VENTILATION CRITERIA AND DESIGN FOR GOOD INDOOR AIR QUALITY

P.H. Appleby
Building Health Consultants Ltd., 42 Upper Grosvenor St., London W1X 0AP, U.K.

ABSTRACT

An overview of current recommendations for the provision of outdoor air for the comfort of occupants engaged in sedentary activities is presented. The relationship between odour control, effective ventilation and room air movement is explored, in the context of both mechanically and naturally ventilated buildings. The contribution that ventilation can make in the prevention of "sick building syndrome" and the relative importance of building and occupant dependant odour sources and maintenance are discussed.

INTRODUCTION

The average person will spend more than 90% of their time in an artificial environment of one sort or another. Much of this time is spent working in an office or a factory. In many countries expanding economies and centralisation of services have led to a concentration of office space in the cities. The cost of land has shaped buildings into deep-plan high-rise structures. The cost of materials and the popularity of mirror glass has led to the sprouting of hundreds of "glass boxes" in the world's city scapes.

These boxes are sealed to keep out noise and pollution - mainly from traffic - and access to a window has become associated with status. Hence clerical staff, vdu operators and other junior personnel are relegated to the internal reaches of the building, whilst senior staff occupy individual offices at the perimeter.

Frequently the perimeter offices suffer from environmental problems associated with solar gain or draft, whilst the densely light absorbing mirror glass can give the impression of winter in summer and dusk during day.

Regardless of whether buildings are sealed their occupants require a continuous provision of outdoor air in order to ensure that the inhaled air does not reach an unacceptably high odour level. "Unacceptably high" is usually defined as a level above which 20% or more of the occupants are dissatisfied. The North

American standard "Ventilation for Acceptable Indoor Air Quality"(1,2) uses this level of dissatisfaction in its definition of acceptable indoor air quality . A more elaborate model for acceptable indoor air quality may be evolved by combining this concept with the World Health Organisation's basis for establishing comfort guideline values for individual chemicals (3). Thus, indoor air quality may be said to be "acceptable" if less than 50% of the occupants can detect any odour, less than 20% experience discomfort, less than 10% suffer from mucosal irritation and less than 5% experience annoyance for less than 2% of the time.

The quantity and quality of outdoor air introduced to the space must be compatible with these aims. It is the quality of the air in the breathing zone of the occupants which is important, hence it must be introduced in such a manner that each occupant receives maximum benefit from the outdoor air which enters the buildings via windows or the external louvres of a ventilation plant.

ODOUR AND IRRITATION

Exposure to the constituents of non-industrial atmospheres usually involves exposure to a cocktail of thousands of substances all having relatively low concentrations compared to their occupational exposure limits. Typical individual concentrations are frequently in the order of one thousandth of the occupational exposure limit, or less (4).

The human nose is extremely sensitive to low concentrations of some chemical substances. For example it can detect 1 mgm^{-3} of Toluene (3), one of the most common of the volatile organic compounds (VOC's) to be found in the non-industrial atmosphere, whereas the ACGIH Threshold Limit Value, time weighted for a 40 hour working week, is 375 mgm^{-3}.

A substance which enters the nasal cavity may be sensed by two separate detection systems. The olfactory sense, which is responsible for odour detection, and the common chemical sense, which is sensitive to irritants. These two senses interact. For example it is possible for an odour to be disguised by irritation and vice versa (5). A single substance may evoke sensations of odour and irritation. Humans are known to adapt to odours with time, whereas irritation may be compounded with time (6,7). In the specific case of exposure to environmental tobacco smoke, a recent study (8) has found that irritation intensity increases by a factor of 2 during the first hour of exposure, after which steady state occurs. The same study found that perceived odour intensity fell off by a factor of 50% and levelled out after only a few minutes.

A lot of everyday occurrences result in the release of odours, some of which may be perceived as pleasant, some unpleasant. Some evolve from the release of potentially harmful substances, although it is not usual for exposure to airborne contaminants in non-industrial buildings to be associated with irreversible health

effects. Exceptions have be
gas - mainly in homes - and
Apart from the occupancy
tobacco smoke, most modern
such as organic compounds,
furniture, carpets, curtain
released from photocopiers
such as mould spores, and s
which are not removed by or
Because odour perception
difficult to measure. Olfac
trained panelists (9,10) bu
developed which accurately
Sensors are available which
quality. For example CO_2 se
indicative of the contribut
levels. Unfortunately odour
materials which do not emit
An "air quality" sensor
a semiconductor, the conduc
of gas adsorbed. Gases are
Unlike the nose, it cannot
of odour. Adsorption depend
volatility of the substance
related to the odour streng
isobutylpyrazine and ethan
0.00000054 ppm and 120,000 p
x 10^{11}. Whereas the adsorpti
are likely to be similar. In
air quality sensor calibrate
give a good indication of t
and vice versa.
Studies have indicated (
are at their lowest at humi
at normal comfort temperatu
nature of the contaminant.
many materials, such as pai
etc. tends to reduce with f
The adsorption of odours
subsequent desorption as te
pressures change, can lead
levels as conditions become
recent study (12) a panel c
the odour intensity in bars
occupants had left. On aver
higher in the bars once unc
primarily due to the desorp
smoke, which had been adsor
the particulate matter, du

effects. Exceptions have been thought to include exposure to radon gas - mainly in homes - and lead from emissions in vehicle exhaust.

Apart from the occupancy-dependant body odours and environmental tobacco smoke, most modern offices contain other odour sources, such as organic compounds, used in the manufacture and cleaning of furniture, carpets, curtains and the building fabric, ozone, released from photocopiers and laser printers, micro-organisms, such as mould spores, and some of the gaseous external pollutants which are not removed by ordinary dry fabric filters.

Because odour perception is highly subjective it is extremely difficult to measure. Olfactometers have been developed for use by trained panelists (9,10) but no automatic sensor has yet been developed which accurately simulates the response of the nose. Sensors are available which give an approximate indication of air quality. For example CO_2 sensors provide a signal which is indicative of the contribution of body odour to the overall odour levels. Unfortunately odours are also emitted by processes and materials which do not emit CO_2.

An "air quality" sensor adsorbs gases onto the porous surface of a semiconductor, the conductivity of which changes with the amount of gas adsorbed. Gases are alternately adsorbed and desorbed. Unlike the nose, it cannot distinguish between different potencies of odour. Adsorption depends on a number of factors, including the volatility of the substances. These factors are not directly related to the odour strength. For example 2-methoxy-3-isobutylpyrazine and ethane have odour detection thresholds of 0.00000054 ppm and 120,000 ppm respectively, a potency ratio of 2.2×10^{11}. Whereas the adsorption efficiencies of the two substances are likely to be similar. In more prosaic terms this means that an air quality sensor calibrated to respond to body odour would not give a good indication of the odour associated with tobacco smoke, and vice versa.

Studies have indicated (11) that general perceptions of odour are at their lowest at humidities in the range of 45 to 65%sat (rh) at normal comfort temperatures, although this varies with the nature of the contaminant. However the odour emission rate from many materials, such as paint, rubber, upholstery, floor coverings, etc. tends to reduce with falling humidity.

The adsorption of odours onto internal surfaces, and their subsequent desorption as temperature, air velocity and vapour pressures change, can lead to a considerable increase in odour levels as conditions become favourable for desorption. During one recent study (12) a panel of non-adapted people were asked to judge the odour intensity in bars during normal use and after all occupants had left. On average, odour intensities were judged to be higher in the bars once unoccupied. This was thought to be primarily due to the desorption of gaseous components of tobacco smoke, which had been adsorbed onto internal surfaces, along with the particulate matter, during occupancy.

It has been suggested (13) that for every occupant and associated odours in an air conditioned building, there could be up to 6 or 7 odour equivalents (olfs) associated with environmental tobacco smoke, building materials, furniture, mould spores and the internal components of the air handling system.

One study of eight air handling units (14) found that perceived odour intensity increased by an average of 0.81 decipol (0.19 - 1.67) through the units. Where 1 decipol is the odour intensity perceived by a trained panellist of the odours emitted by a standard person (1 olf) ventilated by 10 litres/s of odourless air.

Odours are released from the fungicides used to treat filter material and thermal wheels, as well as the lubricants and fan belts associated with motors and fans. Poorly maintained air handling systems release odours from accumulated dirt in filters and other internal surfaces. Bio-fouling of cooling coils, moisture eliminators and spray ponds is a particular problem.

This study (14) found that the filters were major polluters in nearly all of the ventilation systems examined, contributing 0.4 decipols on average. Two of the systems had thermal wheels and one a cross-flow heat exchanger which did not contribute to the perceived odour level in that system. The mean odour intensity for the three heat exchangers was 0.35 decipol. Three of the systems had inoperative spray humidifiers and one had a working steam humidifier which did not contribute to the perceived odour intensity. The mean odour intensity for the four humidifiers was 0.4 decipol.

VENTILATION

In recent years there has been a tendency to blame many of the complaints from people working in air conditioned office buildings on a lack of "fresh" air. Investigations (15,16) have shown that a perception of inadequate fresh air is frequently associated with lack of air movement, stuffiness, or the inability to open windows. There is usually very little correlation between the incidence of this complaint and the ventilation rate provided. Infiltration of outdoor air into naturally ventilated buildings in winter is frequently below recommended quantities, particularly for occupants working 5 or 6 metres from a window, yet SBS-related symptoms associated with these free-running buildings would appear to be less common than in the sealed air conditioned buildings. So just how important is "fresh" air? Should more attention be focussed on other aspects of air conditioned buildings, such as remoteness of some workers from a view or daylight, lack of personal control and prolonged vdu operation?

Outside air must reach certain minimum standards to be considered suitable for supply to occupants within a confined space. The new ASHRAE Standard (1) uses ambient air quality

standards produced by the U
basis for their definition
short term limits for commo
records shows that these ar
suitable air cleaning appar

Country	Application
UK	odour control light smoking heavy smoking v heavy smoking
USA	offices (some smoking) auditoria conference rms smoking lounges
Finland	office room open office smoking room
Sweden	non-smoking are smoking areas
Nordic C'ntries	non-smoking are smoking areas
FRG	general spaces
Italy	offices/conf. theatres restaurants
Japan	general spaces

Table 1 Fresh air requir

standards produced by the US Environmental Protection Agency as a basis for their definition of "fresh air". This specifies long and short term limits for common pollutants only. If examination of records shows that these are exceeded then it is recommended that suitable air cleaning apparatus be installed.

Country	Application	f.a rate	Source
UK	odour control light smoking heavy smoking v heavy smoking	8l/s/pers 16l/s/pers 24l/s/pers 32l/s/pers	CIBSE Guide (1986) Section B2: Vent'n & Air cond'g : Requirements
USA	offices (some smoking) auditoria conference rms smoking lounges	10l/s/pers 8l/s/pers 10l/s/pers 40l/s/pers	ASHRAE Standard 62-1989
Finland	office room open office smoking room	10l/s/pers 1l/s/m² 10l/s/pers 1.5l/s/m² 10l/s/pers	National building code of Finland: Indoor climate & vent'n in buildings (1987)
Sweden	non-smoking areas smoking areas	5l/s/pers 10l/s/pers	Swedish Building Code SBN 1988: Air Quality
Nordic C'ntries	non-smoking areas smoking areas	10l/s/pers 20l/s/pers	Nordic Building Regs 1989 (Prelim.)
FRG	general spaces	5.6-8.3l/s /m²	DIN 1946 Part 2 (DE6)
Italy	offices/conf. theatres restaurants	8.3-19.4 7-8.3 11-13.9 (l/s/pers)	Standard UNI-CTI
Japan	general spaces	CO<10ppm CO_2<1000ppm RSP<0.15mg /m³	Building Sanitation Management Standards Law

Table 1 Fresh air requirements of a number of countries

Exposure to CO_2 at low concentrations is not harmful to human health. An acceptable concentration is considered to be 2500ppm but it has been found that this level is not compatible with acceptable concentrations of odour emitting contaminants in the office environment (17). It is usual to work to a level of 1000ppm.

It can be estimated that a man standing quietly with a metabolic rate equivalent to 1.2met (1met = 58.5 Wm^{-2}) expires about 0.005 litres s^{-1} of CO_2. If the outside air contains 300ppm of CO_2, it can be shown that a dilution air flow rate of 2.3 litres s^{-1} would prevent the concentration in the room rising above 2500ppm, assuming perfect mixing. After the oil crisis of the 1970's a fresh air rate of 2.5 litres s^{-1} per person was adopted in North America as a minimum for sedentary activity with no smoking. At about the same time in the UK, CIBSE were recommending a minimum of 5 litres s^{-1} per person.

Chamber studies carried out in North America (17) and Denmark (18) have shown that these rates were inadequate when considering odour levels perceived by non-adapted people, and that the density of occupants has no bearing on fresh air requirements. Minimum fresh air requirements have been increased accordingly to 8 litres s^{-1} per person (see Table 1). These recommendations resulted also from concern over the incidence of ventilation-related problems in air conditioned buildings. These studies showed that there is a difference in perception between people entering a space and those who are acclimatised. Even with no smokers present, up to 40% of people entering a room supplied with 2.5 litres s^{-1} of air per person will be dissatisfied, whereas if 8 litres s^{-1} is available dissatisfaction was found to reduce to the acceptable level of 20%.

Unfortunately ventilation rate recommendations up to now, have not taken account of ventilation efficiency or odours released by the building and services. The new ASHRAE Standard (1) allows for the designer to calculate an appropriate ventilation rate from first principles. This "Indoor Air Quality Procedure" involves the calculation of a dilution or displacement ventilation rate, based on limiting concentrations for non-industrial exposure to contaminants and a prediction of the ventilation index. There is, however, a dearth of published limits for non-industrial exposure to contaminants.

Environmental Tobacco Smoke

Leaderer (17) has shown that allowances for environmental tobacco smoke (ETS) have also been inadequate in the past, particularly when catering for non-smokers entering the space. The issue is complicated by the fact that smoke evolves at a rapid rate and there may be high local concentrations the decay of which depend on room air movement. For low level supply systems smoke may rise vertically into the high level extract and dilution will occur at the central air handling unit, if recirculation is permitted. The plume will be very sensitive to cross-draughts from opening

doors, to the wakes genera
disturbances.
Leaderer found that, i
visitors to a space (i.e.
fresh air rate of 85m³ pe
takes 7.5 minutes to burn
in a large space may be s
of 17.5 litres s^{-1} should
The new ASHRAE Standar
a lower smoking rate than
change in US smoking habi
occupants. This results i
of tobacco smoke equal to
8 litres s^{-1} per person.
"office space", having a
14 m², is 10 litres s^{-1} pe
the minimum rate, such as
classrooms, are either of
contain smokers. Table 1
from the proposed ASHRAE
compared with recommendat
CIBSE recommendations
among non-adapted occupan
"some", "heavy" and "very
ventilation rates of 16,
respectively.
Fanger et al (13) foun
to the emission of odours
their panel being smokers
smoking rates.

Intermittent and Transito
For applications in wh
fleecy surfaces, cluttere
pre-dilution by bringing
the occupancy arrives. Fo
possible to hold back fre
are approaching unaccepta
The new ASHRAE Standard
the lead and lag times de
their fresh air allowance
to determine how long bef
particular ventilation ra
with overnight desorption
previous day, along with
sources. The nomogram is
rates for spaces with car
and ceilings. For example
and a fresh air rate of 16

doors, to the wakes generated by moving people, and to other disturbances.

Leaderer found that, in a room with perfect mixing, 75% of visitors to a space (i.e. non-adapted occupants) are satisfied if a fresh air rate of $85 m^3$ per cigarette is provided. If each cigarette takes 7.5 minutes to burn and if it is assumed that 10% of people in a large space may be smoking at any one time, a fresh air rate of 17.5 litres s^{-1} should suffice.

The new ASHRAE Standard uses a different approach (2), based on a lower smoking rate than used by Leaderer, to account for the change in US smoking habits, and satisfying 80% of adapted occupants. This results in a minimum ventilation rate for dilution of tobacco smoke equal to that required for odour dilution, i.e. 8 litres s^{-1} per person. However the fresh air rate proposed for "office space", having a maximum occupancy density of 1 person per 14 m^2, is 10 litres s^{-1} per person. The areas listed as requiring the minimum rate, such as auditoria, reception areas and classrooms, are either of a transitory nature or less likely to contain smokers. Table 1 gives selected recommendations extracted from the proposed ASHRAE "outdoor requirements for ventilation" compared with recommendations from other countries.

CIBSE recommendations are based on attaining 80% satisfaction among non-adapted occupants. They refer to rooms in which there is "some", "heavy" and "very heavy" smoking, corresponding with ventilation rates of 16, 24 and 32 litres s^{-1} per person respectively.

Fanger et al (13) found that a further 2 olfs were contributed to the emission of odours by cigarette smoking: this is with 30% of their panel being smokers, although they provide no information on smoking rates.

Intermittent and Transitory Occupancy

For applications in which odours are likely to accumulate, on fleecy surfaces, cluttered shelving etc.,it is useful to provide pre-dilution by bringing in the ventilation plant some time before the occupancy arrives. For rooms with smooth surfaces it may be possible to hold back fresh air provision until the odour levels are approaching unacceptable levels.

The new ASHRAE Standard (1) provides a technique for determining the lead and lag times depending on the room volume per person and their fresh air allowance. Nomograms are provided which can be used to determine how long before occupancy enter a space (lead time) a particular ventilation rate should be provided in order to deal with overnight desorption of contaminants adsorbed during the previous day, along with overnight outgassing from non-human sources. The nomogram is based on typical adsorption/desorption rates for spaces with carpets, soft furnishings, and textured walls and ceilings. For example, for an office density of $30 m^3$ per person and a fresh air rate of 16 litres/s per person a lead time of 2 hours would be required.

Similarly, for low emission spaces, containing minimal fleecy surfaces or shelving, it can be determined that the fresh air damper could be kept closed for 30 minutes (lag time) after occupants first enter, assuming the same density and fresh air allowance as above.

Control methods are available which can be used to adjust fresh air rate according to the prevailing contamination levels. The CO_2 or air quality sensors mentioned earlier can be installed in the space or in extract ductwork and arranged to adjust the mixing dampers or switch fans accordingly. These methods can be used to provide automatic control over lag and lead operation and adjust fresh air volumes for transient and intermittent occupancy. However Fanger (13) found no correlation between CO_2 concentrations and odour perception, a finding which may throw some doubt on the validity of using CO_2 sensors for control of ventilation systems.

ROOM AIR MOVEMENT

Most air-conditioning and ventilation systems rely on grilles and diffusers to discharge supply air across a ceiling, which may also contain extract openings. Heat transfer and contaminant dilution rely on mixing of supply and room air, most of which occurs above the heads of the occupants. The usual aim is to create uniform temperature and air purity throughout the occupied zone, with a ventilation efficiency of unity. Usually some short-circuiting occurs, resulting in values less than unity. The momentum from supply jets can generate draughts and transfer contaminants, such as tobacco smoke, from source to recipient.

Systems which discharge air into the lower part of the room (20) are not usually designed to mix the supply and room air. Room air movement is primarily due to upward room convection currents, displacing room-generated contaminants which stratify above head level. Hence ventilation efficiencies are usually much higher. Unfortunately contaminants which are generated below head level, such as a smoke evolving from a cigarette lying in an ashtray, may find there way into the breathing zone of nearby occupants.

DISCUSSION

Swedish codes may soon reflect the trend, which is already prevalent in some Scandinavian countries, for full fresh air ventilation plant, with no recirculation but heat transfer by air-to-air heat exchanger. This follows the widespread adoption of displacement ventilation in those countries, which requires 100% outdoor air to maintain stratification of contaminated air above head level (20).

By contrast the new ASHRAE Standard (1) allows for a reduction in outdoor air rate, provided particulate and gaseous contaminants

are removed from the air
space equivalent to that
fresh air rates were empl
reduction in outdoor air
emissions in multiple-roo
returning from low contam
contaminated regions.

The American approach
to minimise outdoor air s
the massive amounts of en
buildings, with floor are
square metres, which are
particularly with the wid
conditioning and supply a
proximity.

1. ASHRAE Standard 62-19
Quality, American Soc
conditioning Engineer

2. J.E. Janssen, Ventila
CIBSE/ASHRAE Conferen
1986. Chartered Insti
Balham, UK, 40-49, (1

3. Air Quality Guideline
Geneva, (1987)

4. B. Berglund, The role
nonindustrial indoor
Industrial Hygiene Co

5. W.S. Cain, Perceptual
B. Pierce Foundation

6. W.S. Cain, L.C. See a
formaldehyde: Chamber
Air for Health and En
Heating Refrigerating
USA, 126-137, (1986)

7. L. Gunnarsen, P.O. Fa
In Healthy Buildings
Swedish Council for B
(1988)

are removed from the air by filtration, so that the level in the space equivalent to that which would be obtained if the recommended fresh air rates were employed. It also allows provision for a reduction in outdoor air rate to account for uneven contaminant emissions in multiple-room buildings, allowing for the air returning from low contamination zones to help with dilution in contaminated regions.

The American approach to ventilation, which allows the designer to minimise outdoor air supply, is no doubt born from concern about the massive amounts of energy required to ventilate their buildings, with floor areas commonly in the tens of thousands of square metres, which are very difficult to ventilate efficiently, particularly with the widespread use of variable air volume air conditioning and supply and extract air terminals in close proximity.

REFERENCES

1. ASHRAE Standard 62-1989 - Ventilation for Acceptable Indoor Air Quality, American Society of Heating Refrigerating and Air-conditioning Engineers, Atlanta, USA, (1989)

2. J.E. Janssen, Ventilation for acceptable indoor air quality. In CIBSE/ASHRAE Conference, Dublin, S. Ireland, September 15-17, 1986. Chartered Institution of Building Services Engineers, Balham, UK, 40-49, (1986)

3. Air Quality Guidelines for Europe, World Health Organisation Geneva, (1987)

4. B. Berglund, The role of sensory reactions as guides for nonindustrial indoor air quality. Preprint for American Industrial Hygiene Conference, St Louis, USA, May 21-26 (1989)

5. W.S. Cain, Perceptual Characteristics of Nasal Irritation. John B. Pierce Foundation Laboratory, New Haven, USA, (1989)

6. W.S. Cain, L.C. See and T. Tosun, Irritation and odour from formaldehyde: Chamber studies. In IAQ '86: Managing the Indoor Air for Health and Energy Conservation, American Society of Heating Refrigerating and Air-conditioning Engineers, Atlanta, USA, 126-137, (1986)

7. L. Gunnarsen, P.O. Fanger, Adaptation to indoor air pollution. In Healthy Buildings '88, eds B. Berglund and T. Lindvall, Swedish Council for Building Research, Stockholm, 3, 157-167, (1988)

8. G.H. Clausen, K.S. Nielsen, F. Sahin and P.O. Fanger, Sensory irritation from exposure to environmental tobacco smoke. In Indoor Air '87, Berlin, eds B. Seifert et al, 2, 52-56, (1987)

9. ASHRAE Handbook: Fundamentals, Chapter 12: Odors. American Society of Heating, Refrigerating & Air-conditioning Engineers, (1989)

10. P. Bluyssen, Olfbar, Laboratory for Heating and Airconditioning, Technical University of Denmark (1989)

11. D.A. McIntyre, Indoor Climate, Applied Science, London, (1980)

12. J. Pejtersen, G.H. Clausen, and P.O. Fanger, Olf-values of spaces previously exposed to tobacco smoking. In Healthy Buildings '88, eds B. Berglund and T. Lindvall, Swedish Council for Building Research, Stockholm, 3, 197-205, (1988)

13. P.O. Fanger, J. Lauridsen and G. Clausen. Air pollution sources in offices and assembly halls, quantified by the olf unit. Energy & Buildings, 12, 7-19, (1988)

14. J. Pejtersen, P. Bluyssen, H. Kondo, G. Clausen and P.O. Fanger. Air pollution sources in ventilation systems. Laboratory of Heating and Airconditioning, Technical University of Denmark, (1989)

15. I.D. Griffiths, J.W. Huber and A.P. Baillie, Effective ventilation in offices: The occupants' perspective. In Effective Ventilation - the 9th AIVC Conference, Air Infiltration and Ventilation Centre, Coventry, UK, 1, 311-328, (1989)

16. S. Wilson and A. Hedge, The Office Environment Survey: A Study of Building Sickness, Building Use Studies, London, (1987)

17. B.P. Leaderer and W.S. Cain, Air quality in buildings during smoking and non-smoking occupancy. ASHRAE Trans, American Society of Heating, Refrigerating & Air-conditioning Engineers, Atlanta, USA, 89, 2A & 2B, 601-623, (1983)

18. P.O. Fanger, Body odour and carbon dioxide, minimum ventilation rates. IEA energy conservation in buildings and community systems programme, Annex IX final report, (1986)

19. CIBSE Guide, Section B2, Chartered Institution of Building Services Engineers, London, (1987)

20. P.H. Appleby, Displacement ventilation, a design guide. Building Services J, 11(4), 53-56, (1989)