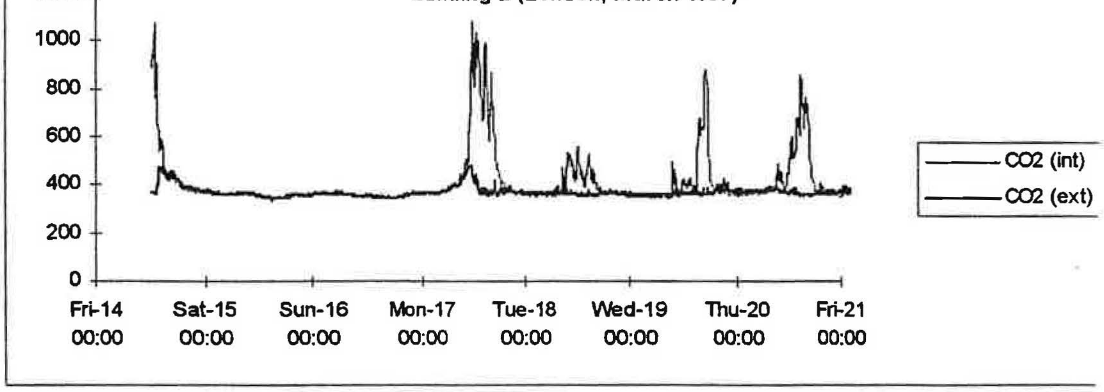

Figure 10: Nitrogen dioxide and Nitric oxide concentrations (ppb) Building B (London, 14-21 March 1997)

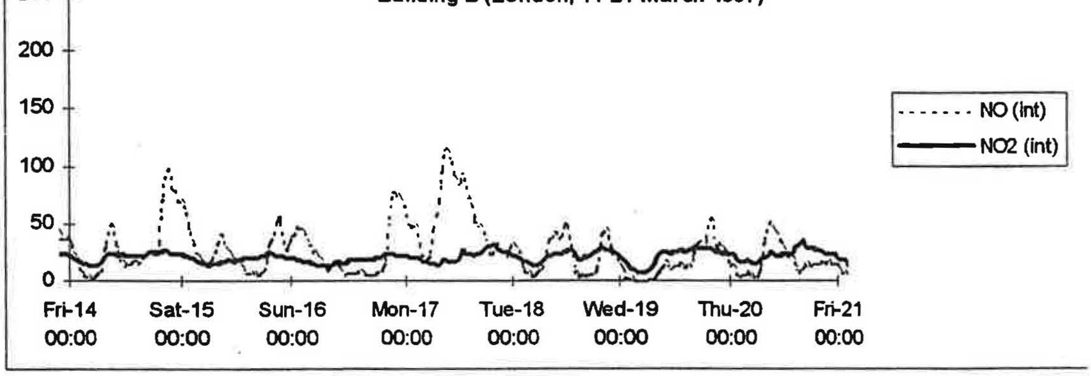

Figure 11: Sulphur dioxide concentrations (ppb) Building B (London, 14 - 21 March 1997)