AIR POLLUTION LEVELS INSIDE BUILDINGS IN URBAN AREAS: A PILOT STUDY

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This paper reports the findings of a pilot field study carried out to investigate the internal and external pollution levels in two buildings, one naturally-ventilated and the other air-conditioned and to investigate their relative attenuation of external pollution levels. The study is a precursor to more extensive studies aimed at providing guidelines for the design of energy-efficient buildings with a good indoor environment in urban areas.

Concerns about energy usage and CO_2 emissions from buildings require that adequate indoor air quality is obtained in an optimal manner within low-energy design criteria. There is thus an increasing number of buildings employing natural ventilation strategies. At present, however, little is known about the interaction between indoor air quality and external air pollution. Therefore, no formal guidelines exist on designing for natural ventilation in non-domestic buildings in urban areas with respect to external air and noise pollution.

The buildings investigated were adjacent to one another and located near a major road in a city centre where the local air pollution levels were known to be relatively high. During the study, concentration levels of typical urban pollutants, such as sulphur dioxide, nitrogen oxides and carbon monoxide were monitored. Concurrently, measurements of carbon dioxide, ventilation rates, humidity and temperature within the buildings including some measurements of noise and particles were also carried out.

Analysis of the data reveals a number of interesting points. The concentrations of external pollutants in the buildings follow the daily external variation, but at reduced levels. Generally, pollutant levels were higher in the naturally ventilated building than in the mechanically ventilated building. However, on a number of occasions, combustion products from heating boilers were entrained into the air-conditioned building via the high level air intake of the ventilation system. This raised the levels of nitrogen oxides and carbon dioxide inside the building to higher than those found externally.

1. INTRODUCTION

An increasing number of buildings are employing natural ventilation strategies as a result of increasing concerns about high energy usage required for mechanical ventilation and air conditioning and the environmental penalties arising thereof. However, in urban areas and city centres where external air pollution and noise levels are relatively high, it is assumed that natural ventilation cannot provide suitable internal air quality. This has led to an increase in the installation of mechanical ventilation and air-conditioning systems to 'clean' the incoming air, even though there is evidence that such systems do not automatically provide clean fresh air to the occupants of the building (1). Furthermore, little is known regarding the interaction between the indoor air quality and external air pollution levels. As a consequence, no formal guidelines exist on designing for natural ventilation in non-domestic buildings in urban areas.

The aims of this pilot study were to investigate internal and external pollution levels of a naturally and an air-conditioned building in close proximity to one another and to investigate their relative attenuation of external pollution levels. The study is a precursor to more extensive studies aimed at providing guidelines for the design of energy-efficient buildings with a good indoor environment in urban areas.

Previous work in this area is limited and has not been directed specifically to a comparison of the two design approaches. A study in Switzerland by Turner and Binnie (2) of a mixture of naturally and mechanically ventilated buildings tended to indicate that externally produced CO was more prevalent in the mechanically ventilated buildings than the naturally ventilated buildings. This was thought to be a consequence of ingress into the air handling units of contaminated air from underground car-parks. A study by Phillips, et al (3), of four naturally ventilated buildings, concludes that the air change rate was the determining factor for air quality; the greater the supply of external air the greater the presence of pollutants indoors.

Evidence from recent buildings employing natural ventilation as a design strategy (rather than simply providing openable windows) is showing that acceptable ventilation rates can be achieved without resort to mechanical ventilation (4). However, the level of external pollution experienced in these buildings has not been considered directly. To develop suitable design guidance, the manner in which buildings can attenuate the effects of external pollution and noise requires investigation.

2. EXPERIMENTAL

2.1 Selection of buildings

Two buildings, one naturally-ventilated and the other air-conditioned, were selected for investigation. These were adjacent to each other in the centre of Birmingham and located on an eight-lane major road (Figure 1). The naturally-ventilated building was a four storey building with openable vertical sash windows and secondary glazing. The measurements were made in a ground floor office with windows facing onto the main road on one side and an internal court-yard on the other.

The air-conditioned building was ten storeys high with a limited number of unused openable windows, but otherwise with a facade which was mostly sealed. The third floor open-plan office was chosen for monitoring because the lower floors were recessed from the road and shielded by the access stairs to a foot-bridge. The mechanical ventilation system drew external air from the tenth floor level, via the roof-top plantroom, filtered and heated it prior to distribution to the ceiling voids for terminal re-heat and cooling. There was no heat recovery. A radiator system also provided heating to the offices. The mechanical ventilation system was taken as found and there were no reported problems. Its performance was assessed by the measurement of the air change rate as part of this pilot study.

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.

2.2 Measurements

Measurements were made of the following:

- sulphur dioxide (SO_2)
- carbon monoxide (CO)
- oxides of nitrogen (NO_x)
- carbon dioxide (CO_2)
- building air change rates
- temperature
- humidity
- traffic density
- noise
- particles

Each building was provided with a set of high quality gas analysers and the outputs from these instruments were recorded at five minute intervals, for the whole of the monitoring period (13 to 20 February 1996) using a data-logging system. By using a switchable pump sampling system the instruments in the naturally ventilated building were also used for measuring the external levels of the pollutants. The instruments used chemiluminescence, fluorescence, NDIR, or electrochemical techniques as appropriate and were capable of detecting the pollutants at the concentrations anticipated. They were calibrated immediately prior to the monitoring and the instruments 'zeroed' on alternate days by using a supply of uncontaminated air.

The building air change rates were measured by using the conventional technique of observing the decay of an injected tracer gas (sulphur hexafluoride) seeded into the areas of interest. During unoccupied periods, the decay of CO_2 generated by the occupants previously in the building, was used as a measure of the air change rate. Traffic densities on the main road were taken by periodic direct observation and by using video recording. The wind speed, direction and precipitation levels, were obtained from Birmingham University.

Internal and external noise levels were measured using data-logging noise meters. All measurements were 'A' weighted and hourly levels recorded. Internal levels were recorded in a second-floor office of the naturally ventilated building. The external levels were recorded at second floor level above the kerbside.

Particles in the office of the naturally ventilated building were monitored using impaction samplers. Because of the large diameter of the sample pipes, access to the exterior was not possible so only internal samples could be taken. The intrusive noise of the sampling equipment restricted its use to the weekend.

3. RESULTS

3.1 Pollutant Concentrations

Measurements were carried out for a seven day monitoring period, although for clarity of presentation, concentration results for the various pollutants from Friday to Monday only are shown in Figures 2-6. However, Table 1 gives the minimum, maximum and mean concentrations for the whole monitoring period. The external levels are typical of that found in an urban area and represent the situation that is likely to face the building designer (5).

Table 1. Concentrations of Major Pollutants from 13 to 20 February.

Pollutant	External			Internal					
				Naturally ventilated			Mechanically ventilated		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
CO (ppm)	0	10	0.9	0	4.1	0.9	0	4.6	0.7
CO_2 (ppm)	329	478	361	331	1197	446	368	1472	521
NO (ppb)	0	798	53	0	241	36	0.8	1250*	60
NO_2 (ppb)	0	85	21	0.4	33	19	0.9	151	23
SO_2 (ppb)	0	40	6	0	10.6	1.9	0	14.7	1.8

*estimate (value was off scale)

There were times when no significant levels of pollutants were recorded - either outside or inside the buildings. As the data covers seven successive days, the buildings do not therefore appear to harbour external pollutants for long periods. The ability of the buildings to attenuate the external pollutants is shown by the fact that in most cases the maximum internal concentrations were lower than that recorded externally, although the mean values (with the exception of SO_2) are comparable. Furthermore, it is apparent that neither building reacted to the rapid and sudden fluctuations seen in the external levels. The buildings tended to smooth out the external pollution levels over a period of about an hour.

In the mechanically ventilated building, the maximum recorded and mean concentration values of NO, NO_2 and CO_2 were higher than in the naturally ventilated building and higher than the external values. However, the external concentrations of SO_2 and CO were higher than in the two buildings.

Generally for occupants, the period of interest is the occupied day of 08:30 to 17:30, Monday to Friday. The results for this period are given in Table 2 which also shows, for each building, the ratio of the internal to external pollution concentration. As a first approximation, it is suggested that this can be used as a measure of the effectiveness of each of the buildings in attenuating the external pollutants.

Table 2. Concentrations of Major Pollutants for the Occupied Periods for Monday to Friday

Pollutant	External		Internal							
			Naturally ventilated				Mechanically ventilated			
	Max	Mean	Max	Mean	Internal/External Ratio		Max	Mean	Internal/External Ratio	
					Max	Mean			Max	Mean
CO (ppm)	9.6	1.8	4.1	1.7	0.4	1.0	3.0	0.9	0.3	0.5
CO_2 (ppm)	478	366	1197	650	1.5	1.8	800	646	1.0	1.8
NO (ppb)	798	114	241	97	0.3	0.9	256	78	0.3	0.7
NO_2 (ppb)	70	31	33	28	0.5	0.9	45	25	0.6	0.8
SO_2 (ppb)	40	11	10.6	4.4	0.3	0.4	13.4	3.9	0.3	0.4

Values in Table 2, in comparison to those in Table 1, show that the mean values of NO, NO_2 and CO_2 concentration levels are lower in the mechanically ventilated building, although the maxima are still greater than in the naturally ventilated building. This feature will be examined in more detail in the forthcoming longer period of measurement.

3.2 Air change rates

Table 3 shows the results for the air change rates for the two buildings. In the mechanically ventilated building, the air change rate varied little whilst the system was operating. However, as expected, the air change rate in the naturally ventilated building was more variable and was dependent upon the circumstances of operation and weather conditions. Over the period of the tests, wind speeds were recorded at the nearby Meteorological site as being higher than normal, ranging from $5ms^{-1}$ to $10ms^{-1}$ with gusts of about three times the mean wind speed (Figure 7).

3.3 Noise

The analysis of the noise survey in the naturally ventilated building showed the internal background (L90) levels falling to around 30dB(A). Internal occupational noises were clearly discernable above intrusive noise from external sources. External noise measurements showed a clear cyclic variation in noise level from day to day.

3.4 Particles
The particle sampling exercise was limited because of the insufficient time available to perform the sampling and the inability to sample the external air. Previous tests had shown that a sampling period of at least ten days would be required to obtain a sensible reading of the concentration of particles. However, the results obtained showed an average indoor particle concentration of about 87 μgm^{-3}.

Table 3. Air Change Rates - (air changes per hour)

Day	Naturally ventilated		Mechanically ventilated	
	Occupied	Un-occupied	Occupied	Unoccupied
Tuesday	-	0.7	1.22	0.58
Wednesday	1.62	0.81	1.33	0.44
Thursday	0.9	0.81	1.03	0.35
Friday	1.62	0.83	1.05	0.40
Saturday	-	-	-	0.54
Sunday	-	-	-	-
Monday	2.24	1.26	1.48	0.32
Tuesday	1.53	-	1.25	-
Average	1.58	0.84	1.23	0.42

4. DISCUSSION

The short period of monitoring in this pilot study limited the scope for a detailed investigation of the performance of the buildings with regard to the indoor and outdoor air quality. However, there are a number of useful observations which can be made, and the initial findings will assist in the execution of future studies.

4.1 Sources of Pollution
In this study, traffic appeared to be the major source of CO and NO_x. The concentrations of these pollutants varied with the traffic density on the main road. However, SO_2 concentrations were not so clearly associated with the traffic as can be seen from the low levels which occurred on the Saturday evening when the high levels of other pollutants suggest a considerable flow of traffic.

The most prominent feature of the data is the exceptionally high levels of CO_2, SO_2, NO and NO_2 in the mechanically ventilated building on the Saturday morning from 06:00 to 12:30 - coincident with the period between the start-up and shut-down of the building's ventilation system. Levels were well in excess of the external concentrations and not seen inside the naturally ventilated building. The obvious source for these gases in such high concentrations, is either cross-contamination from the ventilation exhaust or high level discharges from boiler plant being drawn into the ventilation inlet. There are a number of boiler flues close to the building which could have been responsible for this, if not those on the building itself. A similar event on the Monday morning suggests that this was not an isolated incident.

4.2 Attenuation of Pollutants
The results show that the buildings significantly attenuated the concentration of the external pollutants. The ratio

of the internal/external maximum values in the occupied periods (Table 2), indicate that the levels of the external pollutants monitored inside the buildings were generally less than 50% of the maximum external concentrations. This was consistent over the period of monitoring and shows that this damping of the fluctuations of external pollutant levels would be valuable in reducing short-term exposure levels. There was less attenuation of the average pollutant concentration but both buildings show better internal air quality than externally. The attenuation of the CO in the mechanically ventilated building was greater than in the naturally ventilated building. However, for the other pollutants the difference was less marked.

Carbon Monoxide

In the naturally ventilated building the CO concentration closely followed the trend in external levels (measured 5 metres above the road level). In the mechanically ventilated building the CO levels tended to be lower than external levels. This is likely to be due to a vertical concentration gradient reducing the levels of CO by the time it reached the high level intake.

In both buildings, the concentration level of CO internally tended to be higher than that found externally when the external concentration reduced at the end of the evening rush-hour due to greater dispersion. Lower air change rates during unoccupied periods, appeared to retain the CO in the building for longer periods. However, by early morning and over the weekend, the levels in both buildings were reduced either to external levels or lower.

Nitrogen Oxides

NO concentrations followed the same general trend as external values over the monitoring period. In the mechanically ventilated building, however, NO concentrations were lower during the daytime but higher during the unoccupied periods compared with the naturally ventilated building.

NO_2 concentrations also followed the same general trend as external values. However, in the mechanically ventilated building, NO_2 levels were generally higher than in the naturally ventilated building.

It is apparent that the variation of the nitrogen oxides was complex and a number of possible explanations could be given for this. For example, the sources of the external air for each of the buildings varied with time; the main source for the mechanically ventilated building being at high level during the day when the mechanical ventilation plant was operating. Also, the lower air change rate at night may have allowed the NO in the building to slowly oxidise to NO_2 giving higher concentrations of NO_2. It is intended that these observations will be addressed more fully in the forthcoming monitoring period.

Sulphur Dioxide

The SO_2 levels in the buildings tended to follow the trends in external levels but at much lower concentrations. This can be seen by the internal to external ratios given in Table 2. An exception being the anomalously high value in the mechanically ventilated building on the Saturday morning when the internal concentration was greater than that externally.

Particles and noise

The analysis of the impactor trials was inconclusive for the reasons already given. The internal particle concentration measured was comparable to that recorded by Owen, Ensor, Sparks (6) of a figure typically in excess of 50 μgm^{-3}. However, to be able to provide realistic results, a longer monitoring period is required. The noise survey captured only three days of internal noise measurement and from these results no realistic conclusions could be drawn on the performance of the facade.

4.3 Correction for building air change rates

In order to compare the two buildings studied here, to allow for the fact that they experienced different air change rates and sources of external air, a form of correction procedure is required. Investigations into suitable techniques for performing this 'correction' are currently being carried out.

5. CONCLUSIONS

From the measurements made in this pilot study a number of conclusions can be drawn about the relationship between internal and external pollution levels.

1. In both the naturally and mechanically ventilated buildings the indoor air quality reflected that of the external air to which they were exposed. However, the concentrations of the pollutants were attenuated by the building and the transient peak concentrations measured externally were approximately halved in value.

2. The possibility of drawing combustion products into buildings at high level has been shown to exist in the mechanically ventilated building. The building was chosen only for its location with respect to traffic density. However, the findings highlight the real danger of cross-contamination between ventilation exhausts and inlets at roof level and contamination from other sources.

3. This pilot exercise has indicated the necessity for more accurate pollutant measurements over a longer monitoring period and as experienced by the building as a whole. A single measurement provides only a broad indication of external pollution levels and may not suffice when concentration differences in the external environment are to be expected.

4. The complex relationship of the nitrogen oxides has been shown, but not fully explained. This will be investigated in detail in further field experiments.

ACKNOWLEDGEMENTS

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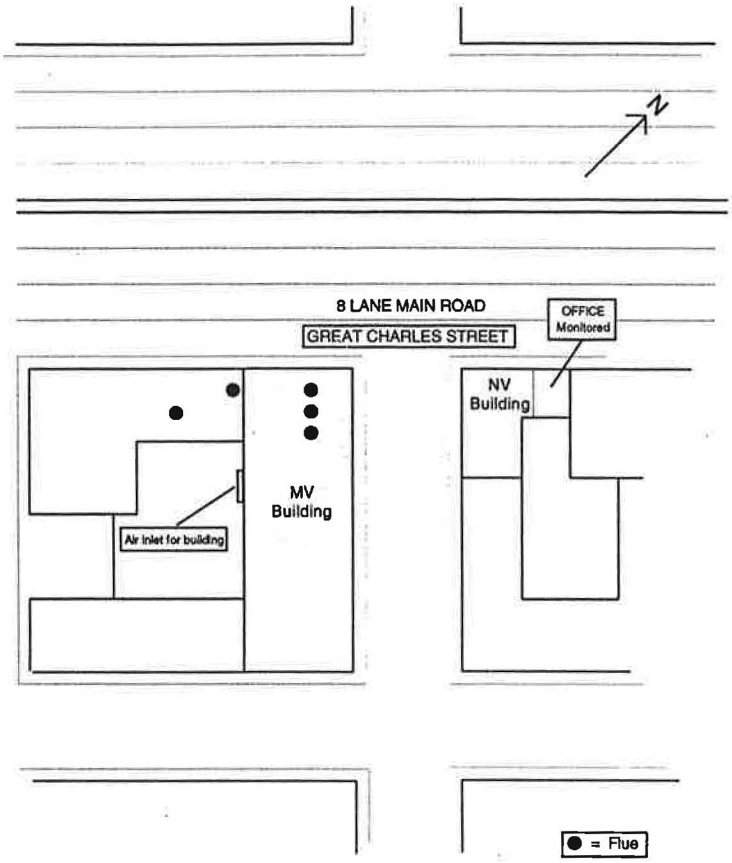

Figure 1. Site layout

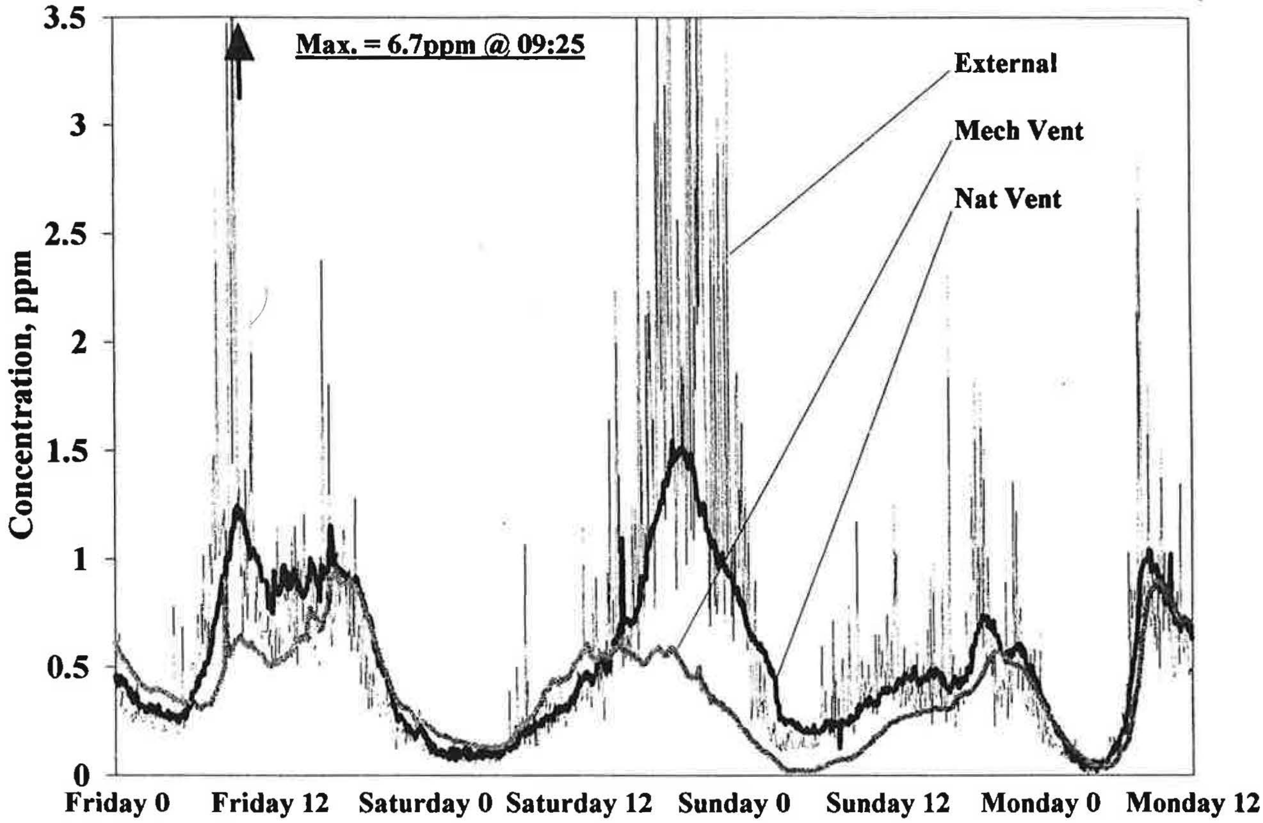

Figure 2. **Carbon Monoxide**

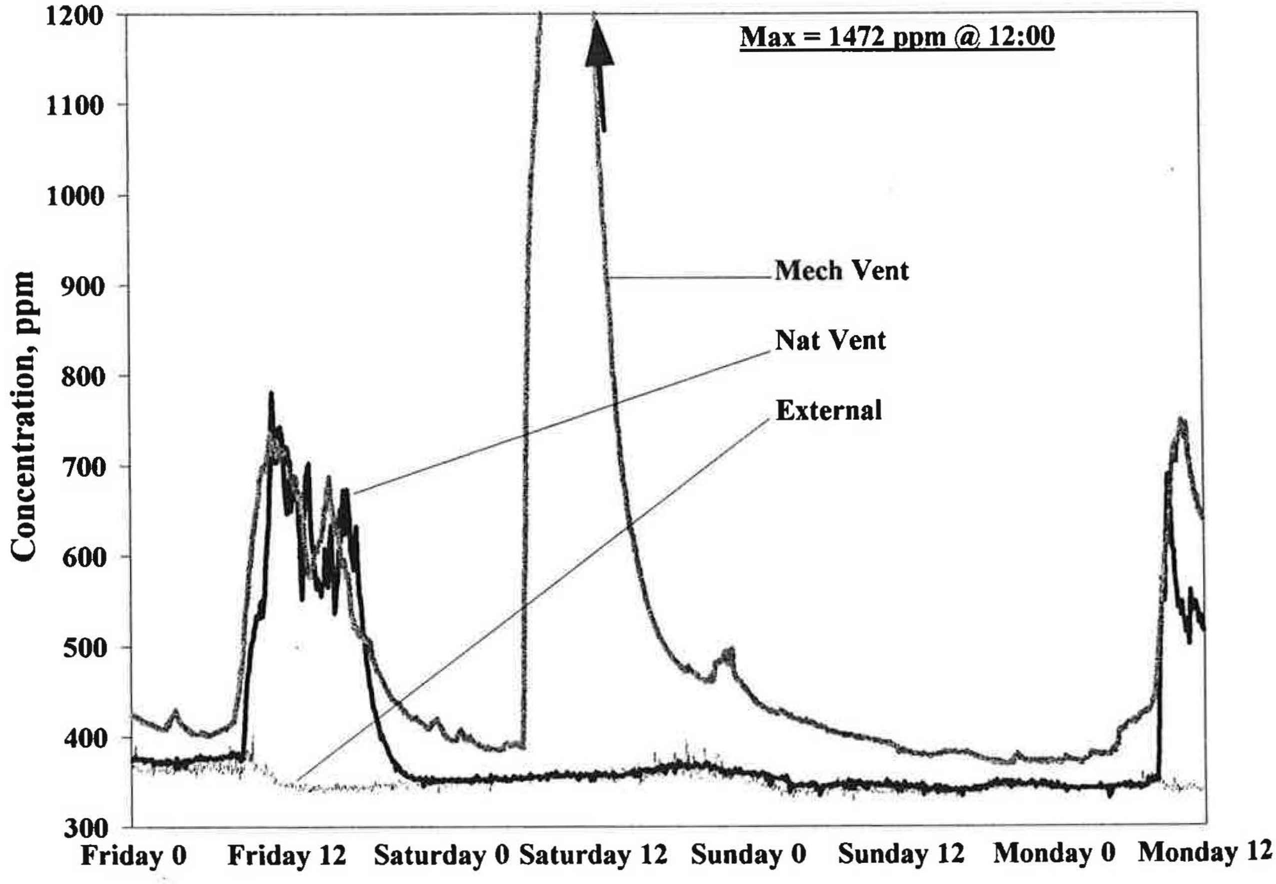

Figure 3. **Carbon Dioxide**

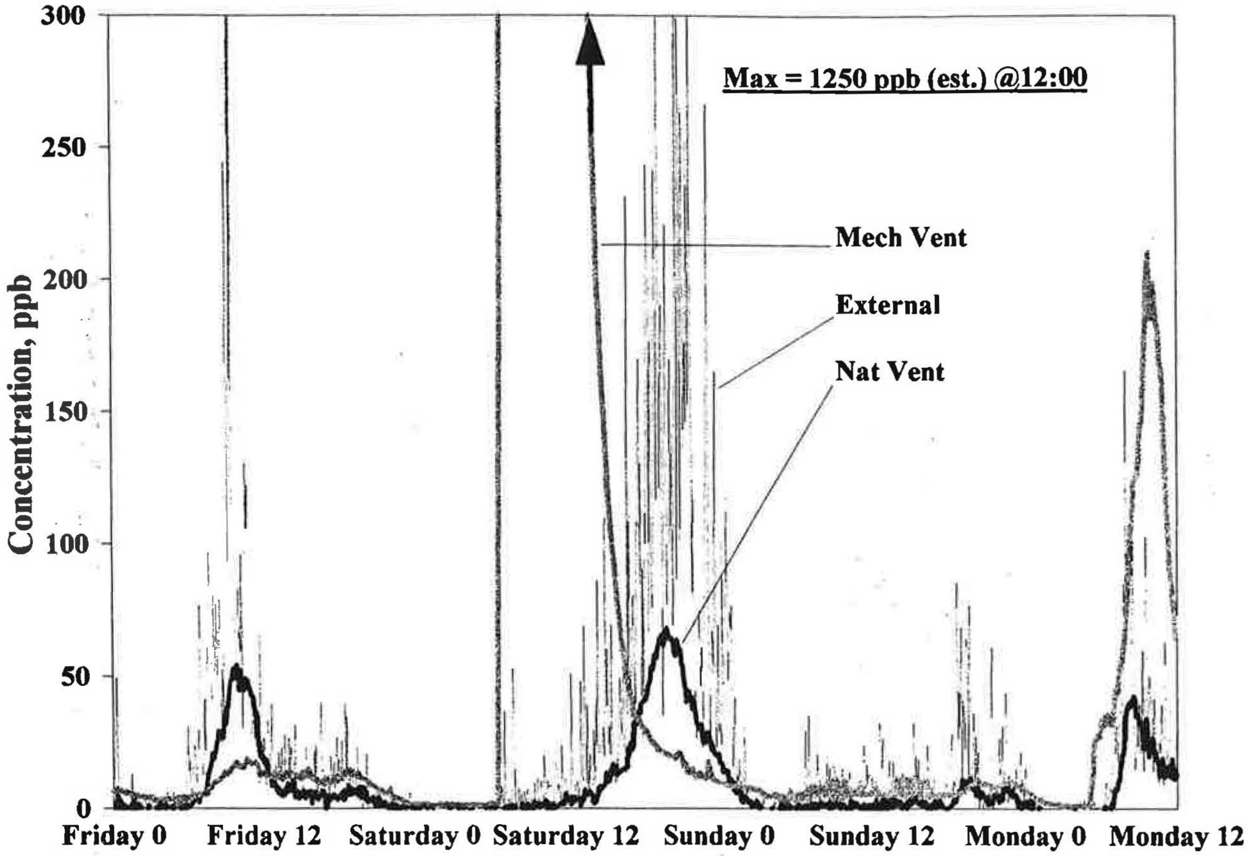

Figure 4. Nitric Oxide

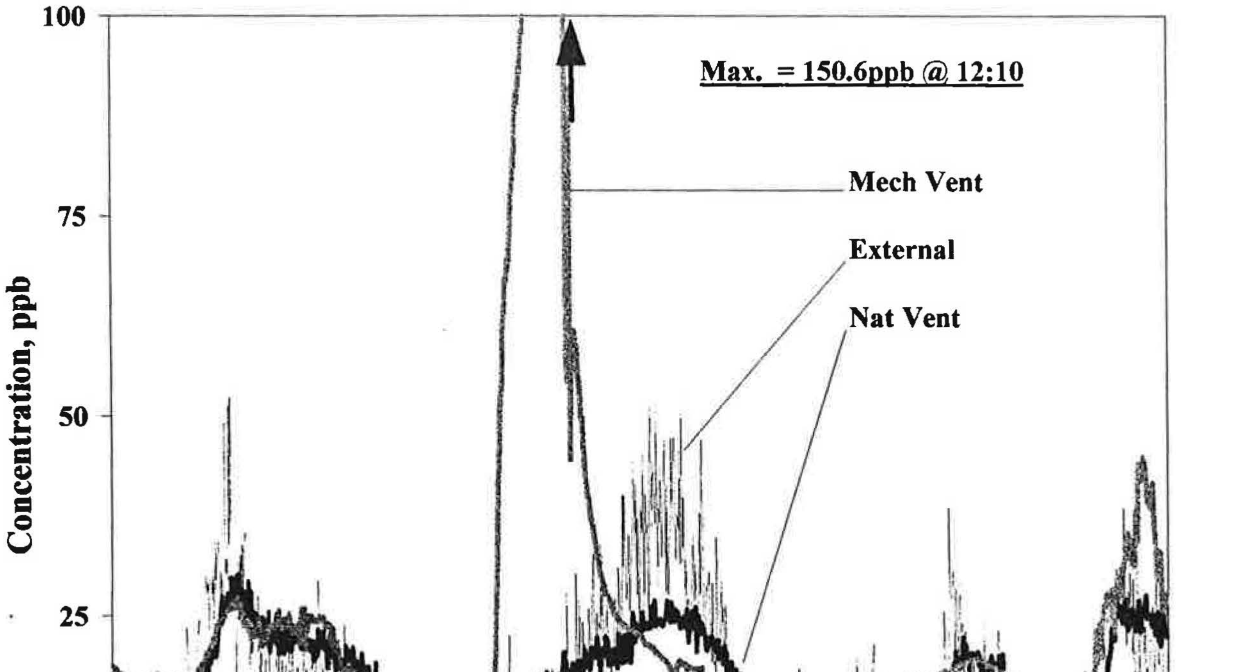

Figure 5. Nitrogen Dioxide

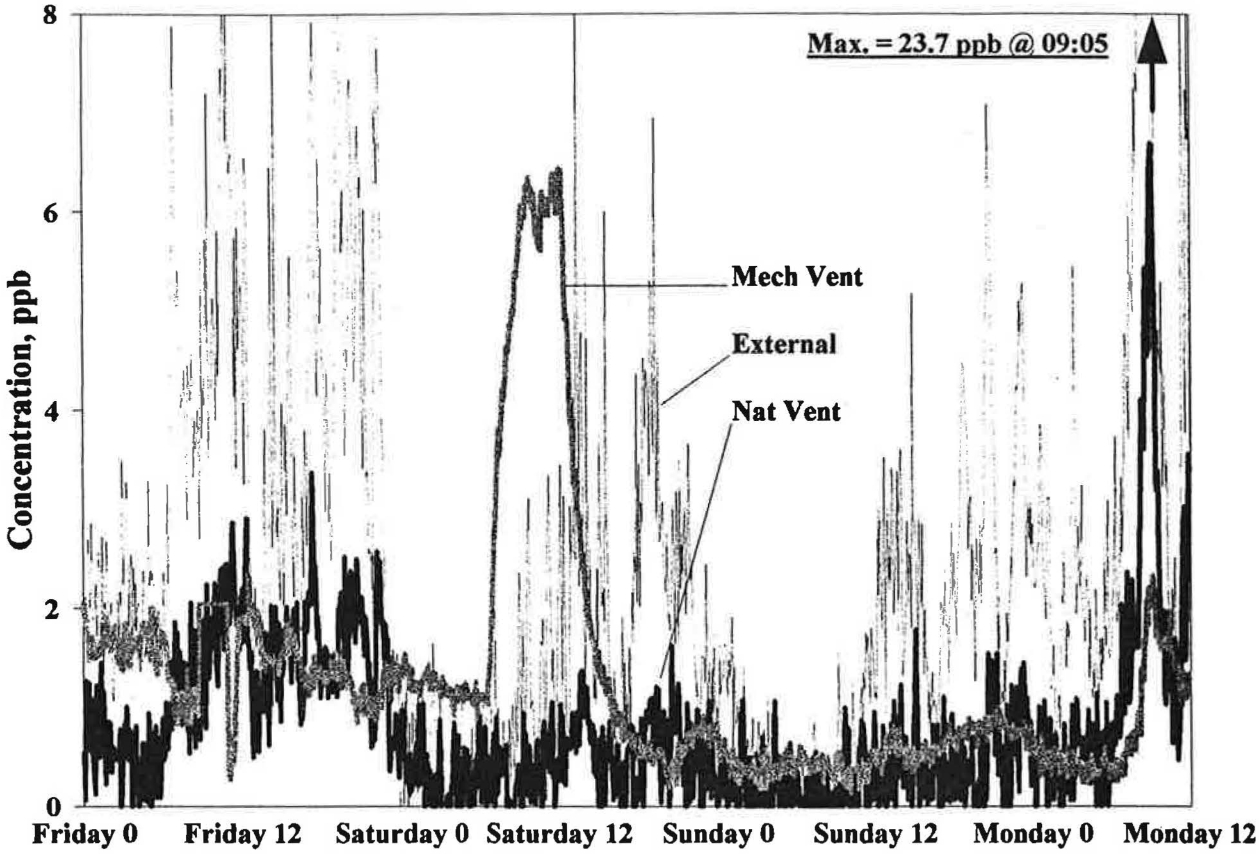

Figure 6. **Sulphur Dioxide**

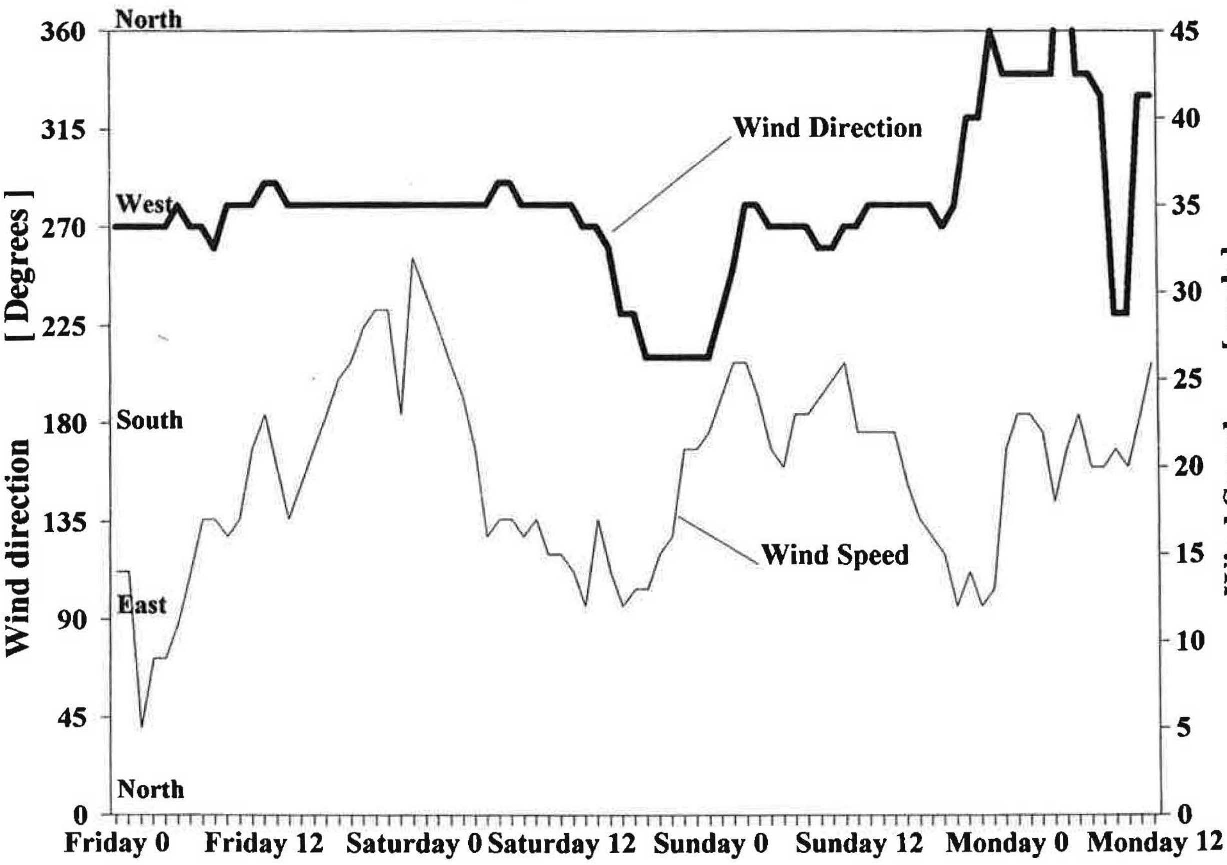

Figure 7. **Wind Speed and Direction**

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