Technical Research Paper 04

The Ventilation System in the CH_2 Building

city of Melbourne

Contents

Disclaimer

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An Australian Government Initiative
AusIndustry

6 star rating
green star Office Design v1
This rating represents World Leadership

CH_2

Preface

Council House 2 (CH_2) is a visionary new building that is changing forever the way Australia – indeed the world – approaches ecologically sustainable design.

With its Six Star Design Rating granted by the Green Building Council of Australia, CH_2 is one of the cleanest and greenest buildings on earth.

This paper, one in a series of 10 technical papers, investigates the design and systems of CH_2 prior to occupancy and availability of operational performance data. The papers have been written by independent authors from Australian universities, as part of the CH_2 Study and Outreach Program – a coordinated effort to consolidate the various opportunities for study, research, documentation and promotion generated by CH_2.

The aim of the CH_2 Study and Outreach Program is to raise awareness of sustainable design and technology throughout the commercial property sector and related industries.

While the pre-occupancy research papers are a valuable resource, they do have some limitations. For instance, these studies have been written before operational experience. This means the authors' views are based on existing knowledge, which can be difficult to apply when significant innovation exists.

Many of the innovations in CH_2 have been subject to limited, if any, rigorous or directly relevant research in the academic field, which is reflected in the lack of literature cited for systems such as the shower towers and phase change materials used in the cooling system.

Another major limitation is the exclusion, by academics generally, of industry experience of new technologies. The extensive knowledge gained by industry is often not well documented and can be difficult to access through traditional academic channels.

One example, where industry expertise exists, is the use of phase change materials for reducing peak cooling loads and energy use in commercial and institutional settings, such as offices, hospitals, prisons and factories.

In addition, to enable the authors to complete their task, they have based their study on CH_2 project reports prior to the design being finalised. This means some of the descriptions of systems and findings in the papers are to some extent out dated. In particular, findings related to the wind turbines and the heating, cooling and ventilation systems have changed somewhat as a result of final design decisions.

To reduce the impact of these limitations for readers, the Council has provided additional comment as footnotes in some papers.

It is important to inform readers the target audience for these papers is professionals and academics involved in the research, design, engineering, construction and delivery of high performance buildings. This helps to explain the technical detail, length and complexity of the studies.

Although these papers may be of interest to a range of audiences it's important that readers, who possess a limited knowledge of the subjects covered, obtain further information to ensure they understand the context, relevance and limitations of what they are reading.

For more information or to make comment and provide feedback, readers are invited to contact the Council. The details are available at the end of this document.

We hope you enjoy reading these technical studies and find they are a useful resource for progressing your own organisation's adoption of sustainable building principles and encouraging the development of a more sustainable built environment.

Foreword

In 2000 the City of Melbourne made the decision to embark on a revolutionary new project called Council House 2 (CH_2). The decision was due to a pressing need for office space for its administration and the desire to breathe life into an under-used section of the city.

The project gave the Council the opportunity to exercise its environmental credentials by creating a building that was at once innovative, technologically advanced, environmentally sustainable and financially responsible.

This approach allowed the Council to insulate itself against exposure to rising energy and water prices, the diminishing availability of resources and the uncertain long-term availability, while providing a healthy workplace attracting the best workforce in a labour-constrained market.

CH_2 has been designed to reflect the planet's ecology, which is an immensely complex system of interrelated components.

From the revolutionary cooling storage system in the basement to vertical gardens and wind turbines on the roof, the building has sustainable technologies integrated throughout its 10 storeys.

Although the majority of the technologies and principles adopted in the building are not new, never before in Australia have they been used in an office building in such a comprehensive and interrelated fashion.

This includes innovations such as: using thermal mass for improving comfort; phase change material to reduce peak energy demands and energy use; generating electricity onsite from natural gas; and using waste heat for cooling and heating.

Through CH_2, the Council plans to trigger a lifestyle and workstyle revolution. The building will be used as a living, breathing example, demonstrating the potential for sustainable design principles and technologies to transform the way industries approach the design, construction and philosophy of our built environment.

As with many revolutions, there are sceptics. The Council's response has been to patiently press ahead with the construction of CH_2 while actively and energetically encouraging lively debate.

Some of the papers in this pre-occupancy study and outreach series make compelling points in favour of the case for sustainable development. Others reflect a more subtle or sometimes overt scepticism that may be encountered throughout the community.

The City of Melbourne welcomes all of this debate but in the long term intends to demonstrate the effective performance of CH_2 and prove the doubters wrong. Collectively, the studies demonstrate the enormous value to be gained by researching the case for sustainable development and the scope for much more study and documentation in this field in the future.

The City of Melbourne wants CH_2 to be copied, improved on and enthusiastically taken up throughout Melbourne and far beyond.

Technical Research Paper 04

The Ventilation System in the CH_2 Building

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Introduction

A study of 56 European office buildings found that their air quality was poor and there was substantial dissatisfaction among the occupants (Bluyssen et al., 1996). These buildings were fitted with conventional Heating, Ventilation and Air Conditioning (HVAC) systems. The study substantiates the view that modern office buildings with HVAC systems do not necessarily provide healthy working environments, despite the use of energy-intensive conditioning equipment and sophisticated control systems. The proposed ventilation concept adopted for the CH_2 building differs markedly to this conventional HVAC approach. This difference is driven by a design philosophy based on three considerations. Firstly, reducing the electrical energy, which is a greenhouse-intensive energy source in Victoria. Secondly, de-coupling the multiple purposes of conventional HVAC systems, which use ventilation air as the transport medium for heating and cooling the indoor occupied space in addition to providing air for occupants' healthy breathing requirements. The other motivation for the departure from conventional ventilation thinking is the belief that the quality and quantity of air in buildings is vital for occupant health, wellbeing and productivity. By increasing the level of fresh air intake substantially, it is believed that these indicators will be improved.

The aim of this paper is to assess the proposed CH_2 ventilation design and likely indoor air quality in the light of international precedents and best practice. Since the building is still under construction, no measured data from the building is available to verify performance, and the main source of information has been CH_2 design consultants' reports. Therefore the proposed design has largely been evaluated using a selection of the design consultants' documentation and refereed literature in international journals. Design changes made subsequent to this evaluation are obviously not considered. Some assessment of the effectiveness of particular aspects of the proposed design has also been attempted using local data.

In assessing the ventilation system and likely air quality, this paper addresses a number of questions. What is the nature and magnitude of the hazards that can be found in a typical office building? What is the quality of the outside air being introduced into the CH_2 building? How well are the individual components likely to perform? What is the evidence that improved health and productivity will result from this approach? And finally, what has been the experience of users of similar buildings?

This study begins with a brief summary of the potential hazards that may need to be addressed in the CH_2 building. The quality of the air in Melbourne's Central Business District is then discussed, as large quantities of outside air are to be introduced into the building. An overview of standards and strategies deemed necessary for good ventilation practice is then given, followed by an introduction to the two key elements of the CH_2 ventilation system. The overall objectives and operation of the CH_2 ventilation system are then described, followed by a review of the individual components and their expected performance. Finally, the performance of other buildings is reported, particularly with respect to the influence of their ventilation system on air quality, and the health and productivity of their occupants.

Indoor Air and Occupant Health

It is likely that if occupants were as knowledgeable about the quality of the air they breathe within their buildings as they are about the food they eat, then much greater action would be demanded to improve the indoor environment. A healthy indoor environment can be defined in terms of safe levels of chemical, biological, physical and ergonomic hazards. Some of the physical and ergonomic hazards (such as noise and illumination) are not relevant to an assessment of air quality and the ventilation system. Table 1 indicates the possible diseases and their chemical or biological causes, related to air quality which may be encountered in buildings.

Disease	Cause
Rhinitis sinusitis	Moulds, laser toner, carbonless copy paper, cleaning agents
Asthma	Moulds, laser toner, carbonless copy paper, cleaning agents
Hypersensitivity pneumonitis	Moulds, moisture
Organic dust toxic syndrome	Gram-negative bacteria
Contact dermatitis	Moulds, laser toner, carbonless copy paper
Contact urticaria	Office products, carbonless copy paper
Eye irritation	Low relative humidity, volatile organic compounds, particulates
Nasal irritation	Low relative humidity, volatile organic compounds, particulates
Central nervous system symptoms	Volatile organic compounds, carbon monoxide, cytokines from bioaerosol exposure
Legionnaires' disease	Aerosols from contaminated water sources, shower heads, water faucet aerators, humidifiers, potable water sources (hot water heaters)

Table 1: Diseases and their causes related to buildings. (Extracted from Table 1, American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), 2001, Chapter 9-Indoor Environmental Health.)

In order to protect the health of building occupants, ventilation and exposure standards are in place to ensure acceptable levels of contaminants (gaseous and particulate) known to be harmful to human health. Many countries and organisations have established such guidelines. For example, the World Health Organisation has published guidelines for Europe for some gaseous contaminants, and some of those considered relevant to this study are shown in Table 2.

Pollutant	Time-weighted average		Averaging time
	mg/m³	ppm	
Carbon monoxide	10 30	8.7 25.0	8 h 1 h
Nitrogen dioxide	0.04 0.20	0.02 0.11	annual 1 h
Ozone	0.12 0.20	0.06 0.10	8 h 1 h
Formaldehyde	0.10	0.081	30 min
Benzene[a]	No safe level		–

a – from WHO, 2000, Chapter 5.2 Benzene.

Table 2: Selected gaseous contaminants and WHO recommended safe levels. (From Table 4, Chapter 9, ASHRAE, 2001, – except where noted.)

Particulate contaminates can come from natural or anthropogenic sources. The former includes windblown dust and smoke from forest fires, both of which, on occasion, can visibly influence Melbourne's air quality. Particles from anthropogenic sources are those generated by human activities including fuel combustion (such as motor vehicles and wood burning stoves) and industrial processes. Since the CH_2 building is located in a city centre, motor vehicle particulates are of particular interest. Air pollution from wood burning stoves is also of particular concern in winter in Melbourne, when its contribution to particulate emissions can be twice that of motor vehicles.

Particulates come in all sizes and those up to 50 microns (a micron is one millionth of a metre) are known collectively as Total Suspended Particulates (Holmes, 1999). Those smaller than 2.5 and 10 microns are known as $PM_{2.5}$ and PM_{10} respectively. While all these particles can enter the lung airways, it is the smaller particles, particularly the $PM_{2.5}$, which can penetrate deep into the lung lining or alveoli and cause serious health problems. The smaller the particle, the longer it can remain suspended in the surrounding air. According to Holmes (1999), a 30 micron particle will take about 30 seconds to fall two metres, while a one micron particle will take about 12 days to fall the same distance. This means that the small particles can travel considerable distances from the point of origin.

Some particle size diameters of interest to this study are shown in Table 3. The large range of particle sizes from both internal and external sources illustrates the challenge for filtering systems in buildings. In terms of exposure levels, various recommendations exist. In Australia, the recommended exposure standard for non-toxic inspirable dust in general should be 10 mg m^{-3} (NOHSC, 1995a).

Particle description	Particle diameter (µm)
Dust mites	100 – 300
Pollen	10 – 100
Spores	3.0 – 35
Vehicle emissions	1.0 – 150
Copier toner	0.4 – 3.0
Bacteria	0.3 – 30
Burning wood	0.2 – 3.0
Air freshener	0.2 – 2.0
Clay	0.1 – 40
Paint pigments	0.1 – 5.0
Viruses	less than 0.01 – 0.05

Table 3: Sizes of selected particles. (From Owen et al., 1992, cited in ASHRAE, 2001, Chapter 12.)

Carbon dioxide, while not a pollutant, can be harmful at high levels (>35 000 ppm) due to oxygen displacement. At lower levels, it is also used as an indicator of indoor air quality. The European standards organisation, the European Committee for Standardisation (CEN), has established four levels of CO_2 above the outside level, with an associated qualitative description of the air quality (Table 4).

Description	CO_2 above the outside level (ppm)
High indoor air quality	less than or = 400
Medium indoor air quality	400 – 600
Acceptable indoor air quality	600 – 1000
Low indoor air quality	greater than 1000

Table 4: Levels of CO_2 and associated air quality level. (Source: Olesen, 2004.)

Odours

Unpleasant odours in a workplace can come from a variety of sources, either inside or outside the building. Indoor sources include paints, furnishings, cosmetics used by occupants, photocopiers, mould and toilets. Outdoor sources include vehicle and industrial emissions, sewage and refuse sites, and vegetation. Strong bad-smelling air is often assumed to be unhealthy, but this is not necessarily the case. Some unpleasant odours are not necessarily harmful to human health. However, if the air is perceived to be unpleasant then it does not matter very much whether it is harmful or not; the problem must be addressed. Perceptions of unpleasant air also vary considerably, with some people more sensitive than others to particular odours. Some adaptation will also occur as the exposure time is prolonged.

The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) (2001) has defined the threshold limit value (TLV) for selected pollutants, and Table 5 lists some of those compounds, which may have relevance for the CH_2 building occupants. The odour threshold is that level of the compound which would be detected by 50 per cent of the population, denoted as ED_{50}. The TLV is “the concentration of a compound that should have no adverse health consequences for a worker exposed for eight hour periods”. When the ratio of TLV and odour threshold is greater than one, most occupants “can detect the odour and leave the area long before the compound becomes a health risk” (ASHRAE, 2001).

Compound	Odour Threshold (ppmv)	TLV (ppmv)	Ratio
Hydrogen sulphide	0.0094	10	1064
Toluene	1.6	50	31
Ammonia	17	25	1.50
Sulphur dioxide	2.7	2.0	0.74
Benzene	61	0.5	0.01

Table 5: Odour thresholds, TLVs and threshold ratios for various gaseous air pollutants. (From Table 1, Chapter 13, ASHRAE, 2001.)

Temperature, relative humidity and airflow can all affect the olfactory senses of occupants, but the research data is not conclusive. Generally, cooler and drier air is perceived to be fresher and therefore more acceptable. The source and strength of the odour will influence the ability of the ventilation system to reduce or remove the problem. Some odours can be quickly reduced by ventilation, but others require greater dilution.

In an attempt to provide a rational basis for building design, Fanger (1988) introduced measurement units to quantify air pollution from odours. The ‘olf’ is defined as the emission rate of air pollutants, in the form of bio-effluents, from a sedentary person. A ‘decipol’ is one olf ventilated at a rate of 10 litres s^{-1} of unpolluted air. Using these units, a relationship between the ventilation rate and the percentage of dissatisfied occupants has been established (ASHRAE, 2001). For a low-polluting office, such as the CH_2 building, where the office occupancy level is one person per 15 m^2, then the total sensory load will be 0.17 olf m^{-2}. To achieve a 10 per cent dissatisfaction rate (i.e. 90 per cent satisfaction), a ventilation rate of approximately 2.6 litres s^{-1} m^{-2} is required. The ventilation rate for the CH_2 building is 1.5 litres s^{-1} m^{-2}, indicating that the dissatisfaction rate will be in excess of 10 per cent[1].

The proximity of the CH_2 building to busy roads, and the use of a night purge system to assist in cooling the building structure, could mean that occupants would detect emissions from traffic first thing in the morning[2]. The use of natural ventilation at all times for the toilets could also mean that the building’s users will experience unacceptable odours[3].

1 City of Melbourne note: Occupancy rates in CH_2 are similar to current office standards, and fresh air ventilation rates for CH_2 are higher than the standard for Australian buildings, so satisfaction is expected to be better than for current Melbourne offices. Odour dissatisfaction rates inside the building also are expected to be reduced by the use of floor-mounted air diffusers and ceiling-mounted air extractors, which will help keep air moving upwards as well as keeping the incoming fresh air separate from the outgoing polluted air.
2 City of Melbourne note: There are several reasons why CH_2’s designers believe traffic odour will not be an issue in CH_2. These include localised pollution levels, which are expected to be minimal because city traffic travels relatively slowly on the laneways near CH_2 and traffic will be light in the early hours of the morning when night purge operations are likely to occur. In addition, the ventilation system is designed to achieve two air exchanges every hour when operating at the design rate of 1.5 litres s_{-1} m_{-2}. At this air-change rate, using 100 per cent fresh filtered air, the air remaining from night purge operations and any potential pollutants, should they exist, will be rapidly expelled once the windows close and the filtered air moves through the building by the mechanical ventilation system. It is expected that within 15 minutes of the mechanical ventilation system operating, half the air in the building will have been replaced with 100 per cent fresh filtered air and in half an hour almost all the air will have been replaced. Refer, also, Footnote 20.
3 City of Melbourne note: The toilets in the City of Melbourne’s Commonwealth Bank building next door to CH_2 use natural ventilation, and no odour complaints have been received during the many years it has been used by the organisation. The ground floor toilets in CH_2 will use mechanical ventilation due to a different floor plan and ventilation system configuration on that floor.

Melbourne Air Quality

The 'Six Cities' study in the US over ten years ago demonstrated that particulates (PM10) were a health hazard. Researchers found that death rates increased almost in direct proportion to the level of particulate pollution. People living in the most polluted cities studied had almost a 26 per cent greater risk of dying young, compared with those in the cleanest city (Boyce, 2000). A study by the NSW Department of Health found that an increase of 0.025 mg m^{-3} of urban particulates resulted in a 2.6 per cent increase in deaths each day (Morgan et al., 1998, cited in Beder, 2001). The researchers conducting the NSW study estimated this resulted in almost 400 additional deaths each year. This estimated increase in deaths was double that determined by US studies (Beder, 2001). The evidence from Victoria is similar. A study has shown that the daily mortality from ambient air pollution in Melbourne is increasing (EPA, 2000). The strongest relationships between various pollutants and this increase were those of ozone and nitrogen dioxide. A primary source of this pollution is the emissions from motor vehicles. The CH_2 building is located in the heart of Melbourne city and will be drawing large quantities of outside air at roof level (38m high). That air is subsequently filtered, and its final quality is crucial to the health and well-being of the CH_2 occupants. The closest ambient air quality monitoring station to the CH_2 building is located approximately 750 metres away on the roof of an inner city university building[4]. The air sampling height is 19 metres above ground level. The normal sampling height is six metres, but there are apparently no vertical gradients at the RMIT site (EPA, 2001).

An indication of inner city Melbourne's air quality may be obtained from the Environmental Protection Agency's (EPA) annual air monitoring tables (EPA, 2004a). Table 6 shows the maximum levels of the four pollutants cited in the EPA's mortality study and measured at the RMIT site in 2003. Also shown in the table is the EPA's outdoor air quality policy objective. While maximum measured levels of ozone, carbon monoxide and nitrogen dioxide met the EPA's policy objective, PM_{10} particulate levels exceeded that level. As stated earlier, PM_{10} particles are of major concern because they penetrate the respiratory system, with the finer particles ($PM_{2.5}$) penetrating even more deeply into the lungs. These include dust, soot, pollen, asbestos and many other chemicals. Exposure to particles increases the risk of death from heart and lung disease. Particles can carry carcinogenic materials to the lungs. They can also exacerbate asthma and other chronic lung conditions.

Pollutant	Units	Averaging Period	Maximum Measured Level	EPA Objective	WHO Guideline Values
Ozone	ppm	1 hour	0.093	0.10	0.06 (8 hours)
Carbon monoxide	ppm	8 hours	3.9	9.0	8.73
Nitrogen dioxide	ppm	1 hour	0.069	0.12	0.114
Particulates (PM_{10})	µg/m^3	1 day	279.4	50	*
Particulate ($PM_{2.5}$)	µg/m_3	1 day	NA	25	*

** No recommended guideline values; n.a. indicates 'not available'.*

Table 6: Maximum levels of four ambient air pollutants measured at RMIT site in 2003/

Future air quality goals have also been set for Melbourne in terms of the number of days when pollution levels exceed certain allowances. In 2003, the ozone and particulate goals set for 2008 were not met. Bush fires and dust storms during this period have been cited for these excesses (EPA, 2004b). But whatever the cause, and these are both naturally occurring events, the incoming air into the CH_2 building may be in excess of EPA objectives[5]. In addition, both CH_2 and the monitoring station are in close proximity to a main road through the heart of Melbourne. The access of private vehicles to this road has been relaxed in recent times, following a period of restrictions, and it is possible that traffic and therefore emissions in the city will increase if traffic levels return to their pre-restricted level[6]. Motor vehicles currently account for 16 per cent of PM_{10} airborne particles.

Ventilation Standards and Strategies

In order to ensure occupants of commercial buildings work in a reasonably healthy environment, minimum ventilation rates have been mandated by standards, both in Australia and overseas. Table 7 shows the current minimum ventilation rates required to remove occupant-related contaminants for medium level activity in offices in Australia and USA.

4 City of Melbourne note: This air monitoring station is about seven city blocks away in an area much closer to wide busy roads than the narrow and often closed-off streets surrounding CH_2. Air quality is also monitored at half the hight (19m) of the air intakes for CH_2 (38m).
5 City of Melbourne note: During the day, indoor air will be filtered thoroughly. The air intake filters are designed to contend with air experienced in the city, and provide safe indoor air. The potential impact of outdoor air is not unique to CH_2, as all filter systems for buildings in the city experience similar conditions. Outdoor air used to cool the building at night will be expelled within half an hour each morning, prior to the arrival of most workers. Refer to Footnote 2. It is important to note the outdoor air referred to is the same encountered by the hundreds of thousands of people who visit the city every day.
6 City of Melbourne note: The nearest main road to CH_2 is Bourke Street, which, in very recent times, has been substantially and permanently closed to all but tram traffic in the vicinity of CH_2. The other main road, which passes both CH_2 and the distant monitoring station, is Swanston St. Reintroducing significantly more traffic to Swanston Street would require the reversal of long-held Council policy, removal of millions of dollars in wide footpaths and street infrastructure and the risk of ending a renaissance in pedestrian and retail activity in the street, as measured in 10 years of City of Melbourne award-winning research (Places for People 2004).

Country	Australia	USA	Europe	International
Standard Number	AS 1668.2 -2002	ASHRAE 62.1 -2004	CR 1752 -1998	ISO/DIS 7730 (2003)
Reference	AS (2002)	ASHRAE (2003)	CEN (1998)	ISO (2003)
Ventilation (litres s^{-1} per person)	7.5 (minimum)	10 (minimum)	24.3xa 17.1xb 10xc (unadapted)	24.3xa 17.1xb 10xc (unadapted)

Adapted = based on satisfying adapted persons (i.e. people who are occupying a space and have adapted to the odour level).
** = Recommended for non smoking, 0.07 person/m² occupancy.*
a = category A, b = category B, c = category C.

Table 7: Ventilation rates for offices in Australia, USA and Europe.

As Table 7 indicates, there is no agreement on what level of ventilation will ensure good indoor air quality and a healthy environment for building occupants. The most commonly used standard for ventilation is probably the American Society of Heating, Refrigeration and Airconditioning Engineers (ASHRAE) standard. In the CH_2 building, a rate of 22.5 litres s^{-1} per person will be used. According to Olesen (2004), current thinking is to introduce different levels of acceptance in the revision of ISO 7730. This concept has already been introduced in CR 1752, the European standard (CEN, 1998). The categories will be based on the percentage dissatisfaction level (PPD). PPD per cent levels of less than six, less than 10 and less than 15 correspond to Categories A, B and C (Olesen, 2004). In the CH_2 offices, a dissatisfaction level of fewer than 15 per cent is the aim (AEC, 2003a), which means that it would meet the lowest of three categories specified in the current CR 1752 standard.

In practice, good air quality will be achieved by good pollution control strategies. Liddament (1996) suggests the following strategies to control outdoor sources of pollution:

- using filtration to remove particulates from the air, although this is difficult for totally naturally ventilated buildings or sections of buildings, such as the toilets in CH_2;
- locating air intakes away from pollutant sources such as traffic, cooling towers and exhaust stacks;
- using air quality controlled dampers to prevent intake of outside air at times of peak traffic; and
- ensuring that contaminant ingress is limited by limiting infiltration. Underground car parks must be adequately isolated from the occupied parts of the building.

For indoor sources of pollution, Liddament (1996) suggests the following hierarchy of control strategies:

- initial avoidance of potentially harmful internal pollutant sources. Once a pollutant is within the building, whatever the source, it can only be diluted;
- enclosing and ventilating localised sources of pollution; and
- using general ventilation to dilute and remove contaminants.

Displacement Ventilation[7] (Separation System)

In a displacement system, the ventilation air is injected into the room at floor level at a low velocity. Li et al. (1998) describe the thermal and flow characteristics that occur in a displacement ventilation system, and illustrate their explanations with figures that show possible contaminant concentration fields, temperature gradients and air movement due to gravity currents and jets. Gravity currents spread air outward across the floor, unlike a jet, which propels the air upward[8]. The air is heated by convection from the floor surface as it moves outward. As the temperature of the air rises, the buoyancy force of the gravity current decreases.

Li et al. (1998) also explain that displacement ventilation[9] creates an upper and low zone of contamination, with the upper zone containing the contaminated air and the lower zone containing the uncontaminated air. When there are rising convection currents, there is unlikely to be much mixing between zones. The interface between the two zones is called the 'clear zone height' by the authors. The measured contaminant concentration field (with the contaminant source at ceiling level) ranges from zero at 0.5-0.75m above the floor, to 1.5m at ceiling level (Stymne et al. (1991) cited in Li et al., 1998). Convection currents are strongest around occupants due to body heat, and therefore induce upward air movement, reducing contamination concentration fields at this level.

7 City of Melbourne note: CH_2's design does not produce true thermal displacement ventilation inside the occupied office space because the flow of ventilation air is disturbed by the use of chilled ceilings and swirl diffusers. (Refer Footnote 9 for an explanation of true DV systems.) The correct description for CH_2's air supply system is 'under-floor air supply using swirl diffusers' or UFAD. Refer to the following web link, www.cbe.berkeley.edu/underfloorair/glossary.htm, for detailed definitions of UFAD, which is summarised here: "A (UFAD) system uses an under-floor plenum (open space between the structural concrete slab and the underside of a raised floor system) to deliver conditioned air from the Air Handling Unit directly into the occupied zone of the building… In contrast to true Displacement Ventilation systems, UFAD systems deliver supply air at higher volumes and higher velocities, enabling higher heat loads to be met. Although the supply air is delivered in close proximity to occupants, the risk of draft discomfort is minimised, as supply air temperatures are higher than those for conventional ceiling-based systems, and occupants have some amount of control (typically volume and sometimes direction and temperature) over their local air supply conditions." The literature cited and descriptions used in the following section do not consider the use of a chilled ceiling in conjunction with the underfloor air supply using swirl diffusers, and their likely effect upon true displacement flow. However, this is considered later.

8 City of Melbourne note: In CH_2, air will be propelled upwards by floor-mounted swirl diffusers.

9 City of Melbourne note: Displacement ventilation (DV) means displacing warmer (lighter, less dense) used air with cooler (heavier, more dense) fresh air, which is introduced into the space at the bottom of the room. The outcome is that a cool-to-warm interface forms in a horizontal layer. DV is designed to ensure better ventilation and fewer pollutants, while also maintaining stratification with warmer air layers lying above people's heads, which means the air at floor level does not need to be cooled as much. The DV approach is very different from delivering cooler air from the top of the room and relying on it mixing as it falls, as is done in mixing ventilation systems.

Mixing Ventilation (Dilution System)

The conventional ventilation system, where a small quantity of outside air is introduced into the space and mixed with the existing air, and simultaneously a similar small quantity is exhausted, can be described as the mixing ventilation (MV) system[10]. Lin et al. (2005) present a comparison between displacement ventilation (DV) and MV systems in terms of indoor air quality. The indicator levels used were carbon dioxide, the mean age of the air and three volatile organic compounds, namely toluene, benzene and formaldehyde. The study was conducted to investigate the performance of a DV system under the high cooling load conditions of Hong Kong. The results of the study are particularly relevant to countries such as Australia, where cooling loads are considerably higher than in Europe, from where most experience of DV systems is derived.

The study by Lin et al. (2005) presented 15 office case studies, which represented a range of configurations. The office heights ranged from 2.4m to 3.0m and the office volume air change rates ranged from 1.5 to 30 per hour. In each case, the ventilation rate was fixed at 10 litres s^{-1} per person, which is considerably less than in the CH_2 building. Another difference between the offices analysed by Lin et al. (2005) and the CH_2 building is that the effect of chilled ceiling panels on the DV systems was not considered. The contaminant sources were heat sources such as printers and photocopiers, and non-heat sources such as building materials. Concentration of contaminants was found to be very sensitive to the location and source of the contaminant. The DV system did not provide the best indoor air quality if the contaminant source was not a heat source. Little difference in CO_2 concentration between the DV and MV systems could be determined, with both systems indicating general levels of 700-800 ppm. However, in the breathing zone of the occupants, the DV system was superior. The mean age of the air surrounding office workers was also considerably shorter in the DV cases. The mean age of the air in the breathing zone of DV systems was 120 seconds compared to 360 seconds in MV systems. For the three volatile organic compounds investigated, little difference could be determined between the two ventilation systems, and both systems produced concentration levels well below those recommended in Europe. Overall, Lin et al. (2005) concluded that DV systems can maintain a better indoor air quality than MV systems, particularly with respect to the breathing zone. The study also concluded that the CO_2 generated by occupants was easier to expel in DV systems.

CH_2 Ventilation – Indoor Air Movement Regime

Chilled ceiling panel positioning, outlet air locations and diffuser design will also affect flow patterns and mixing between zones of contaminants. Designers of the CH_2 building investigated the possibility that air cooled at the ceiling level by the radiant cooling panels would fall back down due to its higher density, causing draughts for occupants. In addition to this unwanted effect, mixing of contaminants would also result[11]. Two positions on the ceiling for the chilled panels were investigated using computational fluid dynamics (CFD) analysis (AEC, 2003a). The simulations indicated that if the chilled panels were located on the lowest part of the curved ceiling, they were more likely to cause 'dumping' of cooled air than if the panels were located halfway along the curve between the ceiling's valleys and peaks (Figure 1). Contamination concentration fields, however, were not investigated.

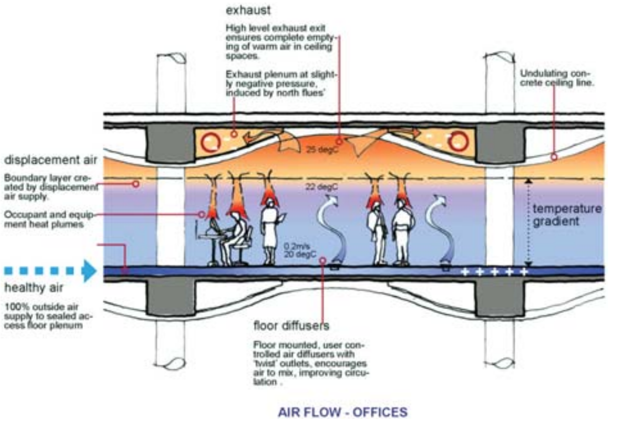

Figure 1: Schematic overview of ventilation system in CH_2 building. (Source: CoM, 2004)

The air supply location influences the performance of a displacement ventilation system. Lin et al. (2004) used computational fluid dynamics (CFD) simulation to investigate the effect of the position of the air inlet on the performance of a displacement ventilation system in a typical Hong Kong office. The analysis indicated that a central position should be chosen for the air supply inlet rather than a location to one side of the room, because the former produced a more uniform thermal condition in the office and was more effective in the removal of volatile organic compounds[12]. While acknowledging the importance of the frequency and location of supply and return air outlets in the performance of the displacement ventilation[13] system, in the CH_2 building, these were fixed in the design investigation by the effect of the chilled ceiling panel position (AEC, 2003a). Alternative locations for the supply and return air outlets and their interaction with other elements do not appear to have been investigated in the CH_2 design[14,15].

10 City of Melbourne note: Mixing ventilation systems are also called dilution systems.
11 City of Melbourne note: CH_2's under-floor air supply will use occupant-controlled swirl diffusers that will partially displace warmer (lighter) used air with cooler (heavier) fresh air that will be swirl diffused into the space at the bottom of the room. The chilled ceilings may disrupt the thermal displacement of air to some extent, however simulations have shown enough stratification will be achieved and downdrafts will be avoided.
12 City of Melbourne note: In relation to thermal comfort, it is important to clarify that the research referenced investigates the capacity of displacement ventilation systems to achieve uniform thermal conditions. Since CH_2 uses a chilled ceiling system as the primary mechanism for thermal comfort, as opposed to cooling with air, the relevance of this research in the CH_2 context potentially is limited.
13 City of Melbourne note: As indicated in Footnotes 7, 9 and 11, CH_2 does not use true displacement ventilation. Instead air is distributed evenly to workers through multiple inlets. About 66 swirl diffusers – or about one per person – are placed evenly across the floor plate of each occupied office level.
14 City of Melbourne clarifying note: Given Footnote 13, the need to consider alternative locations for air inlets is likely to be less critical because the swirl diffusers are distributed evenly across the floor plate. This uniform positioning is expected to be highly effective at producing an even distribution of fresh air to workers.
15 City of Melbourne note: As indicated in Footnotes 7, 9 and 11, CH_2 does not use true displacement ventilation. Instead air is distributed evenly to workers through multiple inlets. About 66 swirl diffusers – or about one per person – are placed evenly across the floor plate of each occupied office level.

Natural Ventilation[16]

Naturally ventilated buildings are attractive because they offer the potential to save energy and are likely to be well received by occupants, if they work satisfactorily. Logan (2002), however, states that naturally ventilated buildings can be problematic for two reasons. Firstly, high wind pressures can cause uneven flows and noise, and generate high leakage, so that the amount of energy saved under design conditions is lower in reality (i.e. normal wind speed is lost by increased infiltration at high wind speed). The second problem is that natural ventilation can be ineffective if the depth of the ventilated space exceeds 12-15m. The CH_2 building is approximately 21m wide. This indicates that the inner sections of the building should receive adequate air flow at night, to cool the exposed thermal mass of the concrete ceilings, provided that ceiling mounted outlets are correctly sited to encourage outside air to move from the windows to the centre of the building.

The direction and strength of wind on a building will have a strong influence on any attempt to use natural ventilation. Two recent studies (Gratia et al., 2004; Moeseke et al., 2005) have investigated the influence of wind pressure distribution on natural ventilation. Wind tunnel experiments and computational fluid dynamics (CFD) simulations have been used in their analyses. While Gratia et al.'s study only took account of the vertical pressure distribution, Moeseke and his co-workers considered both horizontal and vertical factors in their later study. Their building was five storeys high and had offices located either side of a central corridor. There were four openable windows on the external walls of each office and another on the internal wall facing the central corridor. This arrangement permitted cross-ventilation. Despite substantial differences from the CH_2 building, their general findings and conclusions are of interest and relevance to designers planning to use natural ventilation[17] for office buildings located in an urban environment.

The wind speed used in the simulations was 4 m s^{-1}, which is about 33 per cent higher than that experienced in Melbourne. While reasonable room volume air change rates (3-6 ACH^{-1}) at all levels were achieved in an open environment for most wind directions and window opening regimes, a 70 per cent reduction in these air change rates occurred in the urban environment modelled. These results of Moeseke et al. (2005) do not agree with those of Gratia et al. (2004) because the latter assumed 'skimming flow'.

In a dense city environment, similar to the location of the CH_2 building, stable vortexes appear in the street canyons and the bulk of the airflow does not enter the canyon. The complexity of urban forms and the variability of wind regimes mean that predictions of the effectiveness of natural ventilation are too complex to generalise and that "specific studies are still the only way to answer specific questions", according to Moeseke et al. (2005). The authors further believe that "parametrical models limitations make them useless tools to describe accurately real urban environments" and that computational fluid dynamics (CFD) and wind tunnel investigations should be used. The software package that was used in the above studies was also used in the analysis of the natural ventilation potential of the CH_2 building (AEC, 2003b). However, details of the pressure coefficients used, and the computational fluid dynamics (CFD) results obtained, are not given, thus preventing further comparison with the detailed studies described above.

The CH_2 Ventilation System

System Objectives

The main design objective of the CH_2 ventilation system is to avoid recycling any air into the offices. The air entering the offices is to be 100 per cent fresh, filtered and conditioned. In addition, the quantity of introduced fresh air will be substantially higher than required by the Australian Standard. Another goal of the system is to avoid the mixing of fresh and stale air within the occupied spaces, while also significantly reducing mixing within different occupied zones across the floor-plate.

System Overview

The CH_2 ventilation system can be characterised as 'mechanically driven' during the day and 'naturally driven' at night[18]. During day, the fresh air is drawn from the roof level (i.e. from approximately 38m above street level) and travels down ducts on the south side of the building. Some conditioning of the ventilation air takes place prior to its delivery to offices. The system supply temperature is to be 20C and, depending on the outside air temperature, the ventilation air will be heated or cooled to this temperature by heat exchangers. The absorption or electric chillers will provide cooling depending on operational requirements, and heating will be achieved by using waste heat recovered from the gas-fired cogeneration system or natural gas-fired boilers.

16 City of Melbourne note: It should be noted, in the context of the authors' discussion on natural ventilation, that although CH_2 takes advantage of the natural flow of outside air through the building during night purge operation, this "ventilation" air is not intended as "breathing" air. Natural ventilation of the offices will be used only at night in CH_2 as part of the night purge operation to cool the building's thermal mass. Natural ventilation is a term broadly used to refer to the opening of buildings to the outside air. This includes its role in passive cooling and the movement of cool night air to remove the daytime heat absorbed by a building's exposed indoor thermal mass. However the term does not clearly differentiate between the very different requirements of ventilated air for breathing and/or cooling. Night purge can therefore be considered to be a special case of natural ventilation, where the natural ventilation – or natural flow of outside air through a building – is for the purpose of passive cooling alone. The CH_2 design team uses the term night purge as it helps avoid confusion.
The sustainable design objective, in the case of CH_2, is to reduce daytime cooling loads and energy consumption for cooling. Further discussion of the function of night purge, in the operation of CH_2, is considered in the technical studies that investigate energy, and heating and cooling.

17 City of Melbourne clarifying note: These findings will be of interest whether natural ventilation is used for the purposes of passive cooling, as in the case of CH_2, or for providing occupant comfort and quality air for occupants to breathe inside the building using natural ventilation during daytime operation.

18 City of Melbourne note: Daytime air extraction will be assisted by thermal chimney effects, thermal buoyancy and pressure differential at the exhaust outlet cowling. At night, the system will combine thermal chimney effects with wind-assisted turbine extractors to help night purge to cool the building's thermal mass.

The air will be passed through filters prior to its temperature and humidity conditioning and subsequent delivery into the offices at a low velocity (1.5 litres s^{-1} m^{-2}) through occupant-controllable swirl diffuser vents in the raised floor plenum.

The minimum fresh air requirement has been set at 22.5 litres s^{-1} per person to suit an occupancy level[19] of one person for every 15 m^2. Assuming a mean office height of 2.9m, there will be 1.9 air changes per hour (ACH^{-1}). Natural convection forces are used to move the air upward through the office space to extraction vents in the ceiling. The stale air will be exhausted through horizontal void space integrated into the structure of the pre-cast ceiling panels, and then move vertically out of the building along ducts on its north side. The external exposed surface of the north wall ducts are dark coloured, so that they absorb solar heat energy and assist in creating a natural thermal chimney. Roof-mounted wind-driven turbines have also been located on the outlets of these vertical ventilation chimneys, which will be used to generate electricity during the day. The wind turbines can also be used to assist night purge air flow rates when appropriate wind conditions exist. Figure 1 shows the movement of air at office level schematically.

Some parts of the CH_2 building, such as the toilets, rely on direct natural ventilation through windows (Figure 2). It is not clear, however, how a continuous flow of fresh air can be achieved, because only louvres at an upper level are indicated and no low-level openings are shown[20].

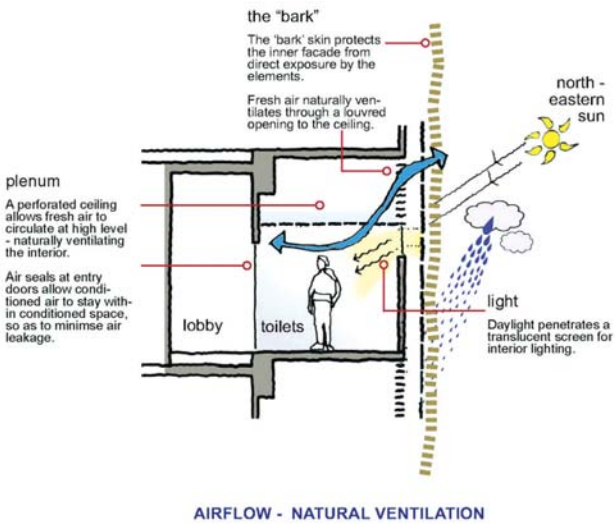

Figure 2: Schematic overview of ventilation system in CH_2 toilets. (Source: CoM, 2004)

At night, one of the strategies employed to simultaneously cool the internal fabric of the building in summer and introduce fresh air into the building is night purging. The windows will be automatically opened at night when outside air temperatures are between 19 and 21°C. The area of open window, found necessary for optimal cooling, is 25m^2 per floor (AEC, 2003c). Air entering the building at night will not be filtered[21].

System Components

The ventilation system in the CH_2 building comprises a number of components. These are now described and their contribution to the efficacy of the system as a whole is discussed.

Air Intakes

The position and height of the fresh air intake has a direct bearing on the quality of the fresh air introduced into the building. If the air intake is placed in an area of high concentration of polluted air, then it is likely that indoor levels will reflect this, irrespective of the quality of the filtering system. The impact of the location of air intake on a naturally ventilated building located close to a busy urban road was investigated by wind tunnel experiments (Green et al., 2001). The authors found that by locating the intakes on the non-roadside of the building, maximum concentrations of tracer gas were 50 per cent lower than for roadside locations. They also found that irrespective of wind direction, roof-mounted intakes resulted in significantly lower concentrations, which supports the air intake location design decision made for CH_2. Concentrations at the first floor level, however, were only five per cent lower than at street level.

The analysis of Melbourne's inner city air quality, described earlier, indicates that on some occasions the level of certain pollutants can exceed desirable levels. The fresh air intakes for the CH_2 building are located approximately 38m above street level and therefore outdoor air pollutant concentrations of intake air should be lower than EPA city measurements. However, in the case of the toilets, fresh air enters from the outside via louvres, and for the lower storeys of the building this could mean that air with an unacceptable level of pollutants will be admitted to these areas on occasions[22]. Ventilation air intake positions should also be carefully sited with respect to the cooling towers. Although the cooling of the CH_2 building is by an indirect system, and the cooling tower water flows in a closed loop, drifts of droplets from cooling towers may enter the building, particularly when the windows are open[23]. According to NOHSC (1989), drift must be eliminated or at least reduced to 0.02 per cent of the circulated water.

19 City of Melbourne update: CH_2 has an office net letable area (NLA) of 7573.97 sq metres. As of April 2006, there were 536 workers allocated to CH_2, including 100 that are shift workers and will spend most of their time out of the office. Based on these figures the building is expected to have an average occupancy density of approximately one person per 14.13 square metres.

20 City of Melbourne note: Low-level air louvres are included on the east and south facades of the toilets for each floor to improve air flow through the toilets.

21 City of Melbourne note: To ensure breathing air quality standards are maintained, night purge air may need to be vented before morning workers arrive. The need for this will be decided once the building is operational. The need for venting with filtered air would seem un-likely given the emission-generating activities in the city are minimal in the early morning period and that all air that has entered during night purge operation will be removed in a little more than half an hour at the design air supply rate of 1.9 air changes per hour. Refer also to Footnote 2.

22 City of Melbourne note: Air in the toilet areas will only be encountered by individuals for short periods and it is worth acknowledging that most people experience far longer contact with this same air while coming and going from the city or sitting in an outdoor cafe.

23 City of Melbourne note: Windows will be open only during night purge operations, which will occur when the building is normally unoccupied. To enter occupants' lungs, water droplets would need to descend down the side of the building, travel horizontally through a flyscreened window at night and remain airborne until the building is occupied in the morning.

Wind Driven Ventilators

Six wind-assisted extraction vanes or wind turbines are to be mounted on top of the north façade. These units are to be 3.5m high and custom-designed for the CH_2 building[24]. At the time of writing no details of their design or performance were available, and therefore a critical assessment is not possible.

The concept of improving ventilation efficiency using turbine ventilators, however, is not new. West (2001) reports favourably on the use of the stack effect and wind-driven long volume turbines (LVTs) on the Science Precinct Building of the University of New South Wales to assist ventilation, where there is a "good, constant wind source". However, no building performance data has been reported for the NSW building.

Some research literature reports the performance of these devices themselves. Lai (2003) discusses the performance of the common turbine ventilator on extraction rates, following wind tunnel experiments. Unfortunately the wind velocity range (10-30 m s^{-1}) used by that author is not representative of central Melbourne, so the research has limited value. The average long-term wind velocity in Melbourne is in the range of 2.6-3.3 m s^{-1} (Roy and Miller, 1981). Wind velocity will increase with height according to the 'seventh-root' law and at 40m the velocity will be approximately four m s^{-1}. At the lowest velocity (10 m s^{-1}) used by Lai (2003), the induced velocity increased from approximately 60 m^3 h^{-1} (with no ventilator) to 140 m^3 h^{-1} for a 0.5m diameter turbine ventilator. The total office volume in the CH_2 building is approximately 28,000m^3. Using six wind turbines, as proposed, each unit would be required to induce 4667 m^3 h^{-1} for an air change rate of 1.0. Assuming that the output of the proposed 3.5m high turbines is proportional to the 0.5m unit, the best achievable ACH^{-1} would be 0.2 at a wind speed of 10 m s^{-1}. When wind speeds are insufficient, the turbines can be electrically driven to induce the necessary level of air change rates, with in the energy consumption cut off limitations discussed earlier.

Air Filters

High efficiency filters are capable of removing 95 per cent of particles with an aerodynamic diameter of 0.03 µm, and can reduce the total indoor concentration of particles of this size by a factor of 10 to 15 (Fisk and Rosenfeld, 1997). Filters may be flat or pleated. The former are suitable to collect large particles and can be made of a variety of materials (glass, synthetic or vegetable fibres, or animal hair). Pleated filters use smaller fibres and can collect smaller particles. However, used filters, while removing particles from the passing air, can also pollute that air instead of cleaning it. According to Clausen (2004), a "used filter in a ventilation system can have an adverse impact on perceived air quality and the performance of office work, and cause Sick Building Syndrome (SBS) symptoms.

Bluyssen et al. (2003) state that filters are one of the main sources of pollution, particularly odours, in normal ventilation systems. Those authors also concluded from a study of the literature that it was still unclear what causes sensory pollution from filters. One clear finding is that the water content of filters emerged as a clear factor contributing to microbial growth. A series of experiments on filters by Bluyssen et al. (2003), performed as part of the European AIRLESS project found that:

- low temperatures (below 0C) and high humidities (greater than 80 per cent) may produce odour intensities;
- micro-organisms were not the main pollution sources in filters, as measured by sensory emissions;
- glass fibre filters had less sensory emission than cellulose;
- new filters (three days old) emitted higher odours than 33 day old filters. As filters age, the pollution level increases again;
- there was no statistical difference in odour intensity or volatile organic compound emissions between filters subject to continuous or intermittent flow; and
- an increase in airflow did not change odour intensity.

All the air entering the CH_2 building is to be passed through primary and secondary filters. This means that the concentrations of many of the particulates of outside origin (see Table 3) may be greatly reduced before air is introduced into the CH_2 ventilation system. Precise details of the filtering system to be used in the CH_2 building were unavailable at the time of writing this study as these design details had not been finalized, so it is not possible to comment on the likely efficacy of the system, but average arrestance rates of greater than 90 per cent have been specified.

Ducting

Ductwork, both new and old, will pollute air passing through it. The cause and extent of the pollution will depend on the manufacturing process, the type of ducting used and the length and design of the system. Concentrations of dust in ductwork provide the conditions for the growth of microorganisms. These concentrations are essentially determined by the quantity of dust in the passing air, which is a function of the filtration system. The velocity of the air determines the deposition rate and the duct geometry determines where depositions of dust accumulate. Dust will adhere to any surface film of oil, if this has been used in the duct manufacturing process. If the water content of the passing air is high, the opportunity for microbial growth is increased. The longer the ductwork, the worse the pollution at the outlet end. In addition, smooth ducting is superior to any spirally wound or flexible varieties.

24 City of Melbourne note: The extraction turbines include a multi-function motor system that can be operated as a braking device in excess wind, and can be used to generate energy when daytime wind conditions are suitable. At night when wind conditions are favourable the turbines will spin, helping the flow of air during night purge operations. When wind conditions and natural buoyancy effects at night are insufficient to achieve the required night purge air flow rate, the wind turbine motors can be electrically driven to achieve the required extraction rate. There will, however, be an optimal energy consumption limit for using the turbines to forcibly extract night air, which will be determined by the amount of energy required to drive the turbines and the passive cooling energy benefit gained.

All the fresh air entering the CH_2 building is drawn down through ducting on the south side of the building, and distributed into the offices via controllable vents. A detailed evaluation of the CH_2 ducting system was not possible from the information available at the time of this study. Table 4 of Bluyssen et al. (2003) suggests 15 strategies to ensure the design and operation of a good ducting system. These are:

- using a material that does not use oil in the manufacturing process;
- using a duct material that does not emit pollutants itself;
- ensuring that the duct has a smooth interior surface;
- avoiding sharp-edged curves, transition pieces or self-tapping screws in walls of ducts;
- closing the end of ducts when not in operation during transport, construction and at any time prior to use;
- keeping all duct accessories in closed boxes;
- removing packaging just before installation;
- cleaning all ductwork before installation;
- installing an air filter to clean air prior to its entry into the ducts;
- preventing condensation points;
- avoiding flexible ducting;
- placing insulation on the outside of any ducting;
- avoiding sealants with high emissions;
- installing inspection and cleaning openings; and
- installing stiffeners and fittings in such a way that dirt and dust does not accumulate and cleaning is easy and effective.

Building Materials, Paint, Furniture and Fittings

Brown et al. (1994) provides a useful table of the total volatile organic compounds (TVOC) emission rates of indoor sources, which include 'wet' household products, and

'wet' and 'dry' construction products. Some of those are reproduced in Table 8 to illustrate the magnitude and range of emission rates. While the variety of measurement methods used to produce the data precludes direct comparison, it can be seen that 'wet' products are significant sources of emissions, which are sometimes orders of magnitude greater than 'dry' products. Household 'wet' products are particularly likely to have high emission rates.

Product	Emission rate (μg m^{-2} h^{-1})
Wet household products	
• Solvent-based waxes and detergents	up to 2.6×10^8
• Toilet deodorisers	up to 3.7×10^6
• Liquid floor detergents	1.7×10^4
Wet construction products	
• Sealants, including silicones	up to 7.2×10^4
• Wood stain	1.7×10^4
• PVA water-based glue	2.1×10^3
Dry construction products	
• Felt carpet	80-110
• Polyurethane foam	120
• Gypsum board	30
• Mineral wool	10

Table 8: Emission rates of TVOC of selected indoor sources. (Source: Brown et al., 1994)

The construction materials, furnishings and fittings used in the CH_2 building have been addressed specifically to reduce emissions. For example, "all materials used in CH_2 are being subjected to a full environmental audit to ensure, among other things, that low volatile organic compound materials are used in products such as carpets, paints adhesives and sealants" (CoM, 2004). A comprehensive database, based on replies to an environmental performance questionnaire of material and product suppliers, has been established to guide material selection decisions (DesignInc, 2003). All input data will be audited by the CSIRO and the outcome will be used as the basis for final product selection. At the time of this assessment, no decisions on particular construction materials had been made. The choice of cleaning products, however, does not appear to be have addressed at this stage, but as Table 8 illustrates, appropriate products must be used to maintain the 'low-emission' environment established in the new building.

Indoor Plants to Absorb Voltaile Organic Compounds

Potted plants will be part of the 'system' used in the CH_2 building to reduce contaminants in the indoor air. Research in Australia has demonstrated the ability of certain plants and their potting mix to reduce the concentration of volatile organic compounds in enclosed spaces (Wood et al., 2002). In experiments conducted in test chambers, *Spathyphyllum wallisi* (Petite Peace Lilies) were shown to reduce concentrations of benzene from 25 ppm to almost zero over two to three days. *Dracaena deremensis* (Janet Craig) were also observed to reduce n-hexane levels from 100 ppm to approximately 70 and 10 ppm in 2.5 and 11 days respectively.

Although the authors did not show the natural decay rate of the two volatile organic compounds in test chambers without plants or growing medium, leak tests were conducted to correct for chamber leakage. The volatile organic compounds removal rate was found to vary with species. For benzene, the highest rate of 686 mg m^{-3} d^{-1} per m^2 of leaf area was achieved by the *Dracaena deremensis*. For n-hexane, *Howea forteriana* (Kentia palm) removed 4032 mg m^{-3} d^{-1} per m^2 of leaf area, almost double that achieved by the next best performing species, *Spathyphyllum wallisi* (Wood et al., 2002).

The number and type of potted plants proposed for use in the CH_2 building had not been decided at the time of this study. The levels of benzene and n-hexane used by Wood et al. (2002) were 25 ppm (80 mg m^{-3}) and 100 ppm (353 mg m^{-3}), which were five and two times the Australian maximum allowable occupational exposure concentration (NOHSC, 1995b). N-hexane is an indoor pollution source emanating from furnishings, cleaning agents, cosmetics and clothes. Some of these (ie furnishing and cleaning agents) can be limited by initial design and ongoing management decisions made for CH_2. Benzene mainly comes from vehicle emissions, and poses a greater hazard because of the building's location and the ingress of unfiltered air at night. Plants with the greatest ability to absorb benzene would therefore be the most appropriate choice.

Performance of Non-conventional Designed Air Conditioned Office Buildings

The CH_2 building uses a mechanically driven ventilation system during the day and a naturally driven system at night[25]. There is no recycling of air (i.e. all daytime ventilation air is outside air). The toilet-bathrooms in the building are primarily naturally ventilated at all times. Comparison with office buildings with similar systems is therefore appropriate in terms of air quality, health and productivity.

Air Quality

For an initial perspective on the levels of total volatile organic compounds (TVOC), concentrations in all types of office building, the work of Brown et al. (1994) is useful. These authors, reviewing 50 overseas studies, found that concentrations of TVOCs are generally appreciably higher in established residential dwellings compared to office buildings (Table 9). The reasons for this difference were unknown. The concentrations in new buildings of both types were of similar levels, and higher than in established buildings. Although the number of offices, included in the studies reviewed, is considerably smaller than the number of residential buildings, the data suggests that office workers are more likely to be exposed to more harmful air in their own homes than in their workplace.

When various studies of buildings specifically using natural ventilation were reviewed, the findings are mixed. For example, Hedge et al. (1989) found no statistical differences in concentrations of carbon dioxide and monoxide, ozone and total oxidants in two office buildings with different ventilation systems. However, concentrations of formaldehyde, volatile organic compounds and respirable particulates were higher in the building with a conventional HVAC system.

Building Type	No of Buildings	TVOC WAGM (µg m^{-3})
Residential		
• Established	1081	1130
• New	33	4500
• Complaint	14	520
Office		
• Established	60	180
• New	1	4150
• Complaint	51	490

Table 9: Comparison of TVOC concentrations in established, new and complaint residential and office buildings. (Source: derived from Brown et al., 1994)

Three offices in central London and one in a rural location, all naturally ventilated, were evaluated by Phillips et al. (1993). Although the offices of the CH_2 building are ventilated during the day with filtered and conditioned air, the results of the study are indicative of air quality in the toilets during the day and the contaminant in the building during night purge operations. Carbon dioxide (CO_2) levels exceeded 1000 ppm in all of the monitored offices at some time during the day over the two-month monitoring period. Carbon monoxide (CO) levels ranged from 1.9-5.4 ppm, which was 36-76 per cent of the outdoor level. The lowest value was measured in the rural location. Peak levels corresponded to periods of peak traffic. Levels of nitrogen oxides (NOx) followed a similar trend to CO levels and peak values ranged from 0.11-0.137 ppm (23-68 per cent of outdoor level) for the three city offices. Ekberg (1996) confirms these higher values of indoor-outdoor level ratios. For an ACH^{-1} of 1.9, this author demonstrated that the ratio of indoor peak concentration to outdoor peak concentration can be as high as 0.6, assuming a triangle concentration pulse, indoor pollution sources and sinks to be zero, and no filtration, for a mechanically ventilated building.

25 City of Melbourne note: Day-time ventilation performance is designed to provide occupants with air for breathing and comfort requirements, especially humidity, while the night-time system is designed to passively cool the concrete structure.

Health

Fisk (2002) refers to a study that found that there was a 35 per cent reduction in short-term absence in buildings with higher ventilation rates. Another study cited by Fisk (2002) suggested "that a 10 cfm (5 L/s) per person increase in ventilation rates would decrease the prevalence of most common sick building syndrome (SBS) symptoms by one third on average." Even higher ventilation rates have been advocated now for good health. In a review of 105 papers on the effects of ventilation on health, comfort and productivity in non-industrial indoor environments, a multidisciplinary group concluded that outdoor air supply rates below 25 L s^{-1} per person increase the risk of SBS symptoms and short-term sick leave (Wargocki et al., 2002a). The rate proposed for the CH_2 building is 22.5 L s^{-1} per person, which, while considerably higher than current Australian building standards requirements, is still 10 per cent lower than some current thinking in Europe[26,27].

Fresh air at whatever rate may be delivered by a mechanical or natural ventilation system. Both of these methods of air delivery are employed in the CH_2 building[28]. The findings related to the system of fresh air delivery are mixed. In their comparison between an air conditioned and adjacent naturally ventilated office cited previously, Hedge et al. (1989) found that health impacts were significantly lower in the naturally ventilated office, although no significant correlation could be found between the pollutant concentrations and symptom prevalence. There was some significant relationship with feeling ill and formaldehyde levels. The measurements of the indoor climate in 14 town halls were made in Copenhagen and compared with results of a questionnaire study of over 4000 employees (Skov and Valbjorn, 1987). No statistical difference could be established between the naturally ventilated and mechanically ventilated buildings, although the lowest prevalence of mucosal irritation and work-related general symptoms were found in the oldest town halls. This latter finding appears to support the conclusion of Brown et al. (1994) cited earlier. By contrast, another comparison between an air-conditioned and a naturally ventilated building (Parat et al., 1997) found that air microbial content was significantly higher and more variable in the latter building. In addition, the fungal content of the naturally ventilated building was strongly dependent on outside levels. While this was relatively constant in the air-conditioned building, no difference could be observed in various gaseous pollutants.

Higher ventilation levels have been associated with reduced sick leave (Milton et al. 2000). These authors analysed the sick leave over one year for some 3700 employees of a large US manufacturer and found consistent associations of increased sick leave with lower levels of outdoor air supply, but the reasons for this were not clear.

The authors also found an association between humidification and increased sick leave, which they suggest may be due to the longer survival rate of common respiratory pathogens in a more humid environment.

Productivity

It should be noted that office productivity is a complex topic and there are many factors which impact on an occupant's performance in the workplace. Ventilation and indoor air quality are only two contributory factors along with temperature, noise, light, stress, morale, workload and management. Isolating the effect of ventilation and air quality alone is therefore difficult.

Reviewing the linkages between improved environmental conditions and productivity, Fisk and Rosenfield (1997) caution that much of the research is from laboratory experiments and their relevance to "real-world settings is uncertain". For example, Wargocki et al. (2002b) demonstrated the significance of pollution loads on simulated office work. Some more recent measurements in call centres appear, however, to confirm the link between airflow rate and the productivity of the workers in that type of workplace. Tham (2004) found that increasing the supply of outdoor air at 24.5ºC from 5 to 10 litres s^{-1} per person decreased the talk time of call-centre workers in a tropical country significantly, compared to a supply temperature of 22.5ºC. The impact on the productivity of 26 northern European call-centre operators of a variable airflow rate, in conjunction with clean and used air filters, was investigated by Wargocki et al. (2004). Replacing a used filter with a clean filter reduced talk-time by about 10 per cent at the high flow rate but had no significant effect at a lower rate. Talk-time increased by eight per cent with a used filter and high flow rate, but decreased by six per cent with a clean filter. These findings are perhaps of significance to the operation of the CH_2 building air filter system.

Conclusions

Seppanen and Fisk (2004) have summarised the human responses to ventilation from the current research literature. They concluded that "higher ventilation rates reduce the prevalence of airborne infectious diseases" and that "ventilation rates below 10 litres s^{-1} per person were associated with a significantly worse prevalence of one or more health or perceived air quality outcomes." For rates between 10 and 20 litres s^{-1} per person, there was a "significant decrease in the prevalence of Sick Building Syndrome (SBS) symptoms and improvement in perceived air quality."

26 City of Melbourne note: Ventilation rates for CH_2 are twice the Australian standard.
27 City of Melbourne note: Ventilation rates and expectations by occupants are very culturally dependent, which is one reason for the difference between European, Australian and North American standards. It is also important to consider the quality of the air and how it is supplied to the space when determining effective ventilation rates for good health. For example, it would be important to consider the impact of dilution (mixing) versus separation (displacement) supply systems and to evaluate the influence of air recycle rates compared with 100 per cent fresh air supply.
28 City of Melbourne note: The purpose of each method is, however, very different in the operation of CH_2. Daytime mechanical ventilation is for the purpose of supplying suitable quantities of air to satisfy occupant physiological breathing and comfort requirements. Night-time natural ventilation, during purge operations, is for passively cooling the exposed concrete ceilings to reduce energy use for daytime cooling.

Since the building has yet to be completed, commissioned and occupied, conclusions about the effectiveness of the ventilation strategy and its impact on occupant health are necessarily speculative. However, clean fresh air in adequate quantities is clearly required for human health and perceived wellbeing. The daytime fresh air supply for the CH_2 offices will be provided by a mechanical system at a rate of 22.5 litres s^{-1} per person, which is slightly lower than currently advocated in Europe but significantly higher than required by current building standards in Australia[29]. In the toilets and at night, however, ventilation of the offices will be induced by natural means. Ventilation of the offices at night is mainly required for cooling, rather than the removal of pollutants, and ventilation effectiveness at night may not influence indoor air quality during the daytime. However, removal of odours and particulates from the incoming air in the toilets, especially those near ground level[30], may be inadequate if natural ventilation alone is used[31].

High levels of ventilation are now often advocated to improve indoor air quality, health and productivity. However, the survey of 56 HVAC office buildings in nine countries all over Europe found that although there was an average ventilation rate of 25 litres s^{-1} per person, nearly 30 per cent of occupants and 50 per cent of visitors still found the air unacceptable (Bluyssen et al. 1996). High ventilation rates alone are therefore no guarantee of acceptable indoor air quality. The same study concluded that materials, furnishings and activities in the office, and the ventilation system itself, were the important sources of air pollution, not the occupants. The measures taken to reduce the internal sources of pollution in CH_2, such as low emission fittings and the use of plants to absorb pollutants, should be effective, and therefore the major source of pollutants will be external. Given its inner-city location and the possibility of excess particulate levels, the efficacy of the filtering system will be a major determinant in indoor air quality.

Evidence for reduced sickness due to higher ventilation rates does not appear to be conclusive[32]. In the study of over 6500 office workers, Bluyssen et al. (1996) could not establish a correlation between the occupants' health and their acceptability of the air quality, although there was a significant correlation between perceptions of air quality and measured ventilation rates. In terms of a direct link between ventilation and productivity, the evidence to date is mainly from experiments, rather than measured data from real-life conditions. Some measured productivity gains amongst call-centre workers have been linked to airflow rate, but not necessarily at high levels. The effect of ventilation rate on performance is therefore not independent of other factors such as temperature and filter system condition. Productivity increases will be achieved indirectly if there is less sickness-related absence. The current evidence suggests this is likely to be the major benefit of the ventilation system proposed for the CH_2 building.

29 City of Melbourne note: 22.5 litres per second per person is equivalent to almost two air changes per hour, which means that every half an hour almost all the air in the building will be flushed out and replaced with freshly filtered outside air. It is important to recognise this air will be supplied to each worker via individual swirl diffusers, which are expected to result in workers breathing a better quality of air than that provided by traditional displacement or mixing air supply systems. This is because traditional displacement and mixing systems generally supply only 15-20 per cent fresh air, which means occupants are typically breathing air that is recycled at a rate in the vicinity of 80-85 per cent. In addition, these traditional systems generally supply air through a significantly smaller number of outlets, which produce a much less uniform supply of air. Refer also to Footnote 13 and 14.
30 City of Melbourne note: There are no toilets on the ground floor, and the first floor toilets are mechanically ventilated due to a different configuration to the rest of the building. Consequently the lowest level air intake for CH_2 toilets will be a full eight metres above street level.
31 City of Melbourne note: The potential for odour and pollution from unfiltered outdoor air entering the toilets needs to be put in context. This is the same air encountered by those in the many nearby outdoor cafes and the pedestrian-focused surrounding streets.
32 City of Melbourne note: CH_2 does not rely on ventilation rates alone to reduce sickness rates. Other key design aspects include the use of 100 per cent fresh filtered air; relative humidity control to reduce the growth of mould in the building and ventilation duct work; under-floor air supply through diffusers distributed evenly across the floor plate; and vertically correlated ceiling vents to reduce the horizontal mixing of air through the office. This last design feature potentially will have a great impact on health because, for example, if someone sneezes in one part of the office, there will be a greatly reduced chance that infection will spread horizontally to others in the area.

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