VENTILATION CONTROL AS A FUNCTION OF INDOOR & OUTDOOR AIR QUALITY

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The majority of urban pollution is traffic related and often shows daily variations with peaks occurring at rush hours. Poor outdoor air quality can affect the IAQ of local buildings that ventilate with polluted air. This is particularly applicable to buildings where AHU air intakes are at low level and adjacent to busy roads. The effect of pollution peaks can be minimised by ventilation control and this paper presents potential control techniques for periods when outdoor air quality is poor. It demonstrates the variable nature of traffic related pollution, the dynamics of pollution ingress via the ventilation system, pollutant types, control limits, sensing techniques and potential control strategies.

INTRODUCTION

Air quality in urban areas can be poor, creating problems for local buildings that ventilate with polluted air. A major source of urban pollution is the concentration of traffic, often showing a daily variation with the worst periods at rush hours. An example of this is shown in Figure 1 which illustrates an average summer day at one of the UK Government automatic monitoring sites(1). Actual levels are highly variable and dependent on traffic density and weather conditions.

There are many factors in design, construction and operation of a building that contribute to the ingress of polluted outdoor air. One of the most critical is the location of air intakes and basement plant room AHUs often have intakes at low level near busy roads. The operation of HVAC systems will also have a major influence:

- economiser cycles make use of free cooling, which in summer often results in 100% outdoor air
- pre-occupancy purge cycles which may be operated at peak rush hour periods (the International Energy Agency(2) currently recommend this practise).
- CO_2 or mixed gas sensor controls increase the proportion of outdoor air if the IAQ is perceived as poor.

The impact of inadequacies in design and operation can be reduced through pollutant control. One solution is to use carbon filters to remove the gaseous pollutants, although these may not always be appropriate. The new draft ASHRAE Standard 62 recognises potential limitations and states that "treatment may not be practical eg lack of CO filter, inability to accommodate additional pressure losses from gas phase air filters, lack of standards for gas phase filters". Another possible solution is to control ventilation. Where outdoor pollution is variable an opportunity exists to minimise the impact on IAQ and effectively 'lop off' the peaks by reducing outdoor air. This is the subject of a current BSRIA research study, funded by the Construction Sponsorship Directorate of the DoE and industry partners.

Pollutant modelling

The potential effectiveness of ventilation control can be demonstrated by a simple model that calculates the evolution of an indoor pollutant originating outdoors through ingress via the ventilation system:

$$C_i^{n+1} = \dot{V}\frac{(C_s - C_i^n)}{V}\Delta t + C_i^n$$

C_i^n = indoor concentration at start of timestep

C_i^{n+1} = indoor concentration at end of timestep

C_s = supply concentration

Δt = timestep (s)

$\dot{V}$ = supply air flow rate (m^3/s)

V = volume of zone (m^3)

A time-step of one second was chosen to ensure that the calculation results remained stable. The supply concentration (C_S) was calculated from the indoor concentration ($C_i{}^n$), outdoor concentration (C_o) and the proportion of outdoor air (X):

$$C_s = \left(C_o * \frac{X}{100}\right) + \left(C_i^n * \left(1 - \left(\frac{X}{100}\right)\right)\right)$$

The model assumes perfect mixing in the space, a linear relationship between damper position and actual airflow and does not account for internal pollutant sources or sinks. The results are shown in Figure 2. After only 2.3 air changes (typically 30 minutes but potentially less than 15 minutes) the indoor pollutant concentration is 90% of the outdoor level at full 'fresh air', demonstrating the speed at which outdoor pollution episodes can affect IAQ. Conversely, a system operating at minimum 'fresh air' is much less affected and even after a few hours could still be well below the outdoor level. Since traffic related pollutant peaks typically last 2 to 3 hours outdoor air reduction can be an effective control technique. Obviously, in actual buildings some of the assumptions described above will not apply but Figure 2 does show the principle of ventilation control. For example certain pollutants eg Ozone (O_3) react with building materials and indoor levels may be significantly lower than outdoors. Indoor O_3 can vary between 20-80% of outdoor levels and has been shown to be reactive with several building materials, most notably concrete and bricks(3). O_3 concentration is further complicated by the presence of Nitric Oxide (NO). The reaction between O_3 and NO can actually result in indoor Nitrogen Dioxide (NO_2) levels that exceed outdoor concentrations(4). Other traffic related pollutants are unreactive and ingress is more simple to assess.

The type of ventilation control required is dependent on the frequency of pollution episodes. In extreme circumstances, a simple timeclock could be applied to operate minimum outdoor air between selected hours. An analysis of Government pollution data(1) indicates that the timeclock could operate from 07.00 to 10.00 and 16.00 to 19.00, unless local conditions dictate otherwise. However, this type of control is only appropriate where air quality is regularly poor. Alternatively, pollution peaks may be associated with rush hour periods but of a more sporadic nature and in this case some form of direct measurement may be suitable. A third type of pollution episode is more random and could be the result of a nearby bus stop, taxi drop off or lorry unloading. In this case, it may be feasible to determine when a pollution source is present indirectly, without resorting to direct measurement. For example the presence of a lorry could potentially be indicated by the operation of loading bay doors. Ventilation control may be problematic where pollution episodes are short term and localised because excessive cycling can occur.

EXPOSURE LIMITS

Any attempt to apply ventilation control must determine which pollutant(s) to measure and the concentration(s) deemed unacceptable. There are several sources of information, including UK Government, UK Health and Safety Executive (HSE), European Union, WHO and ASHRAE. The exposure limits, excepting the HSE, are similar and typically apply to CO, SO_2, NO_2, O_3 and PM_{10}. The HSE regulate the maximum permitted exposure to airborne pollutants while at work as defined in Occupational Exposure Standards (OES). The OES are generally a factor above the other limits and their application to offices has been investigated in a separate study(5). This study concluded that there were no health based reasons for different limits, but the expectation and perception of office workers required lower limits. Also, OES limits are legally permitted maximums and as such should not be used as target levels. Therefore, lower limits, eg as given by WHO, are applicable for ventilation control.

CONTROL SENSORS

Sensor options

The exposure limits, other than OES, are in parts per billion (ppb) for most pollutants which presents a problem for ventilation control. For use in building services, sensors must be cheap, robust and reliable. Unfortunately, for measuring ppb levels an expensive analyser, sensitive to the environment and requiring frequent recalibration, is generally needed. One of the cheapest sensor technologies is electrochemical cells which can measure a range of gases. These sensors are relatively inexpensive, typically £300-£500, compared to alternative techniques costing several thousand pounds. Electrochemical cells measure in ppm, which is too high for most WHO pollutant limits, with the exception of CO. CO sensors are generally aimed at OES compliance and typically have ranges between 0-100ppm and 0-500ppm compared to the WHO 1 hour limit for CO is 25ppm. Several studies have shown a good correlation between CO and other traffic related pollutants (NO, Polycyclic Aromatic Hydrocarbons [PAH]) and that a concentration of approximately 5ppm CO indicates that, although acceptable in itself, other pollutants may be unsatisfactory(6)(7)(8). Adopting a CO limit of 5ppm and using a cell that measures up to 100ppm pushes the sensor accuracy to its limit and the practicality of this will be tested. An example of high CO and the correlation with PAH is shown in Figure 3 where measurements were from the air intake of an urban building. Note the time when peaks occurred, high level of CO and the correlation between CO and PAH.

Because cheap, reliable sensors are a problem, the use of CO_2 has also been suggested as an indicator of outdoor combustion pollutants. One study(9) recommended that outdoor CO_2 is monitored for a week and, if it fluctuates at least 300ppm, then active monitoring should be included in the ventilation control. It states that, if the outdoor CO_2 is 700-800ppm, then combustion products are likely to be present in high concentrations. Although suggested as a potential solution by other research, measurements taken in several buildings as part of this study did not demonstrate a significant change in CO_2 when traffic related pollutants peaked (see Figure 3).

Mixed gas IAQ sensors are installed in a number of buildings and can be used to vary ventilation in response to 'measured' IAQ. However, in urban areas pollutants may originate from outdoors and Figure 4 shows an example IAQ sensor output from an urban building. In this building the control system increases outdoor air if the sensor output exceeds 10%. The air intakes are at low level near a busy dual carriageway and when peaks occur they coincide with rush hour periods. One building does not constitute a full study but if outdoor pollution is a major factor it may be appropriate for the control action to reduce rather than increase outdoor air at rush hour periods and increase outdoor air at other times. However, any changes require careful analysis to determine if sensor outputs reduce. Mixed gas sensors may also be an option for outdoor pollutant control because, although calibration is a problem, they do react to a wide range of traffic related pollutants. Also mixed gas sensors and are already being used in a similar application by some car manufacturers.

Although CO_2 and mixed gas IAQ sensors may be feasible in certain circumstances, current sensor technology indicates that in general the only cheap, practical option is a CO cell.

Sensor location

A range of sensor locations are possible. The air intake is the most obvious location but the return air is another possibility or at both, if two sensors are used. Different sensor locations were modelled and the results are shown in Figure 5.

- CO sensor in the air intake

This sensor location causes the control to activate if outdoor air quality is poor and continues as long as the outdoor air exceeds the setpoint. With this arrangement, there are two situations when control continues even though it is no longer beneficial. If the pollution episode lasts for an extended period, at some point the indoor concentration may reach that outdoors. Although extended pollution peaks may be a problem in some circumstances, the period would have to be long (see Figure 2) and is unlikely to occur very often. The second is at the end of a pollution episode and Figure 5 shows that the control continues to operate even when the indoor level exceeds that outdoors.

If extended pollution episodes are a problem it may be necessary to apply a more complex control. One solution is to monitor the change in outdoor CO and continue the control as long as it deteriorates, stop the control if it improves but if the outdoor level is relatively stable, calculate the maximum beneficial control period and stop when this is reached. Table 1 shows the number of supply air changes, for a range of outdoor air proportions, that it will take the indoor concentration to reach 90%, 95% or 98% of the outdoor level. The model previously described was used for the calculations. These results can then be used to calculate the maximum beneficial period as follows:

Maximum beneficial control period (hrs)= N/Q
Q– Supply ventilation rate (ac/h)
N= Supply air changes

Table 1. Maximum supply air changes

Outside air percentage (%)(1)	Supply air changes (N) for Ci=90%Co	Supply air changes (N) for Ci=95%Co	Supply air changes (N) for Ci=98%Co
8	28.780	37.443	48.900
10	23.023	29.950	39.117
12	19.187	24.960	32.600
14	16.443	21.393	27.937
16	14.390	18.720	24.447
18	12.790	16.640	21.730
20	11.510	14.980	19.557
25	9.207	11.980	15.643
30	7.673	9.983	13.037
35	6.576	8.553	11.173
40	5.753	7.487	9.777
100	2.303	2.997	3.913

Co= outside pollutant concentration
Ci= internal pollutant concentration

A second, more complicated, technique is for the BMS to calculate indoor pollutant concentration using the algorithms described earlier. The outdoor concentration and damper position are the calculation inputs and, although complex, these algorithms can be included in a BMS configuration. This system compares the measured outdoor level to the calculated indoor concentration and continues the control providing the outdoor level exceeds the setpoint and the indoor level.

SITE TESTS

A number of site tests will investigate the practicality of CO cells, compare the performance of different control strategies and assess the impact of on IAQ. A BMS outstation has been configured to run each control option along with 0-100ppm electrochemical CO sensors. This set up will be used to control AHU dampers on site. An IR CO analyser, chemilluminescence NOx analyser and PAH monitor will take measurements from the intake and return air. This will allow comparison of cheap CO cells and expensive analysers and also different pollutants. Mixed gas IAQ sensor outputs will also be monitored from the air intakes for comparison with other pollutants. In addition zone temperature and CO_2 will be monitored. The results of these tests will be reported in a BSRIA publication.

In addition to the DoE, BSRIA would like to acknowledge the support of Carrier Air Conditioning Ltd, Caradon Trend Ltd, Crowcon Detection Instruments Ltd, ETI Group Ltd, Healthy Buildings International, Johnson Controls, National Power, Parus Environmental Consultancy, Pearson Panke Equipment Ltd, Shawcity Ltd, Solomat Ltd and Woking Borough Council in this research work.

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- CO sensor in the zone or return air

A CO sensor in the return air has the advantage that it will not respond to short term pollution spikes (dampening effect of a large volume) but will recognise when the outdoor air concentration was lower than indoor air (readings fall). However, this location allows pollution to build up indoors before the control responds (see Figure 5).

- CO sensors in the air intake and return air

The obvious solution to the limitations of sensors in the air intake or return air alone is to use them both. Figure 5 shows the response to pollution episodes is quick and the control stops as soon as it is no longer beneficial. However, in practise the use of one electrochemical CO sensor stretches the technology but two would need a deadband sufficiently large to account for the accuracy of both sensors.

CONTROL STRATEGIES

The most appropriate control is a simple on/off type such that the damper switches to minimum when the setpoint is exceeded. Unlike temperature controls, the CO setpoint is not a limit to control to, but an indication that action is required. Also sensor limitations effectively exclude proportional control as an option. A setpoint of 5ppm allows a maximum proportional band of 5ppm but the cell resolution is only ±1ppm and the accuracy between ±1ppm and ±2ppm. The use of simple on/off controls require a time delay or averaging calculation to prevent excessive damper cycling.

Control setpoint

The 5ppm CO control limit was set up such that the control activated at 5ppm and remained on until the level fell below 4ppm. For intake sensors the setpoint was compared to a 5minute average to prevent unrepresentative spikes from activating the control. Return air sensor controls compared an instantaneous value to the setpoint with the check occurring at 5minute intervals (an average is not required because of the damping effect of the zone volume).

When the system activates....

When the ventilation control activates, it can either operate minimum outdoor air or less than minimum for a short period. Full recirculation is preferable because it effectively blocks the ingress of outdoor pollutants, although this can only be short term to prevent problems with indoor pollutant sources. The latest draft of ASHRAE Standard 62 allows temporary reduction below design minimum, providing the average rate each hour is at the minimum. The test work set the full recirculation period to 20minutes followed by 40minutes at 1.5 times minimum outdoor air to achieve an hourly average of minimum outdoor air. Systems that do not have recirculation can reduce the supply rate or even switch off the ventilation system providing the above are complied with.

When the system deactivates....

When the ventilation control deactivates it may be beneficial to purge with full outdoor air, because at this stage the indoor level of the control pollutant concentration can exceed that outdoors. Also a purge will reduce any pollutant build up from indoor sources. It takes approximately four air changes, at full outdoor air, for the concentration of a pollutant indoors to equal that outdoors (see Figure 2) and the purge time can be based on this.

Impact on thermal comfort

The controls outlined minimise the proportion of outdoor air but this could be during periods when temperature/enthalpy control typically maximises free cooling. Under normal circumstances mechanical cooling capacity will be sufficient to maintain the desired internal temperature. However, if mechanical cooling is not installed or of low capacity, temperature may become unsatisfactory. Studies have shown that temperature is the most important perceived comfort parameter[10] and therefore temperature control should have priority over ventilation control.

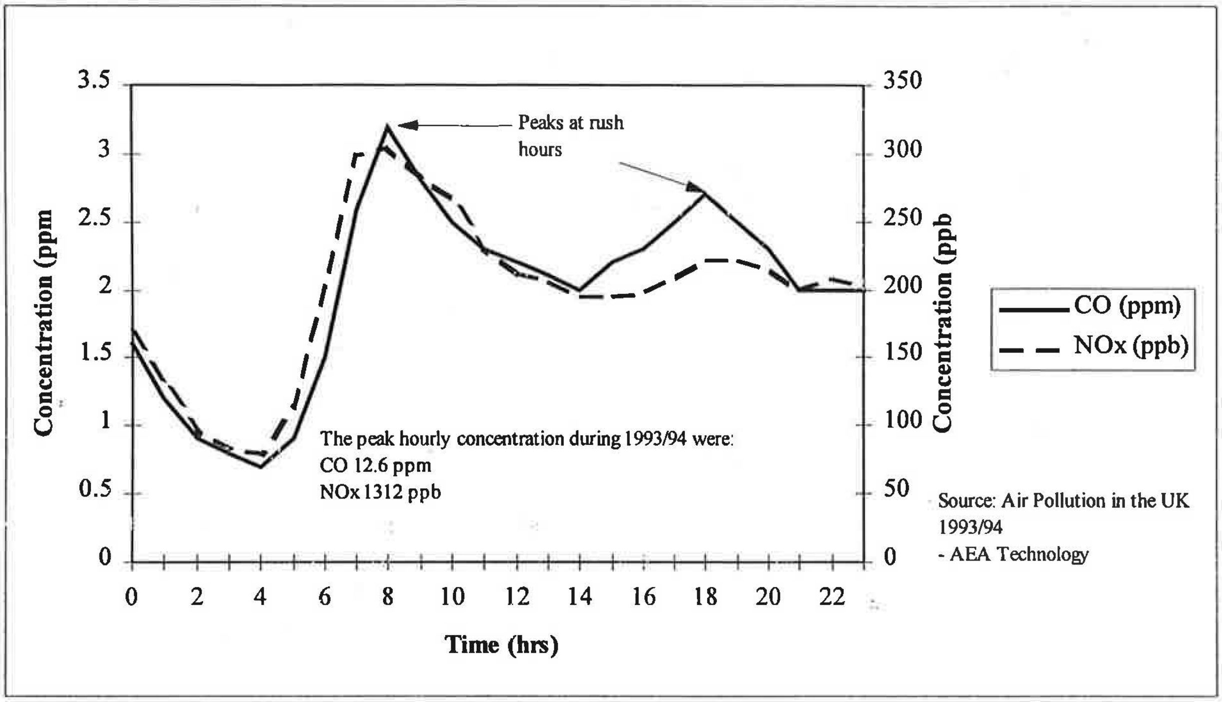

FIGURE 1 CROMWELL ROAD, LONDON - AVERAGE SUMMER DAY

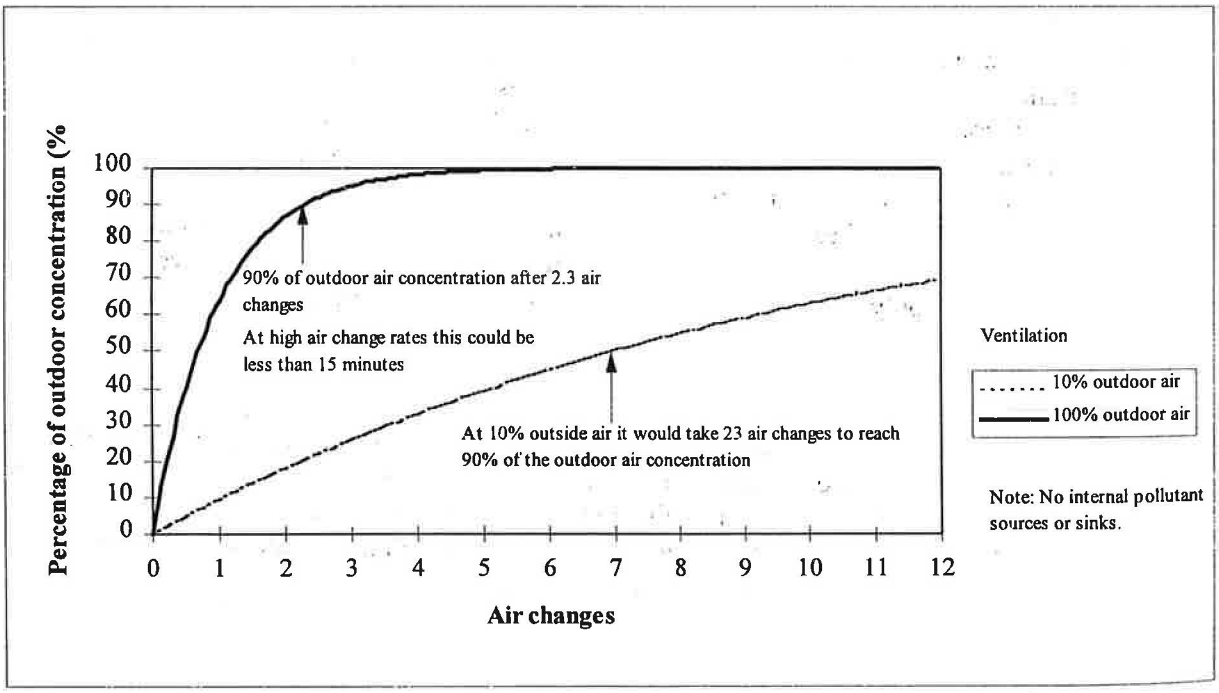

FIGURE 2 CHANGE IN INTERNAL POLLUTANT CONCENTRATION RESULTING FROM A FIXED EXTERNAL SOURCE

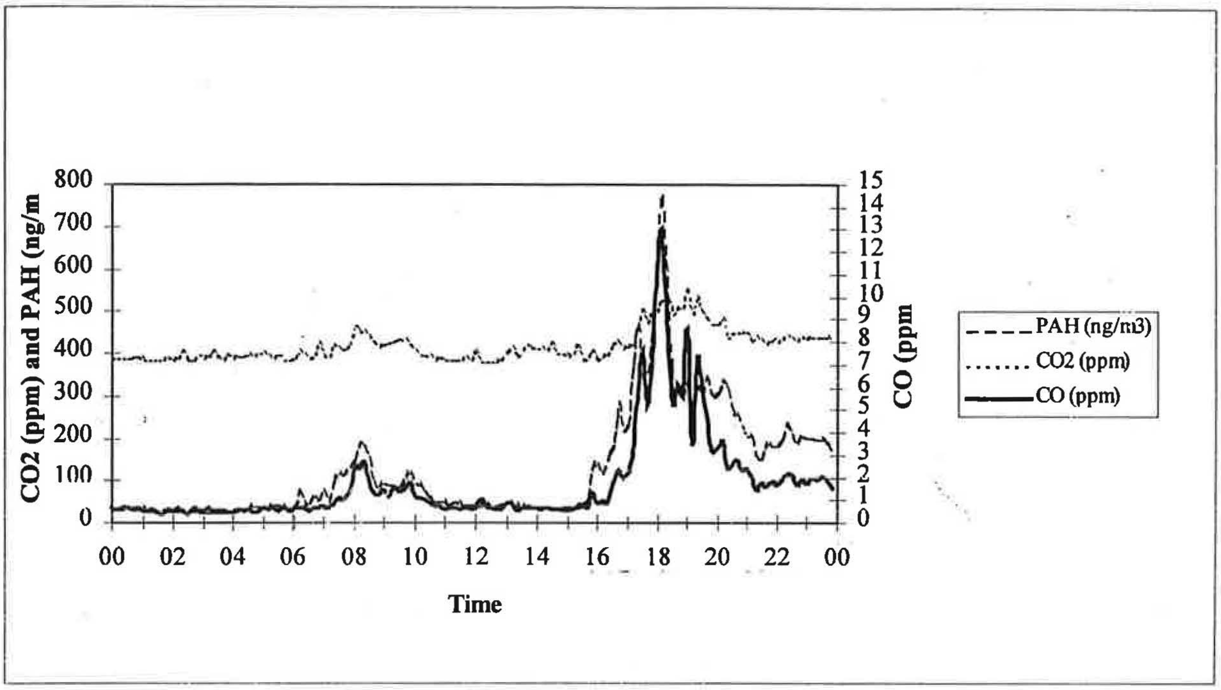

FIGURE 3 EXAMPLE OF AIR INTAKE POLLUTANTS

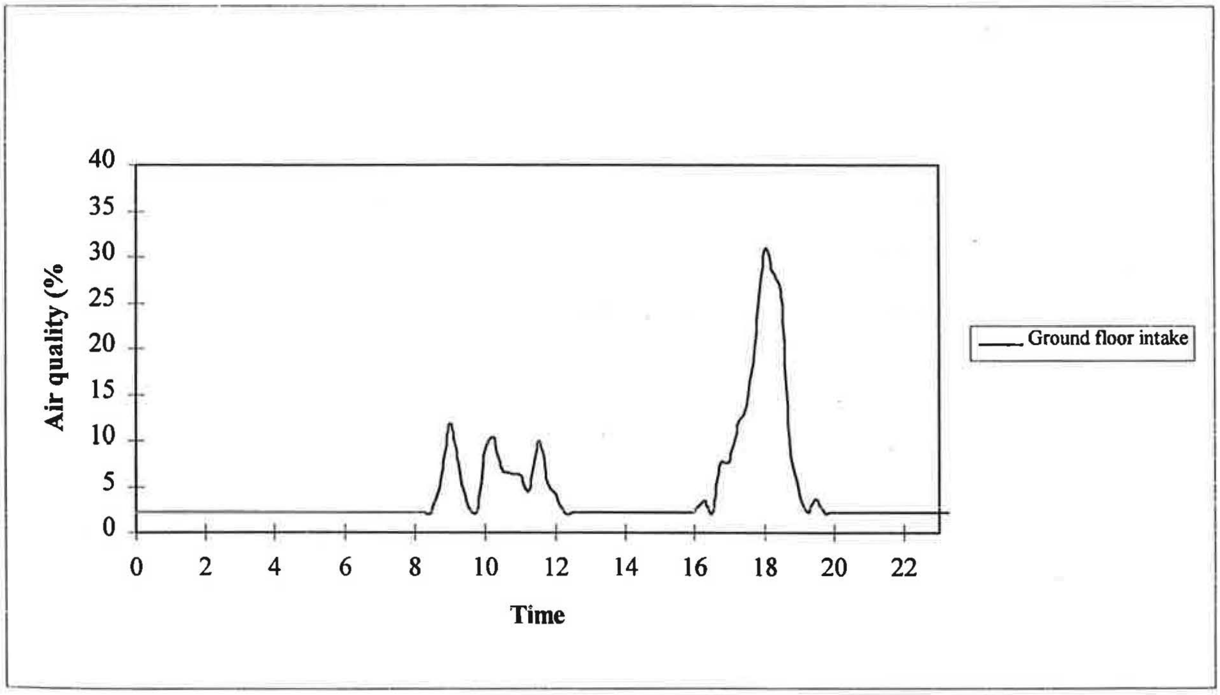

FIGURE 4 EXAMPLE OF IAQ SENSOR OUTPUT FROM AN URBAN BUILDING

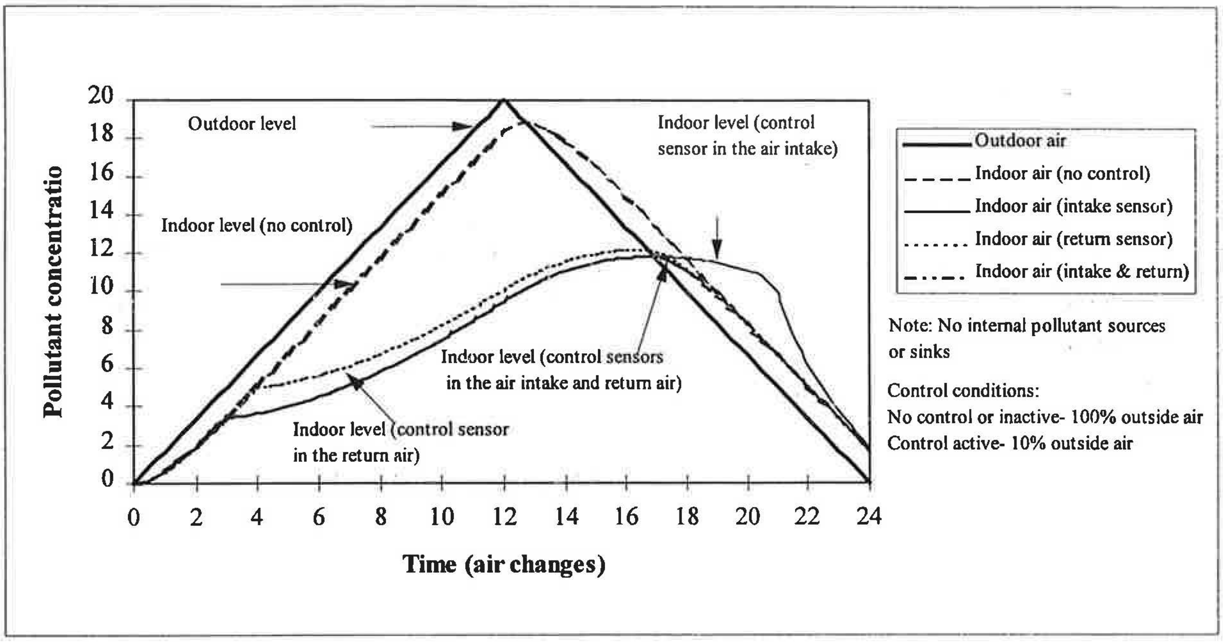

FIGURE 5 MODELLED COMPARISON OF CONTROL OPTIONS