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VENTILATION CONTROL AND TRAFFIC POLLUTION

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GLOSSARY

POLLUTANTS

CO	Carbon monoxide
CO_2	Carbon dioxide
NO_x	Oxides of nitrogen
NO_2	Nitrogen dioxide
O_3	Ozone
PAH	Polycyclic aromatic hydrocarbons
PM_{10}	Particulates less than 10 microns in diameter
SO_2	Sulphur dioxide

ABBREVIATIONS

AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
BMS	Building management system
HSE	Health and Safety Executive
HVAC	Heating, ventilating and air conditioning
IAQ	Indoor air quality
OES	Occupation Exposure Standards
WHO	World Health Organisation

SYMBOLS

C_o	Measured outdoor CO concentration (ppm)
$C_{o\,ave}$	5 minute average of measured outdoor CO concentration (ppm)
$C_{o\,ave}^{n-1}$	Previous 5 minute average of measured outdoor CO concentration (ppm)
C_i	Measured indoor (return) CO concentration (ppm)
C_i^{n-1}	Measured previous indoor (return) CO concentration (ppm)
T_r	Damper position elapsed time (mins)
T_a	$C_{o\,ave}$ elapsed time (mins)
Q	Air supply rate (ac/h)
R	Period at full recirculation (mins)
D_v	Minimum intake damper position with ventilation control (%)
T_{max}	Maximum beneficial control period (mins)
T_c	Maximum beneficial control elapsed time (mins)
T_p	Purge elapsed time (mins)

C_i^n	Calculated indoor (return) CO concentration at start of timestep (ppm)
C_i^{n+1}	Calculated indoor (return) CO concentration at end of timestep (ppm)
C_s	Calculated air supply CO concentration (ppm)
Δt	Calculation timestep (s)
$\dot{V}$	Supply air flow rate (m^3/s)
V	Volume of supply zone (m^3)

SYSTEMS/SENSORS

Air intake	Entry point of outdoor air into a mechanical ventilation system
Zone air	Air in the occupied areas
Return air	Air extracted from the occupied areas by a mechanical ventilation system
Sensor range	The scope of measurement capabilities of the sensor
Sensor accuracy	Variation between the sensor reading and the actual reading of the parameter being measured
Sensor resolution	Minimum possible reading above zero
Sensor drift	Deterioration in sensor accuracy over time
Zero drift	Change in 'zero' output condition over time
Span drift	Change in maximum output condition over time

INTRODUCTION

Traffic pollution causes poor air quality in urban areas and this inevitably has an impact on the indoor air quality (IAQ) of buildings that must therefore use polluted air for ventilation. This Technical Note provides guidance on the use of ventilation control to reduce the effect of outdoor pollution on IAQ. In the context of this publication, ventilation control is defined as the control of ventilation as a function of outside air pollution.

The guidance shows building operators how to reduce the impact of traffic emissions on the indoor air quality of their buildings, by:

- determining if outdoor air quality is poor
- assessing alternative ventilation control strategies if outdoor air quality is found to be poor
- selecting and implementing an appropriate control strategy.

The publication includes detailed control configurations for use by control companies or system houses. Guidance on suitable sensors and the integration of ventilation controls with existing IAQ controls is provided based on computer modelling and the results of strategy tests in actual buildings.

The report is in two parts:

Part A looks at what causes poor outdoor air quality, how to assess a building and measure the relevant pollutants.

Part B sets out eight different strategies and a decision tree to help select the most appropriate. Control strategy flow charts are included for each.

VENTILATION CONTROL AND TRAFFIC POLLUTION

PART A

Assessing and measuring for pollutants

1 OUTDOOR AIR QUALITY

1.1 SOURCES OF POLLUTION

The main sources[Refs 1,2] of traffic pollution are:

- oxides of nitrogen (NO_x)
- carbon monoxide (CO)
- polycyclic aromatic hydrocarbons (PAH)
- particulates
- VOCs
- benzene.

There is good correlation [Refs 1,3] between many of the traffic related pollutants particularly CO, NO_x and PAH. Measuring CO can therefore form the basis of ventilation control strategies.

1.2 DAILY PATTERNS

The main source of many outdoor pollutants is vehicles and therefore the concentration of pollutants often shows a diurnal variation with the worst periods coinciding with rush hours. The variation provides the opportunity for control by minimising ventilation during periods of poor air quality. This method of control is recognised by ASHRAE Standard 62[Ref 4] which states 'the amount of outdoor air may be reduced during periods of high contaminant levels, such as those generated by rush-hour traffic'.

Examples of the potential peak concentrations and diurnal variation of urban pollution are shown in Figures 1 and 2. Figure 1 illustrates the peaks by an example of a particularly bad day at one of the UK Government automatic monitoring sites. Figure 2 illustrates the potential for external pollutants to be drawn in via the mechanical ventilation system. Measurements were taken from the AHU air intake with carbon monoxide (CO) peaking at 13 ppm during the evening rush hour. Both figures also demonstrate the high degree of correlation between CO, NOx and, in Figure 2, also polycyclic aromatic hydrocarbons (PAH).

1.3 BUILD UP OF POLLUTANTS

A pollutant source that originates outdoors can build up quickly indoors - see Figure 3. In this test the air intake of an actual building AHU was seeded with approximately 20 ppm CO and the system set to operate at 100% outside air. After only 30 minutes' operation the return air CO had attained 92% of the intake concentration.

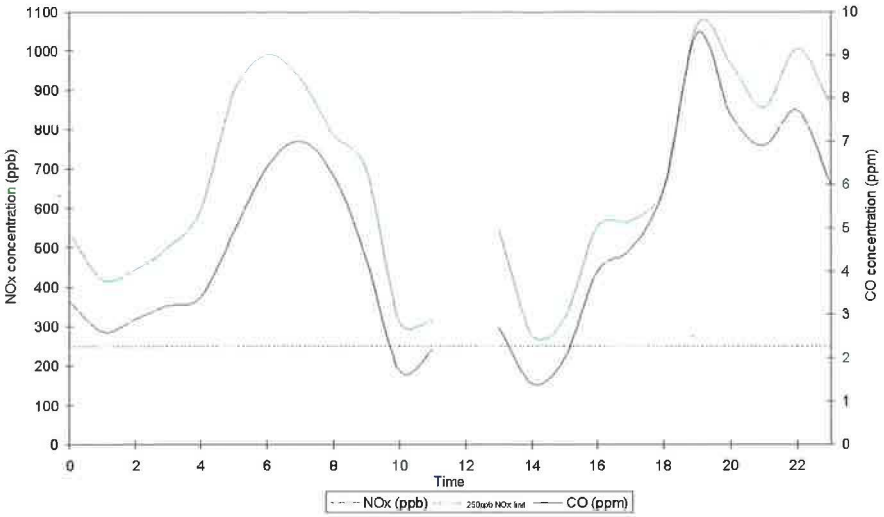


Figure 1
Example of poor air quality (Croydon 3 October 1995)

Source: AEA Technology

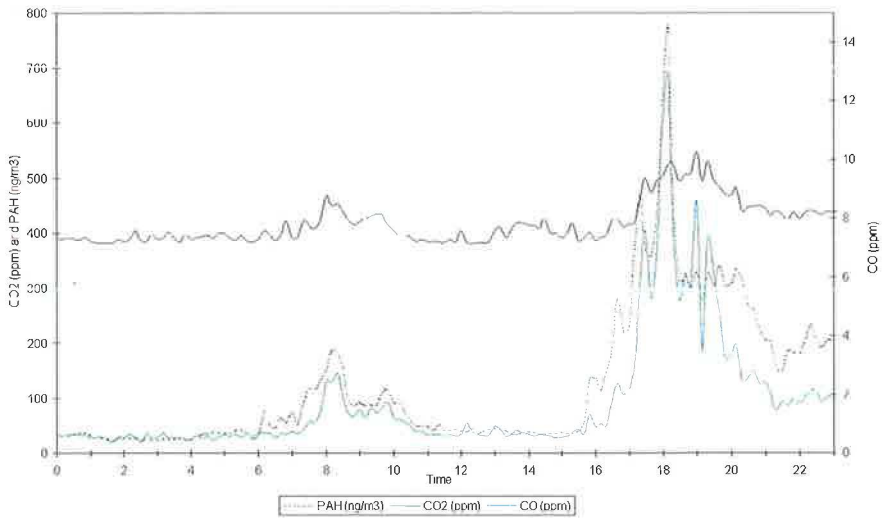


Figure 2
Example building air intake pollutants (21 November 1996)

Source: BSRIA Test Building

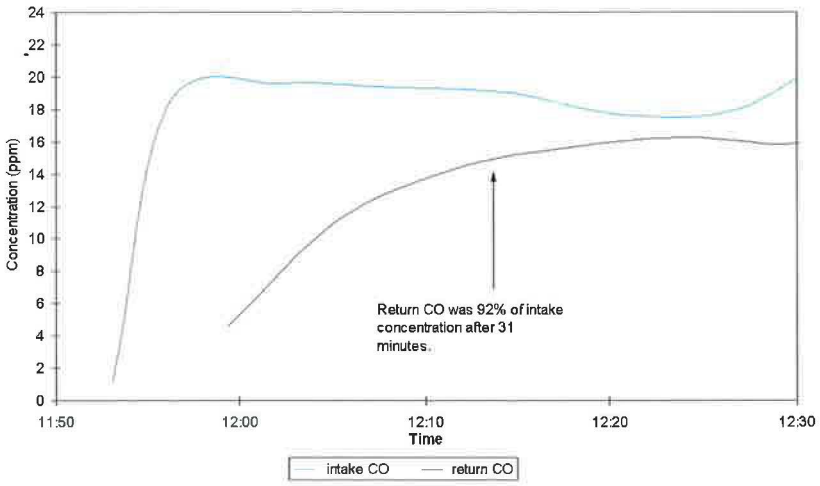


Figure 3
Comparison of indoor and outdoor CO with no ventilation control

Note: System details:
Intake damper position 100% outside air
Supply rate - 9ac/h

Source: BSRIA Test Building

1.4 EXPOSURE LIMITS

There are several sources of information on exposure limits, including UK Government, UK Health and Safety Executive (HSE), European Union, WHO and ASHRAE. The exposure limits, apart from 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 [Ref 5]. This study concluded that the expectation and perception of office workers require lower limits than those specified by the HSE. In addition, OES limits are legally permitted maximums and as such should not be used as target levels; therefore lower limits such as those specified by WHO (see Table 1) are applicable for ventilation control in office type environments.

Table 1
World Health Organisation (WHO) short term exposure guidelines

Period	CO (ppm)	NO_2 (ppb)	SO_2 (ppb)	O_3 (ppb)
1 hour	25	210	122	76-100

Source: WHO quoted in Warren Spring Report [Ref 6]

2 BUILDING ASSESSMENT PROCEDURE

2.1 GENERAL

The concentration of pollutants in outdoor air and their impact on IAQ is influenced by:

- outdoor pollution levels which are dependent on a combination of factors including vehicle type/density, wind speed, wind direction and precipitation
- whether the building and HVAC system encourage ingress of polluted air, perhaps by the location of the entry point into the building or the rate of ventilation
- whether ventilation control can be applied to this system.

2.2 IS THE OUTDOOR AIR QUALITY POOR?

The best option to assess pollution load is to monitor actual concentrations of CO and NO_x in the AHU air intake nearest the pollution source. BSRIA recommends the following:

- for CO an infrared gas analyser
- for NOx a chemiluminescent ambient NOx analyser.

Monitoring

Monitoring should be on a continuous basis for a minimum of one week (longer if possible) to include different periods, eg Monday morning rush hour and weekends, to monitor periods both of high and low pollution loads. If possible, the assessment should be at a time that the air quality is more likely to be poor, eg when low wind speed and dry conditions have prevailed for a few days.

Sources of data

Other techniques and sources of information to make an assessment are available if monitoring is not a practical option. ASHRAE Standard 62 *Ventilation for acceptable indoor air quality*[Ref 4] requires an investigation of outdoor air quality to be made as part of a building assessment procedure and suggests assessing pollution data from a local monitoring site. If local information is not available then data from a 'community similar in population, geographic and meteorological settings, and industrial patterns' is deemed acceptable. It is possible to apply this approach in the UK using data from one of the automatic monitoring sites operated by the UK government. Pollution data from these sites is freely available and covers CO, NO_2, NO_x, SO_2, O_3, PM_{10}, benzene and 1,3 butadiene. An annual report summarising each site is produced by the AEA Technology National Environmental Technology Centre entitled 'Air Pollution in the UK' and is available from:

National Environmental Technology Centre
Culham, Abingdon
Oxfordshire, OX14 3DB

or by phoning the Environmental Helpline on 0800 585 794.

Information from each UK Government automatic monitoring site is also available on the internet at

www.aeat.co.uk/netcen/aqarchive/siteinfo/autoinfo.html

Other potential sources of pollutant data are local authorities which often carry out their own monitoring.

Using the data

The monitored data can be compared to short term exposure limits as specified by WHO (Table 1). ASHRAE Standard 62 states that air quality is deemed to be poor if their stated limits (similar to WHO, UK government etc) are exceeded more than once per year and this criterion can be used for the assessment.

If there is no data

If local pollution data is not available it may still be possible to assess the need for pollutant control by investigating the building and locality. Consider the following questions:

1. Is the building near a pollution source, eg a busy road?

2. Are air intakes located near the pollution source? The location of air intakes can be crucial to the ingress of outdoor air pollutants [Ref 7]. Air intakes are typically located from a plant room layout or space perspective. The result may be an intake at low level near a busy road with little opportunity for dilution of vehicle emissions.

3. Do occupants complain of odours or health effects that could be the result of external pollution? In buildings served by multiple AHUs it may be feasible to distinguish between the number and frequency of complaints from areas supplied by AHUs that take outside air near to a pollution source to other AHUs that do not.

4. Are gaseous pollutant filters fitted, eg carbon filters on the AHUs?

If the answer to questions 1, 2 and 3 is yes then ventilation control may be required. If the answer to question 4 is yes then investigate why they are fitted. (**Note:** ventilation control may still be beneficial in addition to carbon filters because it will reduce the load on the filters.)

2.3 DOES THE BUILDING OR HVAC SYSTEM UNNECESSARILY INCREASE POLLUTANT INGRESS?

An investigation of the building and HVAC system should be made if the assessment of local outdoor air quality indicates that quality may be poor. This will show whether the building set-up promotes the ingress of outdoor pollutants and if this can be minimised prior to considering a ventilation control system. The following questions should be addressed:

- Are windows openable? If yes, are they frequently used? (Openable windows allow unconditioned air to by-pass the mechanical ventilation system and enter the building.)

- Does a pre-occupancy ventilation purge cycle operate? If yes, is it really necessary? (Pre-occupancy purges typically operate on full outdoor air during the peak rush hour period when outdoor pollution is at its worst.)

- Is the minimum outdoor air proportion higher than the recommended guidance for the actual occupancy?
  (Unnecessarily high ventilation rates will increase pollutant ingress.)

- Does the damper control account for damper characteristics?
  (An oversized damper will result in a higher outdoor air proportion than the damper setting.)

- Are IAQ sensors used to control ventilation?
  (These sensors increase ventilation if IAQ is sensed as poor but can react to pollutants that originate outdoors - see Strategy S7a for further information.)

- Are indoor CO_2 sensors used to control ventilation? If yes, is the sensor inaccurate or setpoint too low?
  (An inaccurate sensor or low setpoint may cause unnecessary ventilation.)

2.4 CAN VENTILATION CONTROL BE APPLIED TO THE HVAC SYSTEM?

Ventilation control can be applied to the majority of central HVAC systems. The key requirement is a system that can reduce the amount of outdoor air in response to a pollution episode, eg increased recirculation, air flow reduction or both. Therefore, systems that employ full outdoor air with heat recovery are not appropriate. Their only option would be to switch the ventilation off for a short period but this is very unlikely to be of benefit in any but the most extreme pollution episodes because it could create problems with thermal comfort and/or indoor pollutant sources.

3 CONTROL OPTIONS

3.1 GENERAL

Where IAQ is poor there are three main approaches to the control of pollutants: source control, removal control and ventilation control. If pollutants originate from outdoors, source control is not an option for individual buildings. The second option, removal control, includes particulate and gas phase filters (carbon filters). Although particulate filters are very effective, the use of gas phase filters may not always be appropriate. Ventilation control is the third approach and the diurnal nature of urban pollutants can make this a viable technique.

The type of ventilation control required is dependent on the frequency of pollution episodes. In extreme circumstances, a simple timeclock can be applied to operate minimum outdoor air between selected hours (Strategy 6). 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 pollutant measurement may be suitable. A third type of pollution episode is one which is more random and could be the result of a nearby bus stop, taxi drop-off or vehicle loading area. In the last case, it may be feasible to indirectly determine when a pollution source is present, eg when a gate is opened for loading access, otherwise direct measurements will be needed.

3.2 MEASURING POLLUTANTS

3.2.1 Exposure limits and sensor options

Where ventilation control by pollutant measurement is applied, the appropriate pollutant(s) to be measured and the concentration(s) deemed unacceptable must be specified.

WHO exposure limits are in parts per billion (ppb) for most pollutants, which presents a problem for ventilation control because measurement at this level requires expensive analysers. Cheaper sensor technologies are available, eg electrochemical cells, that measure in parts per million (ppm) but the only pollutants in ambient air at ppm levels are CO and CO_2. CO_2 measurement is generally not practical for control because it does not register a large enough change when other pollutants peak but it may be applicable in certain cases (see Section S7.2). CO, however, does show a large change during pollution episodes and also has a good correlation with other traffic related pollutants (see Section 1.1) which makes it a useful indicator of general outdoor air quality (when the main pollution source is vehicular). The WHO one hour limit for CO is 25 ppm (see Table 1) but this is rarely, if ever, exceeded. Studies have shown [Refs 1, 8] that a CO concentration of approximately 5 ppm indicates that, although acceptable in itself, other traffic related pollutants may be unsatisfactory. Therefore, 5 ppm can be used as the setpoint for control systems.

An alternative indicator of general outdoor air quality may be mixed gas sensors which are used by some car manufacturers in ventilation control. These sensors do register traffic related pollutants but are very difficult to calibrate, making them impractical in most situations. The potential use of existing IAQ sensors for ventilation control is discussed in S7.1.

3.2.2 Advantages and disadvantages of an electrochemical CO cell

There are several different techniques to measure CO but the only practical option for ventilation control is an electrochemical CO cell for the following reasons:

- CO measurement by infra-red techniques is more accurate than electrochemical cells but is very expensive (typically £10,000 to £15,000). Electrochemical CO cells by contrast cost £300 to £500.
- Electrochemical cells are available in both external wall mounted and duct mounted versions, ideal for ventilation control (see Plates 1 and 2).
- Electrochemical CO cells have low cross-sensitivity to other pollutants because measurements are in ppm but the pollutants that can influence cell output are generally at ppb levels.
- Electrochemical CO cells require a 24V dc supply which is a standard feature of a BMS outstation, allowing simple connection.
- The output of electrochemical CO cells is 0-10V or 4-20mA, which are standard inputs for a BMS outstation, allowing simple connection.

Although electrochemical CO cells are the only practical option they are not an ideal option because:

- Sensor accuracy is poor (nominally ±2 ppm) and tests on-site showed a 3 ppm difference between the an infra-red CO analyser and the electrochemical cell.
- Sensor ranges are high because the cells are aimed at Occupational Exposure Standard limits (0-100 ppm is the lowest standard range). This compares to concentrations in ambient air that rarely exceed 10 ppm.
- Sensor drift can be excessive (see Section 3.2.3) and regular calibrations are required.

Plates 1 and 2 show the size and installation requirements of typical air intake and return air CO cells. The air intake type are wall mounted and waterproof. Plate 1 shows the ideal location for an intake sensor (inside the intake plenum). The sensors can also be fitted to an outside wall but should be located as close to the intake as possible (preferably within 2 m) to ensure an accurate representation of pollutant levels drawn into the intake. The return air units work by inducing air from the duct into a sample chamber via pipes inserted in the ductwork and therefore installation is more onerous. Zone air measurement could be used as an alternative to the return air and the wall mounted cell could, in theory, be used for this purpose. However, the visual appearance of the cells would probably make this application impractical.

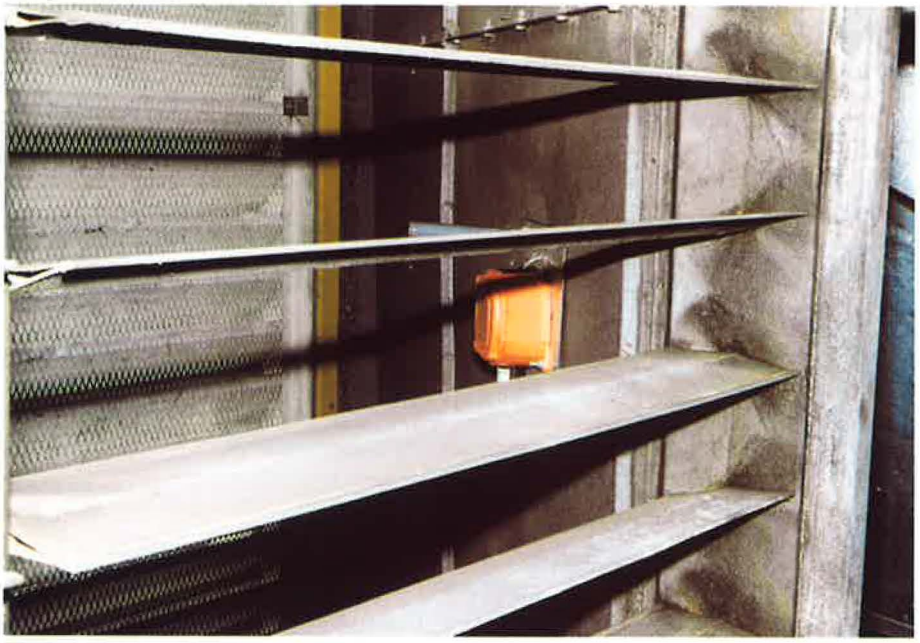


Plate 1
Wall mounted CO cell in an AHU air intake

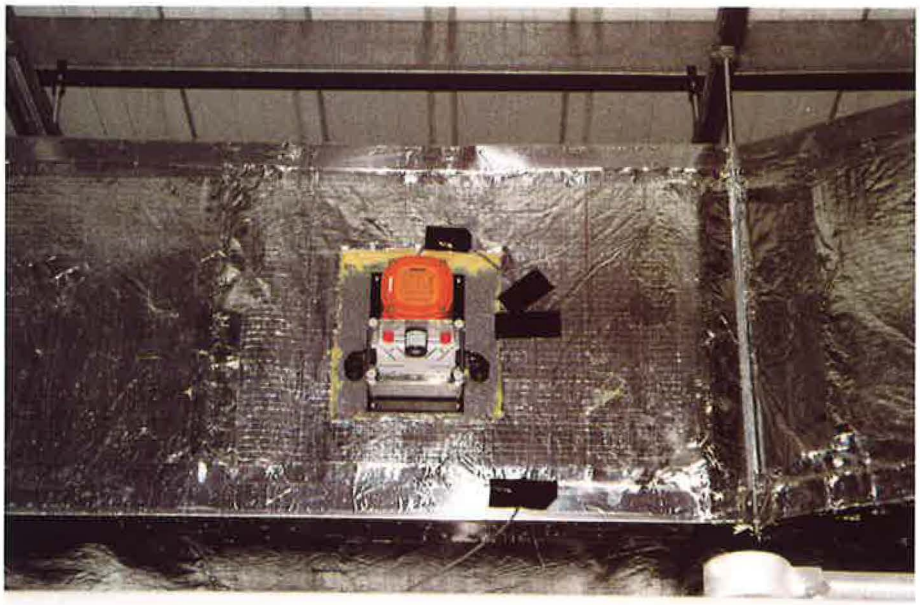


Plate 2
Duct mounted CO cell in return air

3.2.3 Electrochemical cell maintenance

The use of electrochemical CO cells in this application is potentially problematic due to accuracy limitations and therefore regular maintenance is particularly important. The following schedules are recommended:

Period	Test
1 month	Functional test using test gas
6 months	Examination of equipment, functional test and calibration
2 years	Cell replacement.

The maintenance schedule is similar to that for other plant and sensors although expensive calibration gas is required to perform the tests. Calibration involves checking for zero and span drift using nitrogen and CO respectively. Although the CO cell range is typically up to 100 ppm, the maximum level will never be attained in ambient air and accuracy is required at low concentrations. Therefore a concentration of 10 ppm is more applicable for span checks.

The accuracy of the two cells used in this study is shown in Figure 4. The cells were initially within the expected accuracy of ±2 ppm, even at low concentrations. The deterioration over 8 months between the initial and final checks demonstrates the importance of regular checks.

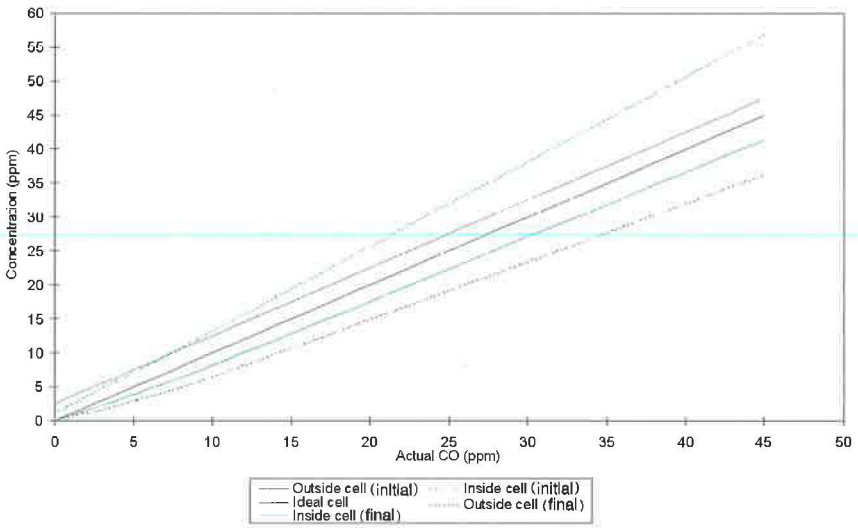


Figure 4
Electrochemical CO cell calibration

VENTILATION CONTROL AND TRAFFIC POLLUTION

PART B

CONTROL STRATEGIES

This part of the Technical Note describes eight alternative control strategies that were developed as part of the research project and also includes a flowchart to assist selection. Strategies 1 to 5 use electrochemical CO cells in different locations and configurations. Strategy 6 is a simple timeclock with no direct pollutant measurement and Strategies 7a and 7b use existing air quality sensors for control. The following summarises each of the strategies:

Strategy	Details
1	CO cell in the air intake (simple control)
2	CO cell in the air intake (includes calculation of maximum beneficial control period)
3	CO cell in the air intake (includes calculation of indoor CO concentration)
4	CO cell in the return air
5	CO cell in the air intake and return air
6	Timeclock
7a	Use of existing mixed gas (IAQ) sensors
7b	Use of existing CO_2 sensors

Control Strategy 1 is the most simple and general purpose control but has limitations and Strategies 2 to 5 were developed to account for the following conditions that Strategy 1 will not recognise:

If a pollution episode lasts for an extended period, at some point the indoor concentration will approach that outdoors and continued control will not be worthwhile.

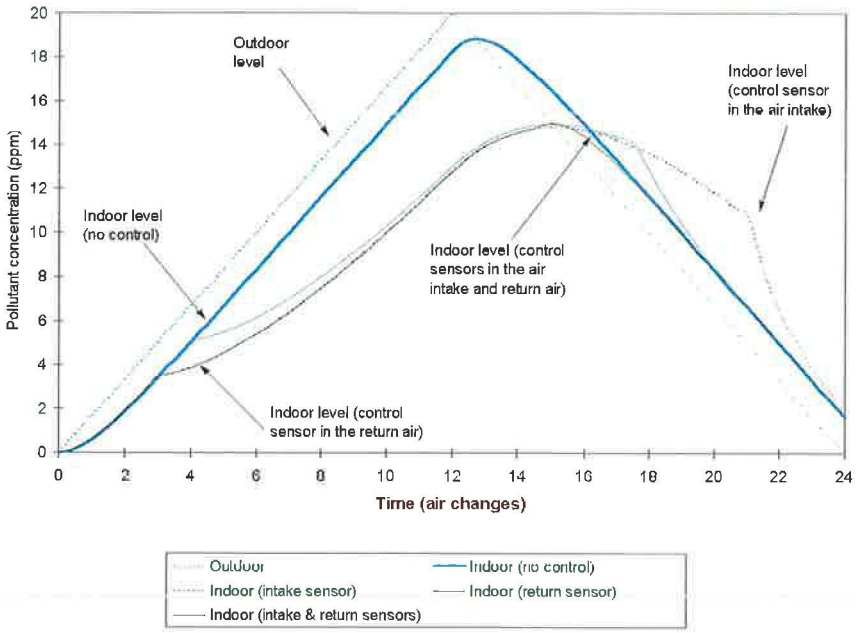
If the outdoor concentration falls, but is still above the setpoint, Strategy 1 continues control even though the indoor concentration may exceed that outdoors.

An example of this is shown in Figure 5 which considers control with sensors in different locations. The intake sensor cannot recognise that the outdoor air quality has improved to a point where it is better than the indoor level, so the control continues.

Figure 5
Modelled comparison of alternative sensor locations

Note: No internal pollutant sources or sinks

Control conditions:
Control off - 100% outside air
Control on - 20% outside air



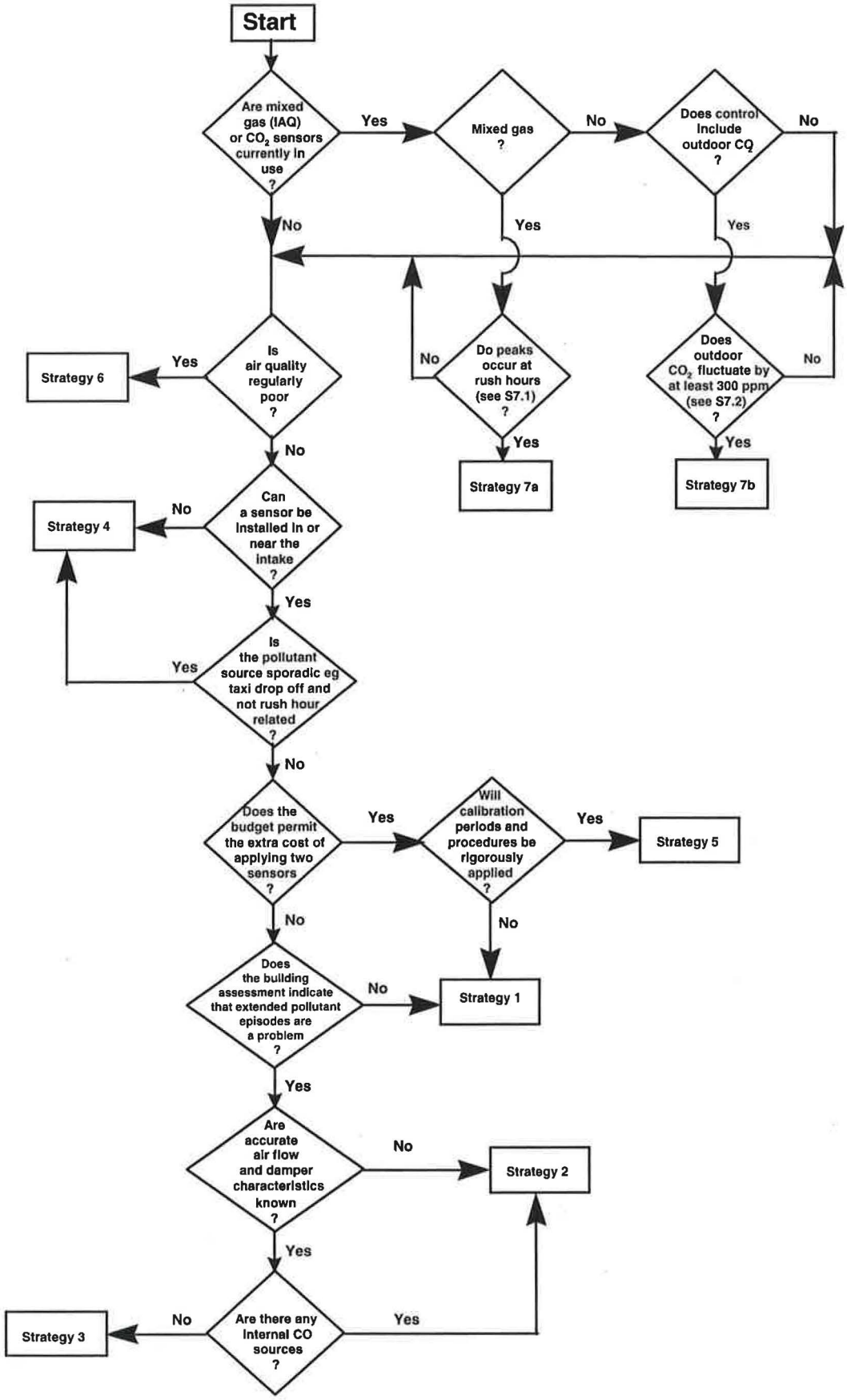
Source: BSRIA computer model

Strategies 1 to 5 include figures which show control operating in an actual building. These tests artificially created pollutant episodes by 'seeding' the air intake of a selected AHU with a controlled concentration of CO. The AHU supplied a single area (lecture theatre) which allowed conditions to be closely monitored and controlled.

Figure 6 shows a decision flowchart for strategy selection. Strategy 1 will be satisfactory for the majority of applications. Strategies 2 to 6 should only be applied if the flowchart questions can be accurately answered. Strategies 7a or 7b may be applicable where air quality sensors are already used to control ventilation.

Many of the strategies contain similar functions and these are fully detailed for Strategy 1 only. Readers are recommended to consult this strategy in addition to that detailing the strategy they have selected.

Figure 6 Strategy selection



STRATEGY 1: CO SENSOR IN THE AIR INTAKE (SIMPLE CONTROL)

For Strategy 1 a CO sensor is installed in the air intake or on an outside wall near to the intake (within 2 m).

S1.1 CONTROL ACTIVATION

The control activates if the CO exceeds a fixed setpoint and continues as long as the level is above the setpoint. The most appropriate control is a simple on/off type such that the dampers switch to minimum outdoor air / full recirculation when the setpoint is exceeded. This is because unlike proportional controls, eg temperature, operating to maintain a setpoint, the CO setpoint represents a threshold value indicating that action is required. Also, sensor limitations effectively exclude proportional control as an option since the control becomes meaningless when trying to maintain a typical CO setpoint of 5 ppm when the cell resolution is only ±1 ppm and accuracy between ±2 ppm. A deadband is necessary with on/off control to prevent unrepresentative pollutant spikes activating the control. Similarly an average reading is used instead of an instantaneous one in order to prevent the control cycling excessively. The averaging period must be sufficiently long to ensure the control only reacts to real trends rather than unrepresentative spikes, but short enough to be responsive.

When the control is activated there are two options for the operation of the system:

- full recirculation for a short period
- minimum outside air proportion.

Full recirculation is preferable because it blocks the ingress of outdoor pollutants but can only be short term to prevent problems arising from indoor pollutant sources. Full recirculation can be applied if it is limited such that the average outdoor proportion over an hour is maintained at the minimum, eg 20 minutes at full recirculation followed by 40 minutes at 1.5 times the minimum. The following should be used to calculate the damper position required to maintain an hourly average of the minimum outdoor air proportion when full recirculation is used for a short period (calculation assumes a linear relationship between airflow rate and damper position):

$$D_v = \frac{D_e x60}{(60 - R)}$$

D_e = Minimum intake damper position with existing control (%)
D_v = Minimum intake damper position with ventilation control (%)
R = Period at full recirculation in any one hour with ventilation control (mins).

Note that D_v cannot in practice exceed 100% (fully open) and if this occurs in the calculation the recirculation period selected is too large for D_e.

The recirculation period (R) can be any figure between 0 and approximately 50 minutes in any one hour but for practical purposes should be restricted to 20 to 40 minutes. If full recirculation is not permitted, eg a system with fixed and modulating intake dampers, the system simply switches to the minimum outdoor air flow setting when the control is activated.

The control strategies assume that recirculation is available. Where this is not the case air flow reduction may be feasible. For example a variable speed fan can be set to minimum airflow or a twin speed fan to low speed if the control activates. If recirculation and air flow reduction are available, both should ideally be applied.

A reduction in outdoor air or air flow rate below that called for by the enthalpy/temperature controls must be carefully considered. It is likely that the ventilation control will be activated fairly infrequently and therefore its impact on energy consumption will be minimal. The potential impact on thermal comfort can be more immediate and is of greater importance (see Section S1.3).

S1.2 CONTROL DEACTIVATION

When the control deactivates it is beneficial to go through a purge cycle prior to reverting to normal control. The purge (100% outdoor air) is necessary because the indoor level of pollutants may exceed that outdoors, particularly if the pollutant episode was for an extended period. Also, a purge will remove any pollutant build up from indoor sources. It takes approximately four air changes, at full outdoor air, for indoor and outdoor concentrations to equalise [Ref 6].

The purge period can be calculated as follows:

Purge time (mins) = 240/Q

Q = Air supply rate (ac/h).

S1.3 IMPACT OF CONTROL ON THERMAL COMFORT

The application of ventilation controls should not be at the expense of thermal comfort. During summer, systems maximise free cooling by increasing the outdoor air proportion, often to 100%. The ventilation controls described in this publication minimise outdoor air flow rate but under normal circumstances mechanical cooling capacity should be sufficient to maintain the desired internal temperature regardless of damper position or air flow rate. If however mechanical cooling is not installed, or is of low capacity, problems of internal overheating could occur in which case pollution control may have to be achieved by alternative measures such as filtration.

S1.4 STRATEGY 1 CONTROL CRITERIA

Table 2 outlines the control criteria for Strategy 1 and a control logic flowchart is shown in Figure 7.

Table 2
Strategy 1 control criteria

Parameter	Criteria
Sensor location	Air intake
Control check interval	5 minutes
Control setpoint	4.5 ppm with ±0.5 ppm deadband
Control on	5 ppm
Control off	4 ppm
Sensor control parameter	5 minute average outdoor CO

S1.5 STRATEGY 1 IN ACTION

Figure 8 shows the operation of a Control Strategy 1 in a test building. This figure demonstrates the following facets of the strategy (A to D are points on the graph from left to right):

A. Control activated when the 5 minute average outdoor CO exceeded 5 ppm. Intake damper moved to full recirculation.

B. Intake damper moved to 1.5 times minimum position when the period at full recirculation exceeded 20 minutes (minimum damper position = 10%).

C. Intake damper moved to full recirculation when the period at 1.5 times minimum position exceeded 40 minutes, ie control on for 60 minutes.

D. Intake damper moved to purge when the 5 minute average outdoor CO fell below 4 ppm.

Note that the control successfully minimised the impact despite very elevated levels of CO in the air intake.

Figure 7 Strategy 1 control logic

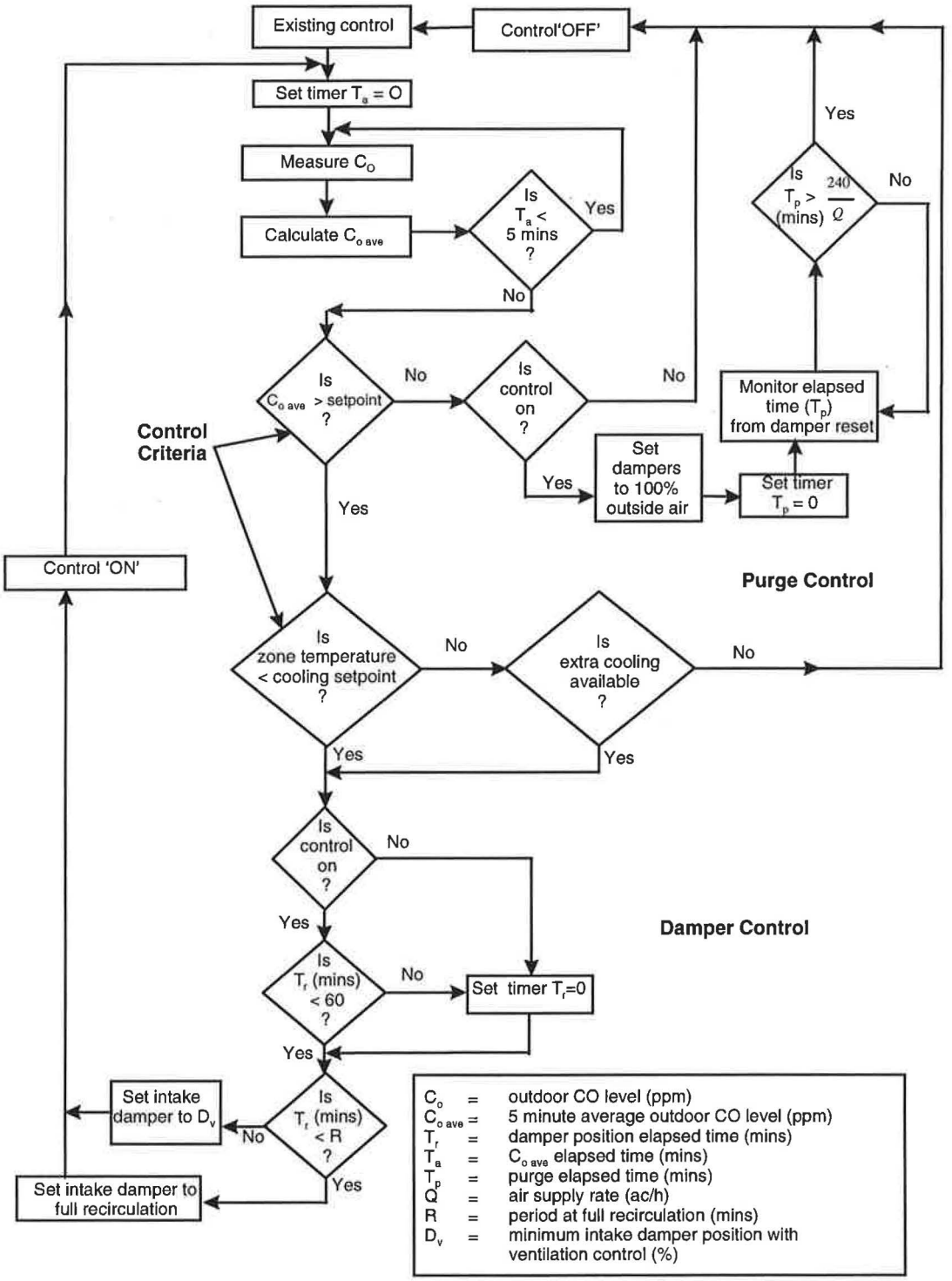
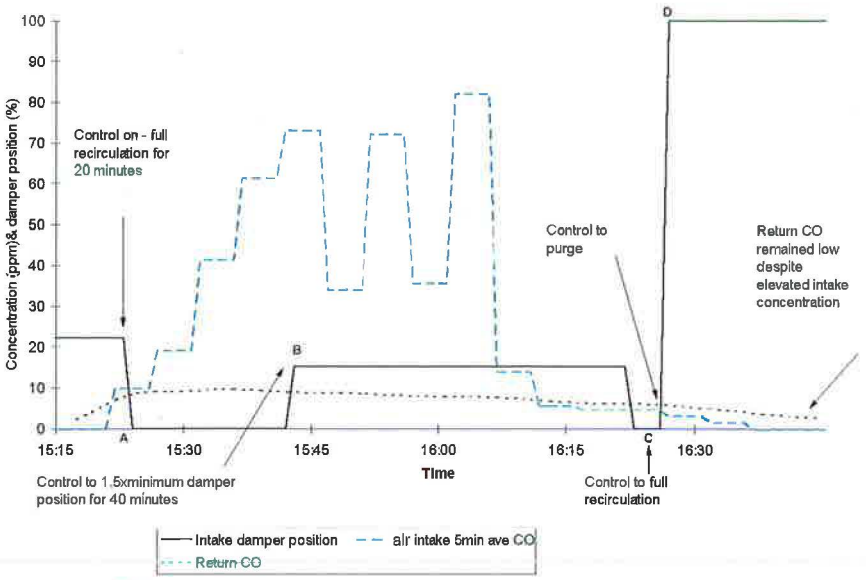


Figure 8
Control Strategy 1 test



Source: BSRIA Test Building

STRATEGY 2: CO SENSOR IN THE AIR INTAKE (INCLUDING CALCULATION OF THE MAXIMUM BENEFICIAL CONTROL PERIOD)

S2.1 STRATEGY 2 CONTROL CRITERIA

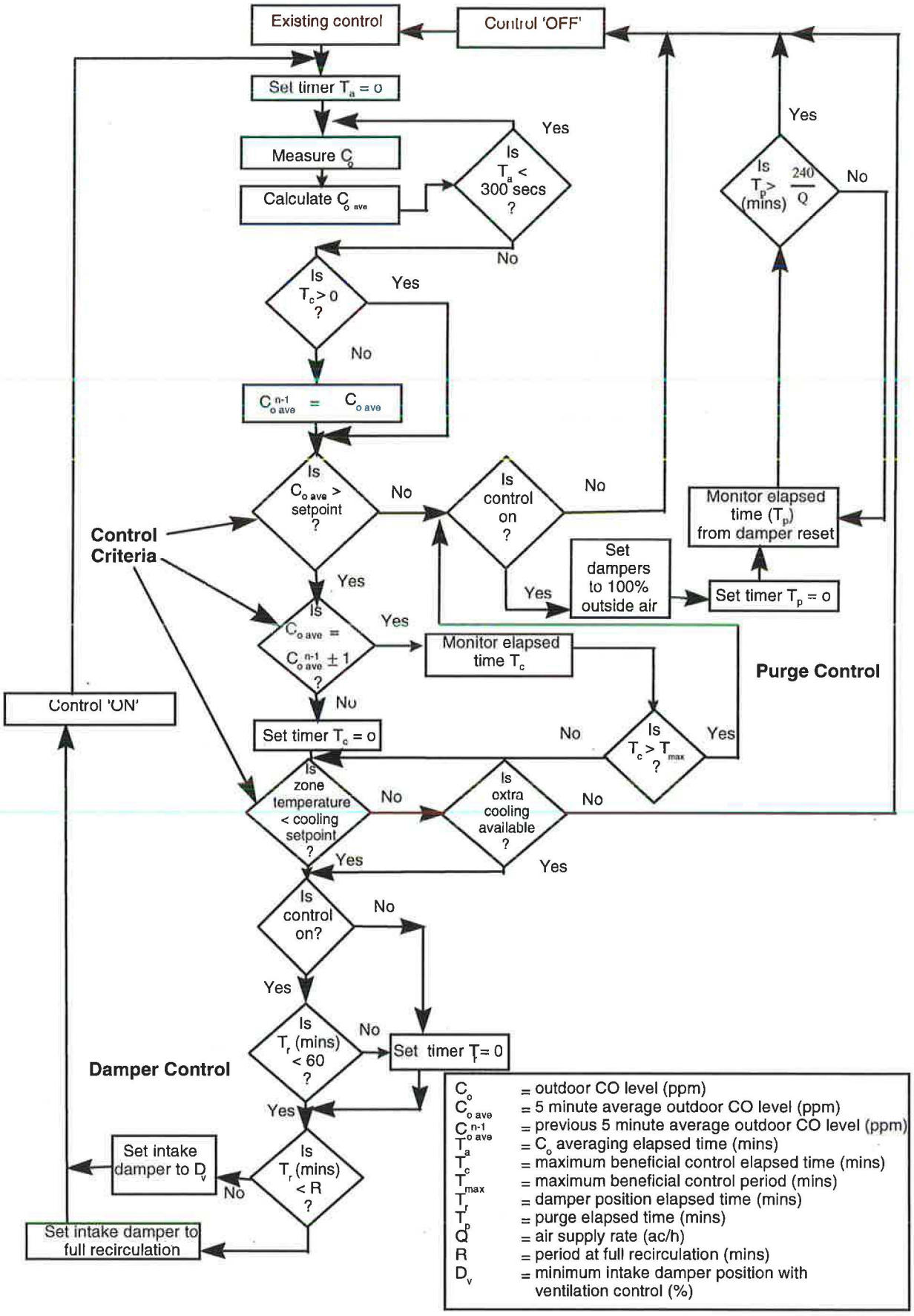
Control Strategy 2 is similar to Strategy 1. A CO sensor is installed in the air intake and the control activation, operation and deactivation are the same, however, this strategy also calculates whether it is worthwhile continuing the control during an extended pollutant episode. The indoor concentration will eventually approach that outdoors, regardless of control, and therefore extra control steps are applied to account for this. Strategy 2 includes a calculation of the length of time that it will be worth continuing the control. This period is termed the 'maximum beneficial control period'.

The control is set up to store a 5 minute average outdoor CO reading and compare it to successive readings. If they are similar (within ±1 ppm) a timer starts. The timer continues providing each new 5 minute average outdoor concentration is within ±1 ppm of that when the timer started. When the timer exceeds the maximum beneficial time (as calculated in Section S.2.2), the control strategy deactivates and normal temperature/enthalpy control is resumed. If any 5 minute average outdoor concentration is outside ±1 ppm of that when the timer started, the timer stops and is reset to zero and the next 5 minute average reading is stored. Table 3 outlines the control criteria for Strategy 2 and a control logic flowchart is shown in Figure 9.

Table 3
Strategy 2 control criteria

Parameter	Criteria
Sensor location	Air intake
Control check interval	5 minutes
Control setpoint	4.5 ppm with ±0.5 ppm deadband
Control on	5 ppm
Control off (1)	4 ppm
or Control off (2)	Elapsed time with stable outdoor CO > maximum beneficial control period (see section 5.2.2)
Sensor control parameter	5 minute average outdoor CO

Figure 9 Strategy 2 control logic



S2.2 CALCULATION OF MAXIMUM BENEFICIAL CONTROL PERIOD

The maximum beneficial control period is dependent on air supply rate, minimum damper position and period at full recirculation and must be manually calculated prior to configuration in the control strategy. The following steps should be followed in order to calculate the maximum beneficial control period:

Step 1- Calculate the minimum damper position with ventilation control (this is dependent on the control period at full recirculation):

$$D_v = \frac{D_e x 60}{(60 - R)}$$

D_e = Minimum intake damper position with existing control (%)
D_v = Minimum intake damper position with ventilation control (%) [for Table 4]
R = Period at full recirculation in any one hour with ventilation control (mins) (typically 20 to 40 mins).

Step 2 - Select control criteria for maximum beneficial period, ie should C_i (indoor pollutant concentration) equal 90%, 95% or 98% of C_o (outdoor pollutant concentration) before the control deactivates? Look up the maximum number of supply air changes (N) in Table 4 using the control criteria selected (90%, 95%, or 98%) and D_v.

Table 4
Maximum supply air changes

Intake damper position [Ref D_v] (%)	Supply air changes (N) for C_i=90%C_o	Supply air changes (N) for C_i=95%C_o	Supply air changes (N) forC_i=98%C_o
8	28.78	37.44	48.90
10	23.02	29.95	39.11
12	19.19	24.96	32.60
14	16.44	21.39	27.94
16	14.39	18.72	24.45
18	12.79	16.64	21.73
20	11.51	14.98	19.56
25	9.21	11.98	15.64
30	7.67	9.98	13.04
35	6.58	8.55	11.17
40	5.75	7.49	9.78
45	5.11	6.65	8.69
50	4.60	5.99	7.82
60	3.84	4.99	6.52
70	3.29	4.28	5.58
80	2.88	3.74	4.89
90	2.56	3.33	4.34
100	2.30	3.00	3.91

STRATEGY 3: CO SENSOR IN THE AIR INTAKE (INCLUDING CALCULATION OF THE INDOOR CO CONCENTRATION)

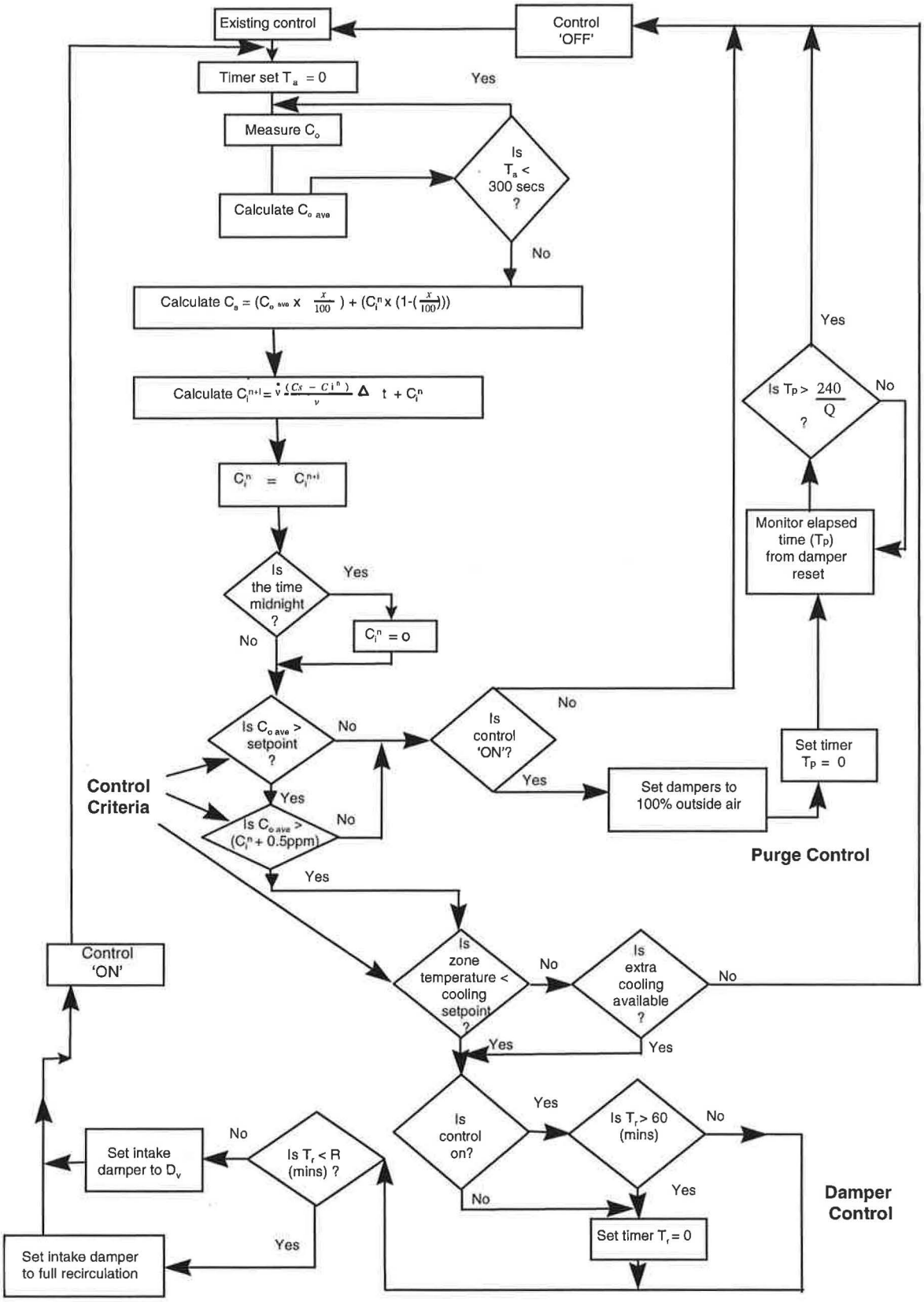
S3.1 STRATEGY 3 CONTROL CRITERIA

Control Strategy 3 is similar to Control Strategy 1 in terms of CO sensor location, control activation and operation criteria (See Section S1). The deactivation criteria are also the same with the exception that Strategy 3 includes a calculation of indoor CO concentration. The calculation of indoor CO allows a determination of whether it is beneficial for the control to continue. The 5 minute outdoor average concentration is compared with the calculated indoor concentration and if the indoor level approaches that outdoors (within 0.5 ppm) the control operates the purge cycle. Table 5 outlines the control criteria for Strategy 3 and a control logic flowchart is shown in Figure 11.

Table 5
Strategy 3 control criteria

Parameter	Criteria
Sensor location	Air intake
Control check interval	5 minutes
Control setpoint	4.5 ppm with ±0.5 ppm deadband
Control on	5 ppm
Control off (1)	4 ppm
or Control off (2)	Calculated indoor CO + 0.5 ppm > = 5 minute average outdoor CO
Sensor control parameter	5 minute average outdoor CO

Figure 11 Strategy 3 control logic



Strategy 3
Control logic flow chart legend

C_o	=	outdoor CO level (ppm)
$C_{o\ ave}$	=	5 minute average outdoor CO level
T_a	=	C_o averaging elapsed time (mins)
T_r	=	damper position elapsed time (mins)
T_p	=	purge elapsed time (mins)
Q	=	supply rate (ac/h)
R	=	period at full recirculation (mins)
D_v	=	minimum intake damper position with ventilation control (%)
C_i^n	=	indoor concentration at start of timestep (ppm)
C_i^{n+1}	=	indoor concentration at end of timestep (ppm)
C_s	=	supply concentration (ppm)
Δt	=	timestep(s) (select minimum permitted by the BMS)
$\dot{v}$	=	supply air flow rate (m^3/s)
v	=	volume of zone (m^3)

S3.2 CALCULATION OF INDOOR CO CONCENTRATION

The algorithms to calculate the indoor pollutant concentration are shown below. The outdoor concentration and damper position are inputs from the BMS and, although relatively complex, these algorithms can be included in a BMS configuration. The supply concentration is calculated from the indoor concentration, outdoor concentration and the proportion of outdoor air:

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

C_s = Supply CO concentration (ppm)
C_o = Outdoor CO concentration (ppm)
C_i^n = Indoor CO concentration at start of timestep (ppm)
X = Outdoor air proportion (%).

The BMS can apply this algorithm by breaking down the calculation into a series of simple steps, eg X/100. A similar procedure can be applied to the calculation of the new C_i concentration [Refs 9,10].

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

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) (minimum permitted by the BMS), eg 5 seconds
$\dot{V}$ = supply air flow rate (m^3/s)
V = volume of zone (m^3).

The calculation of C_i assumes no internal sources or sinks, a linear relationship between damper position and airflow and perfect mixing in the zone. These assumptions will inevitably lead to some drift and to minimise this, C_i is reset to zero each day at midnight.

S3.3 STRATEGY 3 IN ACTION

Figure 12 shows Control Strategy 3 operating in a test building and demonstrates the following facets of the strategy (A to G are points on the graph from left to right):

A. Control activation when outdoor average CO exceeded 5 ppm. Intake damper moved to full recirculation.
B. Intake damper moved to 1.5 times minimum position when period at full recirculation exceeded 20 minutes.
C. Intake damper moved to purge (100%) when calculated indoor CO exceeded average outdoor CO (outdoor CO still above 5 ppm setpoint).
D. Intake damper moved to full recirculation when average outdoor CO exceeded calculated indoor CO.
E. Intake damper moved to purge (100%) when calculated indoor CO exceeded average outdoor CO (outdoor CO still above 5 ppm setpoint).
F. Intake damper moved to full recirculation when average outdoor CO exceeded calculated indoor CO.
G. Intake damper moved to purge (100%) when average outdoor CO fell below 4 ppm.

Note that the calculated indoor CO deviates from the actual concentration when the intake damper is switched to 15%. The calculation assumed 15% outdoor air flow but the results indicate that the damper was actually still shut. This highlights the importance of an accurate assessment of the relationship between intake damper position and actual air flow if the calculated indoor concentration is to match the actual one.

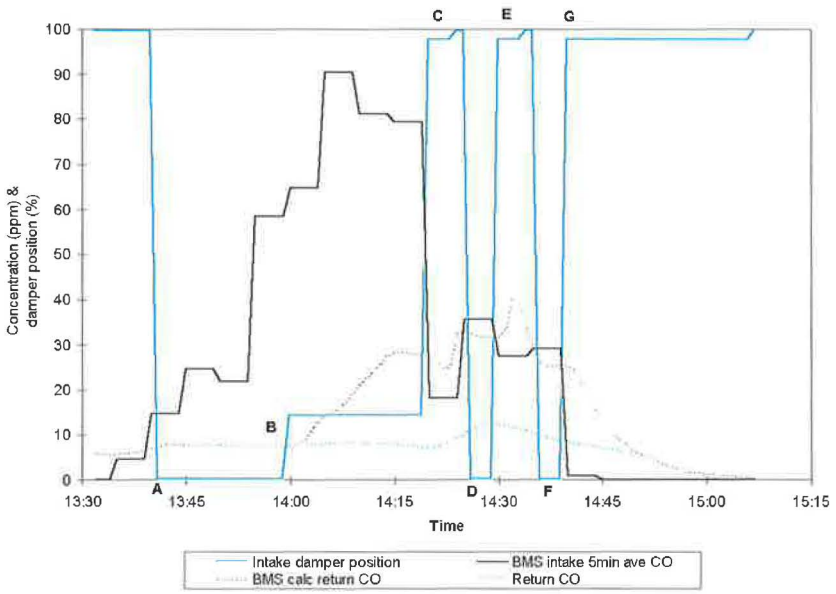


Figure 12
Control strategy 3 test

Source: BSRIA Test Building

STRATEGY 4: CO SENSOR IN THE ZONE OR RETURN AIR

S4.1 STRATEGY 4 CONTROL CRITERIA

An alternative to a sensor in the air intake is one located in the occupied space or return air. This strategy has the advantage that the CO concentration in the indoor air is measured directly and it will indicate if the indoor air pollution level is worse than that outdoors (indoor concentration will start to fall). However, it is slower to react to the start and end of pollution episodes than a sensor in the air intake and allows pollutants to build up before activating.

The control is triggered in a similar manner to Strategy 1 (see Section S.1) with the same 5 ppm setpoint as the other strategies and remains activated as long as the air quality continues to deteriorate. If the indoor air quality improves it is an indication that the outdoor air quality has also improved and the control stops. The control checks the concentration at 5 minute intervals and compares the current reading with the previous one. If the previous reading is more than 0.5 ppm above the current one the system switches to the purge cycle (this occurs even if the concentration is still above 5 ppm). At the end of the purge the system will reactivate the control if the concentration is still above 5 ppm. Table 6 outlines the control criteria for Strategy 4 and a control logic flowchart is shown in Figure 13.

Table 6
Strategy 4 control criteria

Parameter	Criteria
Sensor location	Return air
Control check interval	5 minutes
Control setpoint	4.5 ppm with ±0.5 ppm deadband
Control on	5 ppm
Control off (1)	4 ppm
or Control off (2)	Indoor CO + 0.5 ppm < = Last indoor CO reading (5 minutes previously)
Sensor control parameter	Instantaneous reading

Figure 13 Strategy 4 control logic

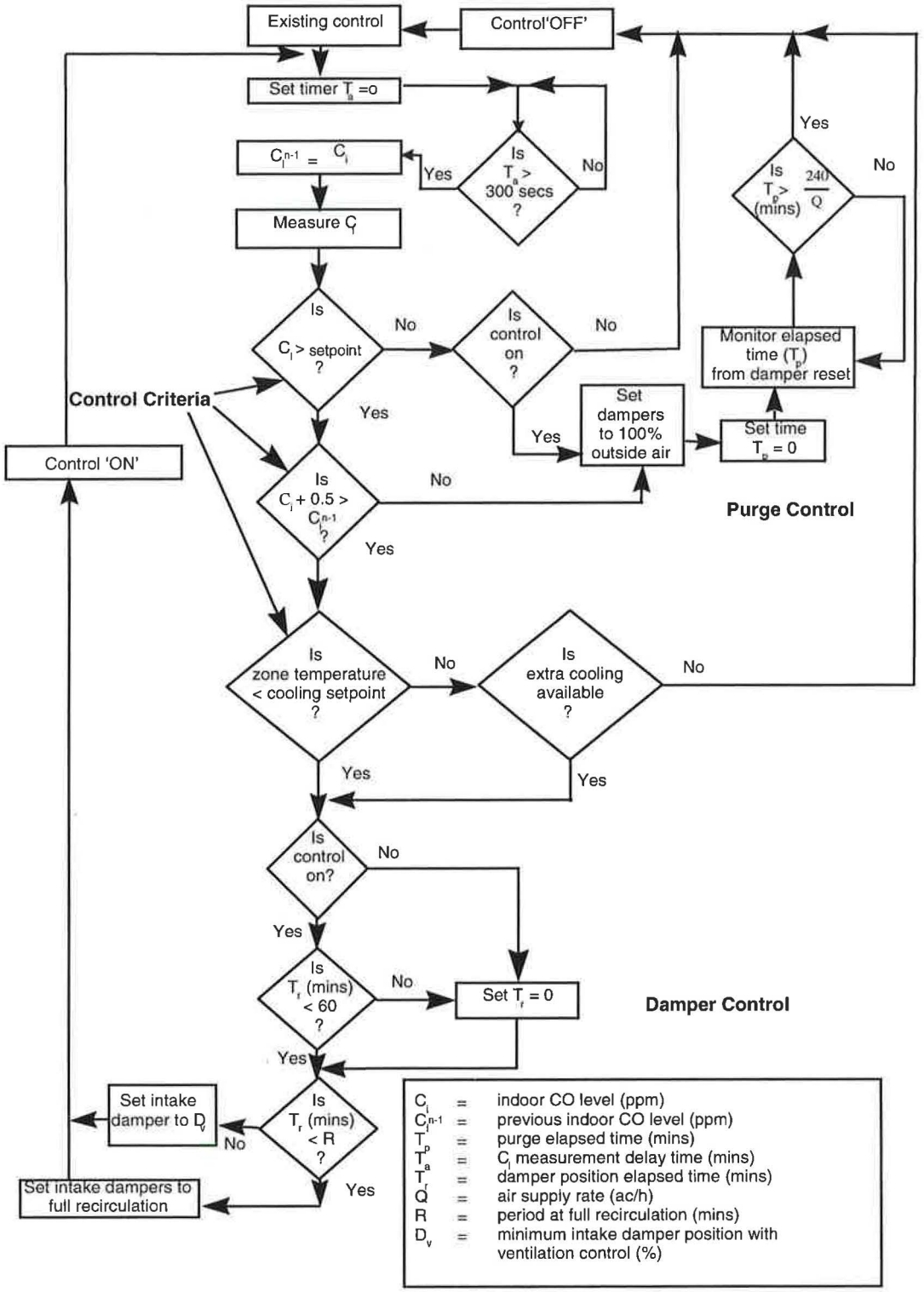
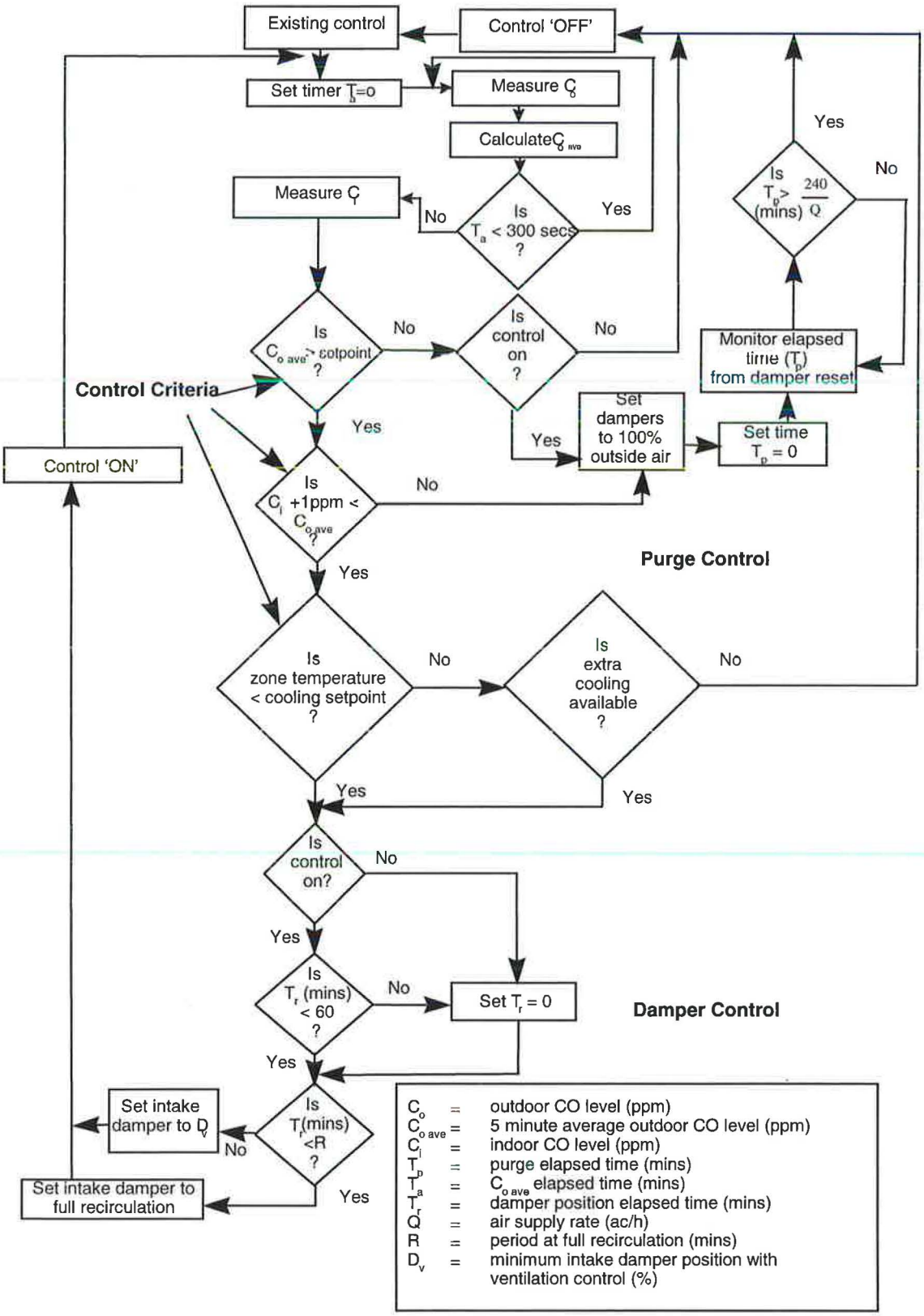


Figure 15 Strategy 5 control logic



S5.2 STRATEGY 5 IN ACTION

Figure 16 shows the results of a Control Strategy 5 in a test building and demonstrates the following facets of the strategy (A to G are points on the graph from left to right):

A. Control activation when average outdoor CO exceeded 5 ppm. Intake damper moved to full recirculation.
B. Intake damper moved to purge (100%) when average outdoor CO fell below indoor CO.
C. Control activation when average outdoor CO exceeded 5 ppm and indoor CO. Intake damper moved to full recirculation.
D. Intake damper moved to 1.5 times minimum position when period at full recirculation exceeded 20 minutes.
E. Intake damper moved to purge when average outdoor CO fell below 4 ppm.
F. Purge for 27 minutes (4 air changes).
G. Intake damper moved to original position at the end of the purge period.

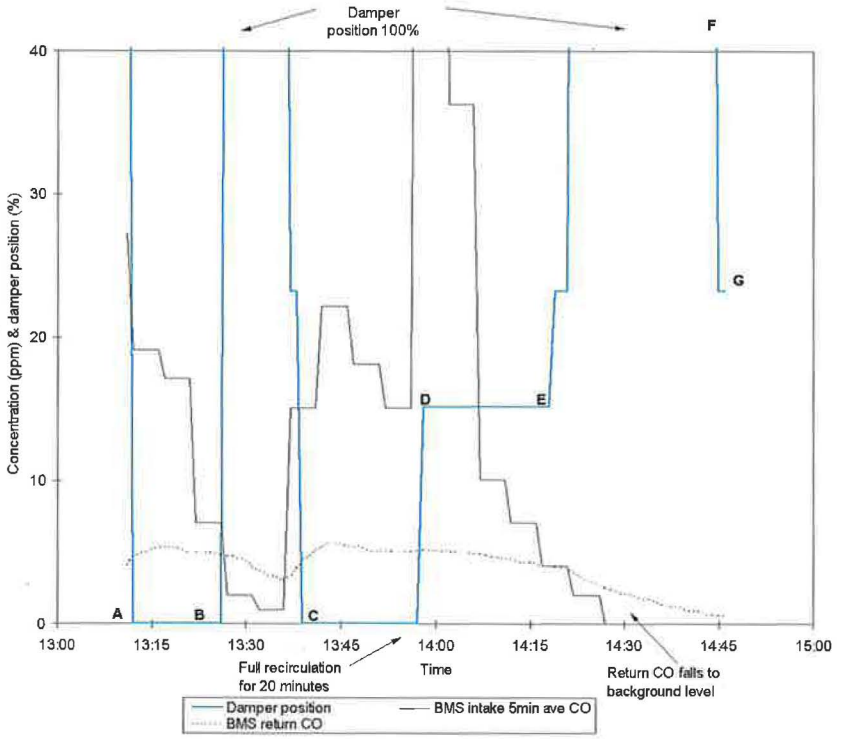


Figure 16
Control strategy 5 test

Source: BSRIA Test Building

STRATEGY 6: TIMECLOCK CONTROL

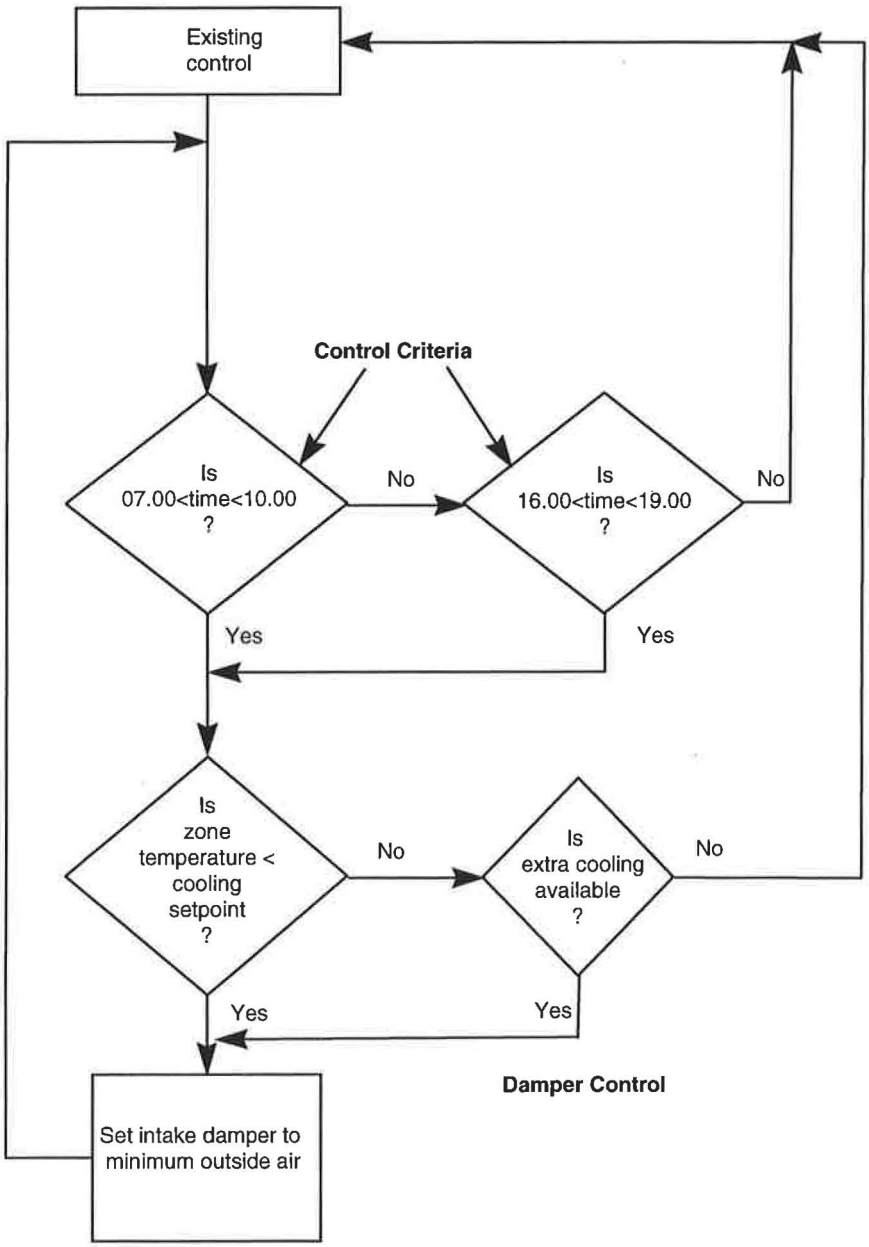
S6.1 STRATEGY 6 CONTROL CRITERIA

The use of a simple timeclock is an alternative to direct pollutant measurement but its application should be restricted to locations where pollutant concentrations are known to regularly exceed recommended limits. The ventilation control is enabled by a timeclock such that between fixed hours each weekday the system operates with minimum outside air. Analysis of local air pollution data may indicate which months, on average, result in the highest pollution loads and the control can then be restricted to those periods. The advantages compared to other controls are low cost, simple, minimum BMS configuration, no demands on outstation inputs/outputs and no additional sensors (purchase cost, installation, calibration). The main disadvantage is that this is an open loop control with no feedback, ie the system will operate regardless of whether it is required. Table 8 outlines the control criteria for Strategy 6 and a control logic flowchart is shown in Figure 17.

Table 8
Strategy 6 control criteria

Parameter	Criteria
Sensor location	-
Control check interval	Instantaneous
Control setpoint	-
Control on (1)	07.00 (Monday to Friday)
Control off (1)	10.00 (Monday to Friday)
Control on (2)	16.00 (Monday to Friday)
Control off (2)	19.00 (Monday to Friday)
Sensor control period	-

Figure 17 Strategy 6 control logic



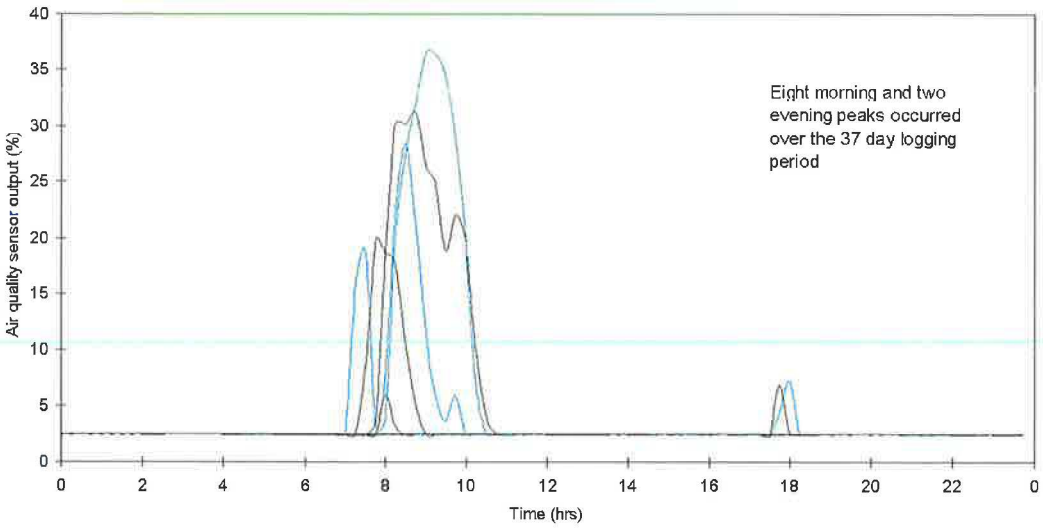
STRATEGY 7: a AND b - VENTILATION CONTROL USING EXISTING AIR QUALITY SENSORS

In certain circumstances it may be feasible to use existing air quality sensors to indicate when outdoor air quality is poor. This generally applies to mixed gas IAQ sensors (Strategy 7a) or CO_2 sensors (Strategy 7b).

S7.1 STRATEGY 7a CONTROL CRITERIA (EXISTING IAQ SENSORS)

Mixed gas sensors measure a cocktail of gases including pollutants that are both generated outdoors and indoors. Therefore, if an existing mixed gas sensor in a zone or return air is reading a high value it could be due to pollutants originating from indoors, outdoors or a combination of both. The typical control response to a high sensor output is to call for more outside air but this could potentially compound the problem if the main source of pollutants is outdoors. Figure 18 shows an example IAQ sensor output from a test building where air intakes are at low level near a busy dual carriageway. When sensor peaks occur they coincide with rush hour periods, indicating that outdoor pollution may be the source of the problem.

Figure 18 Example IAQ sensor output for 37 days (March-April 1997)



Source: BSRIA Test Building

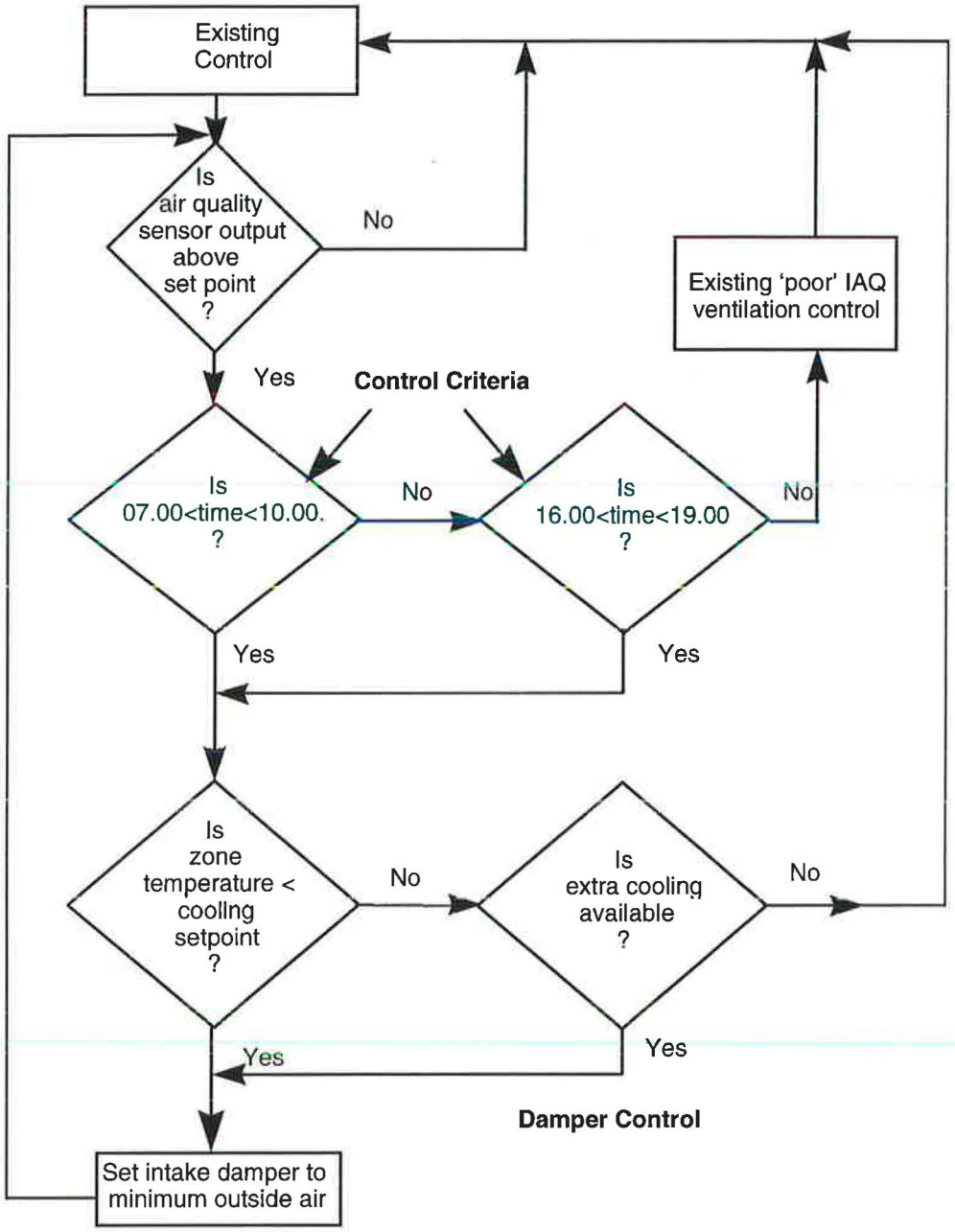
It is possible to assess whether the sensor is registering outdoor pollutants by logging the IAQ sensor output over a few weeks. If the sensor generally records increasing values throughout the day, with perhaps a dip at lunchtime, it is likely that occupant related pollutants dominate. Alternatively, an increase overnight when the plant is off indicates off-gassing of materials is significant. However, where sensor peaks occur at the rush hour times and last for a couple of hours it is likely that outdoor pollution is being sensed. If this is the case the controls can be modified such that the existing ventilation control is limited to core periods outside rush hours. The same setpoint is used but the response is different for different times of the day (see Table 9).

Table 9
Ventilation control strategy using existing IAQ sensors

Time	Control action if poor air quality is sensed
07.00-10.00	Minimum outdoor air proportion
10.00-16.00	Increase outdoor air proportion (existing control setpoint/actions)
16.00-19.00	Minimum outdoor air proportion

Following the control alterations the IAQ sensor output should be logged again to determine whether the size and frequency of peaks has reduced and, if there is an improvement, the new control can continue to be used. It is impossible to determine with absolute confidence what pollutants IAQ sensors react to at any one time but the above method will help determine whether outdoor air quality is a factor. Figure 19 shows the control logic for Strategy 7a.

Figure 19 Strategy 7a control logic



S7.2 STRATEGY 7b CONTROL CRITERIA (EXISTING CO_2 SENSORS)

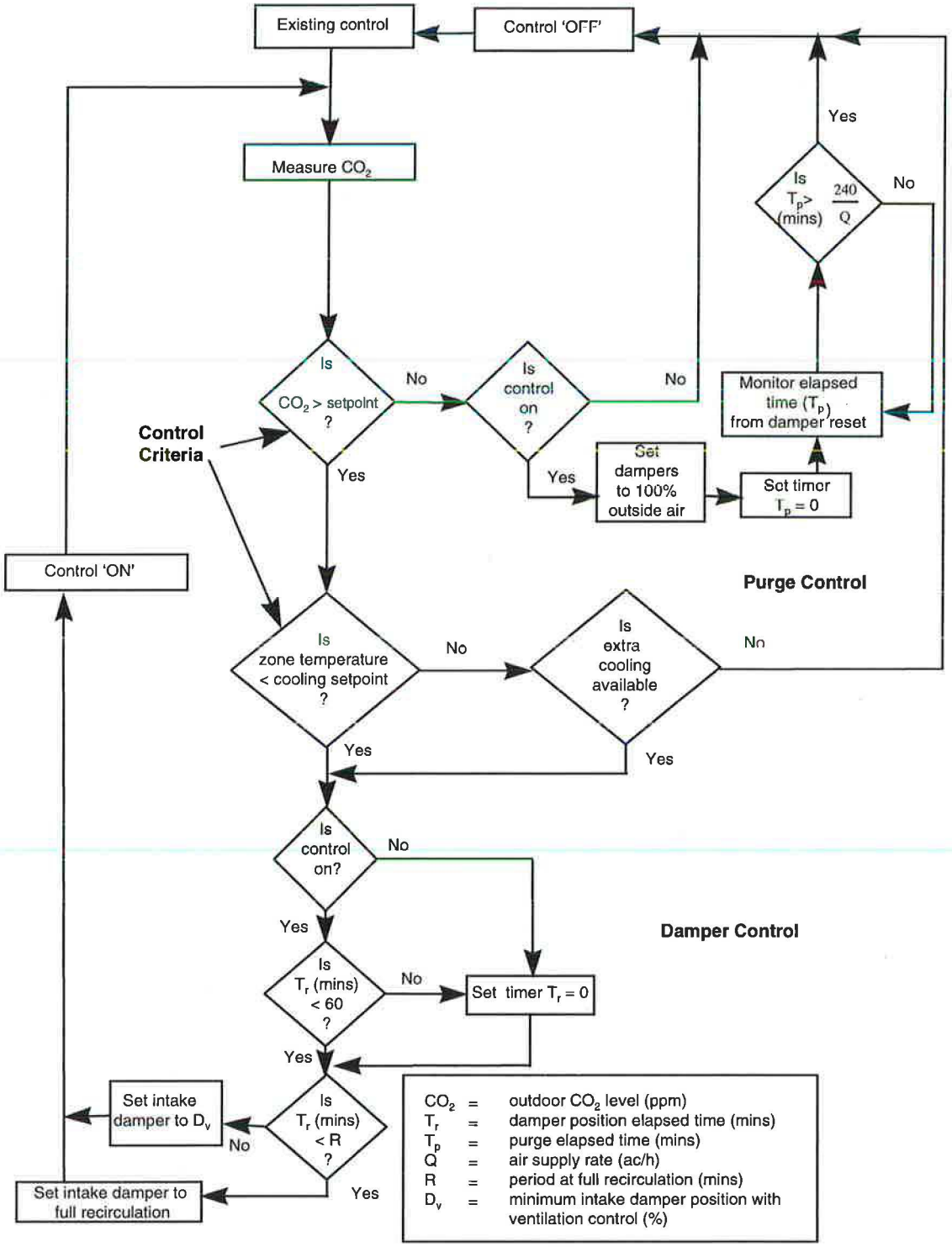
If indoor and outdoor CO_2 sensors are already used to control ventilation it may be possible to use the outdoor sensor as an indication of outdoor air quality. One study [Ref 11] recommended that outdoor CO_2 sensor output is monitored for a week and, if the concentration fluctuates by at least 300 ppm, it has potential as an indicator of traffic related pollutants. The control can then be set up to override the existing CO_2 control if the outdoor CO_2 exceeds 700-800 ppm and shut off for a short period or to minimise ventilation until CO_2 falls below 600 ppm. Although outdoor CO_2 is potentially a measure of traffic pollution, in most situations it is unlikely that it will show enough fluctuation to be worthwhile (see Figure 2). Table 10 details the control criteria for strategy 7b whilst Figure 20 shows the control logic. Note that "volume" can be substituted for "damper position" in Figure 20.

Strategy 7b provides the same damper control as the other Strategies, ie maintaining minimum outdoor air over a one hour period. However, directly measuring internal CO_2 provides an opportunity for more accurate control. The damper is initially set to full recirculation but is then trimmed as the internal CO_2 concentration rises to an unacceptable level.

Table 10
Strategy 7b control criteria

Parameter	Criteria
Sensor location	Air intake
Control check interval	5 minutes
Control setpoint	650 ppm with ±50 ppm deadband
Control on	700 ppm
Control off	600 ppm
Sensor control parameter	Instantaneous

Figure 20 Strategy 7b control logic



PROJECT METHODOLOGY

The development of ventilation control strategies was achieved by a combination of literature review, consultation, computer modelling and site assessment.

LITERATURE REVIEW

The literature review included database searches and an investigation of conference proceedings and relevant journals:

- There were searches of the IBSEDEX and Airbase databases, followed by a review of the relevant articles.
- The proceedings of twelve IAQ conferences were reviewed for relevant articles.
- Recent editions (last two years) of two relevant journals were reviewed (Indoor Air and Indoor Environment).

The literature review provided some good background information including urban pollution, air quality standards and potential control strategies as follows:

- The source of many urban pollutants is traffic and a good correlation exists between pollutants such as CO, NOx and PAH. The correlation is important to potential ventilation control as an assessment can be made of 'overall' pollution by only measuring one pollutant, thereby reducing the complexity and cost of controls.
- Several pollutants have a diurnal variation with peaks occurring at the two rush hour periods. This variation is also important to potential ventilation control because the technique is only a solution for short term pollution problems and is not effective over extended periods.
- The air quality limits specified by UK Government, European Union, WHO and ASHRAE were compared and found to be very similar and the WHO one hour limits were initially adopted as potential control setpoints. The only pollutant which was practical to measure was CO (see *Consultation*).
- The WHO one hour limit for CO is 25 ppm. The UK Government network of air quality monitoring stations show that 25 ppm is not exceeded at any site. Therefore it is very unlikely that a setpoint based on this limit would ever be activated. Other pollutants, such as NOx are likely to be a problem but cheap sensors are not accurate enough to measure ambient concentrations (see *Consultation*). The solution was to measure CO but fix the setpoint at a level that indicates other pollutants are too high. Analysis of pollution data indicated that NOx will be unacceptable if the CO concentration exceeds 5 ppm. This was confirmed by two publications that stated that a CO concentration of 5 ppm or 3 ppm indicated the air quality was poor. Therefore a 5 ppm CO limit was adopted as the control setpoint.

- Having established how to initiate the control it was necessary to determine the control procedure once activated. ASHRAE Standard 62 was under revision and the new draft included a section on ventilation systems that operate intermittently. It stated that intermittent ventilation was acceptable providing that the average over a one hour period was at least minimum ventilation. Although the draft standard as a whole was eventually rejected, this section did provide the concept of how the ventilation control could proceed once activated. If poor outdoor air quality is sensed, the most effective control is to block the ingress, ie switch the ventilation off or operate full recirculation. However this can only apply for a short period before internally generated pollutants will become unacceptable and therefore the measures suggested in draft ASHRAE Standard 62 were adopted as an appropriate compromise.
- One article reviewed demonstrated the rate at which an indoor pollutant will equal that outdoors if 100% outside air is applied and this provided the procedure for switching off the ventilation control. During ventilation control there will always be some pollutant ingress because minimum ventilation must be maintained and therefore at the end of a pollutant episode it is possible that the indoor concentration may exceed that outdoors. The solution is to purge with 100% outside air to equalise the indoor and outdoor levels. A purge also has the additional benefit of removing internally generated pollutants. The article previously mentioned indicated that 4 air changes at 100% outside air was enough to equalise indoors and outdoors and therefore the ventilation control included a purge, based on this period, when it switched off.
- The above shows that the literature review provided much of the raw information on potential ventilation control (Strategies 1 to 5) including how to initiate the control, how to control when 'on' and what to do in the switch-off cycle.
- One of the publications reviewed included details of a ventilation control strategy for demand controlled ventilation (DCV) systems based on CO_2 measurement. It was suggested that the outdoor sensor could also be used an indicator of poor air quality and this strategy is included as a potential option (Strategy 7b).

CONSULTATION

There was an extensive consultation exercise at the beginning of the project:

- Contact was made with a range of sensor and analyser manufacturers to allow a comparison of potential control sensors.
- A questionnaire was developed that included some of the control techniques from the literature review and general questions about ventilation control and sensors. This was sent to ten control companies, twelve systems houses, three researchers and three consultants.
- A message requesting information was posted on an internet building services interest group notice board.

The consultation contributed to the strategy development as follows:

- The consultation exercise demonstrated that there was a general lack of knowledge on the application of this ventilation control technique and that the pollutant sensors currently supplied by control companies were not appropriate.
- The investigation of sensing techniques indicated that pollutant analysers were too expensive and sensitive to external conditions to be appropriate for ventilation control. An alternative was industrial sensors and these were found to be available for a range of gases and in both infrared and electrochemical cell types. The infrared cells, although more accurate than electochemical cells, were generally too expensive for building services applications. Although the sensors were available for a number of gases, the range and accuracy of both cell types was not appropriate for typical ambient air levels. Most pollutant concentrations are in ppb in ambient air whilst the cells measure in ppm level because they are aimed at industrial applications. The only pollutant cell type that matched all requirements was an electrochemical CO cell, although the accuracy was not ideal.
- The internet request resulted in some interesting responses, with one suggesting a simple timeclock control and this was adopted as one of the control options (Strategy 6). An analysis was carried out on the average summer and winter pollution data from eighteen Government automatic monitoring sites to establish the optimum control period.
- A spreadsheet model was developed that calculated the evolution of a pollutant concentration indoors (Ci) when the pollutant originated outdoors (Co). The model was based on algorithms from the literature review[Ref 9] and calculated the change in Ci at 1 second timesteps from Co, damper position and the air supply rate. The model also included the evolution of internal CO_2 concentration which was used as an indication of the build up of internally generated pollutants.

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

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

C_s = supply concentration (ppm)
C_o = outdoor concentration (ppm)
X = air intake damper position (%)
C_i^n = indoor concentration at start of timestep (ppm)
C_i^{n+1} = indoor concentration at end of timestep (ppm)
Δt = timestep(s)
$\dot{V}$ = supply air flow rate (m^3/s)
V = volume of zone (m^3).

- The model assumptions were - perfect mixing in the space, net pollutant sources and sinks are zero and a linear relationship between damper position and airflow.
- The model allowed tests to be carried out with and without ventilation control for a number of different variables:
  * air change rate
  * air intake damper position
  * CO_2 background and internal start concentration and metabolic release rate
  * outdoor pollutant concentration, length of pollutant episode and concentration profile
  * pollutant control setpoint with control sensors outdoors, indoors or both indoors and outdoors
  * with or without an internal CO_2 setpoint.

The model confirmed:

- the potential rate at which indoor pollution from an outdoor source can build up (less than 15 minutes) highlighting the need for control.
- a purge with 100% outside air for a period equivalent to 4 air changes will ensure that indoor and outdoor pollutant levels are equal (to within 2%).
- the rate at which CO_2 concentration builds up when the system is operated on full recirculation.
- the advantages and disadvantages of the different potential sensor locations used in Strategies 1, 4 and 5 (see Figure 5).
- the potential problems from extended pollution episodes. This indicated the need for more complex strategies (Strategies 2 and 3). The model was also used in the development of Control Strategy 2 which includes an assessment of whether it is beneficial to continue ventilation control when there is an extended pollution episode. A number of different intake damper positions were modelled and the period (in terms of supply air changes) that it took the internal pollutant concentration to attain 90%, 95% and 98% of that outdoors was collated (see Table 4). These results could then be used to determine the maximum period that it would be beneficial to continue control if an extended pollution episode occurred.

SITE ASSESSMENT

The site assessment was divided into four parts - BMS configuration and validation, short term monitoring of pollutants from AHU air intakes, control strategy tests using intake air 'seeded' with CO, control strategy tests with no 'seeding'.

Short term pollutant monitoring

- Short term air quality monitoring of one or two weeks was performed in the air intakes of six buildings. Each building was selected for its urban location and the proximity of the air intakes to a busy road. The pollutants measured were:

Pollutant	Analyser	Technique
CO, CO_2, Hexane	Bruel & Kjaer type 1302	Photoacoustic infra-red spectroscopy
PAH	Matter LQ1 air quality monitor	Photoionisation

- Figure 2 shows an example day from one of the test buildings.

Control strategy tests using air intake 'seeding'

- It was not practical, or in some cases even feasible, to test the strategies on-site by configuring and then validating each one separately. To overcome this problem the project used its own BMS outstation. This was configured with the strategies and each strategy was validated prior to the site work. The configuration was set up with an analogue output that was equivalent to the intake damper position calculated by the strategies. There was also a digital output used to enable the strategies. These two outputs were then connected the BMS on site. The only configuration required on site was a 'gate' between the existing damper signal and the actuators. The gate had inputs of the existing damper signal and that from the strategy outstation and the digital signal was used to tell the gate which signal to accept. The only other work was to set up the site BMS to accept the analogue input from the strategy BMS.
- One building from the short term monitoring was used for site assessment of the strategies. The building had a lecture theatre, served by a dedicated AHU, and this was used for the test work.
- A procedure was devised to test the strategies on site by 'seeding' the air intake with CO. CO was introduced into the intake via a number of injection points and the injection rate was varied manually to maintain approximately 10 ppm to 20 ppm in the intake. This test procedure served two purposes, firstly it allowed the strategies to be assessed under controlled conditions and secondly it ensured that results were achieved as the use of the controls depended on poor air quality which could not be guaranteed.
- A Binos CO/CO_2 infrared gas analyser was used to measure CO. The system had a valve box to allow multi-point sampling and it was set up to measure CO from the air intake and return air.
- The results of these tests are included in Figures 3, 8, 10, 12, 14 and 16.

Control strategy tests without air intake 'seeding'

- In addition to the seeding tests a number of longer term tests were carried out with the strategies operational and responding to actual air quality. These tests were performed in two buildings, one was that used for the 'seeding' tests and the other was selected from the air intake monitoring work. Strategies 1, 3 and 5 were tested in the original building and Strategy 1 in the second building.
- The following monitoring equipment was used:

Pollutant	Analyser	Technique
CO, CO_2, Hexane	Bruel & Kjaer type 1302	Photoacoustic infra-red spectroscopy
PAH	ETI PAS 2000	Photoionisation
NOx	Horiba APAN 350E	Chemiluminescence

- Unfortunately for the purposes of this project, the air quality was good during the tests at both sites, the 5 ppm CO setpoint was not exceeded and the controls did not activate. This was in stark contrast to the short term (one week) monitoring used to select potential buildings where CO peaked at 13 ppm in one of the two buildings and the setpoint was exceeded in all five buildings. This demonstrates the highly variable nature of urban pollution.

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