Technical Research Paper 05

Heating and Cooling in the CH$_2$ Building

city of Melbourne

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Disclaimer

This series of research papers was prepared as a body of work funded under a Commonwealth Government AusIndustry Innovation Access Program grant and supported by cash and in-kind contributions from the City of Melbourne, Sustainable Energy Authority Victoria, the Building Commission of Victoria, the Green Building Council of Australia and the CH$_2$ Project Design and Consulting Team. Neither City of Melbourne nor any funding agency or supporting organisation, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, design, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favouring by the City of Melbourne or any party thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the City of Melbourne or any party thereof.

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 05

Heating and Cooling in the CH_2 Building

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Introduction

The heating and cooling of buildings has a long history. Active heating systems began with cave dwellers, who lit open fires for warmth and light in their rock caverns. More advanced heating systems were adopted by civilisations such as that of the Romans, who operated furnaces below their buildings and ducted the resultant hot gases to upper level rooms to provide warmth. The hypocaust, as it was known, has found a modern day equivalent in the form of advanced fabric energy storage systems such as the Termodeck™ system. The provision of cooling in buildings has always presented designers with a greater challenge than heating. Early cooling systems made use of natural draft and evaporative effects, and this knowledge is being revisited today as building designers strive to provide cooling that does not incur a heavy environmental cost.

Heating and cooling systems have become obligatory in most modern office buildings. Aside from issues of occupant comfort and expectations, some believe that the productivity of workers is related to the temperature and humidity of their working environment. This study assesses whether the heating and cooling system proposed for the CH_2 building provides the necessary and/or expected thermal conditions for its occupants. It begins with an overview of the requirements for thermal comfort in terms of temperature, humidity and air movement. Having established the criteria by which any conditioning system should be judged, the system proposed for the CH_2 building is then described and evaluated in the light of these criteria and previous experience, both in Australia and overseas. Finally, the system proposed and the conditions likely to be created within the CH_2 building are reviewed against the current research literature on productivity. Since the building is still under construction, no measured data from the building is available to verify performance. Therefore the proposed design has largely been evaluated using a selection of the design consultants' documentation and refereed literature in international journals. As the building is still being constructed, design changes made subsequent to this evaluation are obviously not considered.

Thermal Comfort[1]

While the human species can tolerate extremes of temperature[2] for prolonged periods of time and even work under these conditions, they are not the choice or expectation of today's office workers who will tolerate a much smaller range of thermal environmental conditions (temperature, air velocity and relative humidity). A widely accepted definition of thermal comfort is "that state of mind that expresses satisfaction with the thermal environment" (ASHRAE, 1992). Many factors (physical, physiological, and psychological) determine whether an individual perceives their environment to be comfortable. The purpose of any conditioning system is to create a local environment which will minimise feelings of thermal discomfort. In general, this means maintaining the body temperature within a certain narrow range with low skin moisture content. The ASHRAE Standard 55 "specifies conditions or comfort zones where 80 per cent of sedentary or slightly active persons find the environment thermally acceptable." Summer and winter clothing levels are assumed to be 0.5 and 0.9 clo respectively (1 clo is equal to an overall equivalent thermal resistance, R value, of 0.16 m^2C/W). For a woman, the summer clo value is the equivalent of wearing a knee length skirt, a short sleeved shirt, panty hose and sandals, while for a man, the winter clo value is roughly the equivalent of wearing a suit with a short sleeved shirt.

[1] City of Melbourne note: From the outset, readers should understand the cooling strategy for CH_2 is to cool by radiant absorption using chilled water pumped through ceiling panels rather than to cool the occupants and occupied space of the building with large volumes of cool air. Therefore, the temperature of the air is not the primary design benchmark, comfort indicator or control variable to achieve thermal comfort in buildings using radiant systems. The basis for the radiant-heat-absorption cooling approach in CH_2 is based on human physiology and the way human skin loses heat and the body senses environmental conditions (i.e. temperature, humidity and draughts). Humans are hot blooded mammals that add heat to their office environment at rates depending upon their physical activity and emotional state. Physiologically, people have cooling systems that are sensitive to air humidity, air movement, surface temperatures. Also, human skin is more responsive to the cooling or heating effects of radiant surfaces within a room than to direct contact with the air surrounding the body. Refer footnote 5.

[2] Author note: Figure 1 from Bennett (1977), cited in Lorsch and Abdou (1994a), indicates healthy people can survive in temperatures above 43º and below -30ºC for extended periods.

The boundaries of the comfort zones can be expressed as a function of operative temperature and the relative humidity (RH) of the surrounding air. As a result, the comfort zones in summer and winter are defined by two quadrilaterals superimposed on a psychrometric chart, as shown in Figure 5 of ASHRAE (2001). Broadly interpreted, in winter a range of 20-24.5ºC and 85-20 per cent RH can be tolerated. As the temperature rises, the RH must be lowered to maintain thermal comfort. A similar picture is evident in summer, but with an extended range, based on the assumption that the occupants will wear lighter clothing. Thus in summer, the thermal comfort range varies from 22.5-27ºC with corresponding RH levels of 80 and 20 per cent respectively. There is a small overlap between summer and winter zones. In the middle of each zone, a person would experience their environment in a neutral way, but at the boundaries sensations of slight warmth or coolness would occur.

The above boundaries may be extended if the building relies on the adaptive response of its occupants. The theory, advanced by researchers (such as de Dear and Brager, 2001) is that building occupants will adapt their behaviour, based on surrounding conditions, and hence tolerate wider extremes in a building's internal environment. The expanded comfort zones should result in energy savings. These ideas are particularly suited to buildings such as CH_2, which use a range of non-conventional technologies and where natural ventilation might also be used[3]. The designers of the CH_2 building, however, have proposed a climate-controlled office, rather than an adaptively controlled one, principally because they do not believe it would be feasible to open windows during the day due to the building's inner city location[4]. The heating and cooling system of the CH_2 building has been designed to maintain office air temperatures in the range of 21-25ºC and provided this is achieved with acceptable levels of relative humidity, the building should satisfy most occupants in terms of thermal comfort[5].

Temperature Gradients[6]

Temperature gradients are experienced in most occupied spaces in buildings. ISO 7730 (ISO, 1984) recommends that the difference in air temperatures at 0.1 m and 1.1 m above the floor, i.e. approximately at ankle and head heights for a seated person, should not exceed 3.0ºC. Thermal gradients can occur for a variety of reasons, but common causes include the downdraught caused by cool internal surfaces, infiltration of cool outside air and the poor mixing of room air, especially following the introduction of fresh air.

Wyon and Sandberg (1996) studied the impact on thermal comfort due to slight departures from thermal neutrality and moderate vertical thermal gradients. A total of nine treatment conditions were established following investigations into whole-body heat loss using a thermal mannequin. The thermal parameters of the study were three heat loss rates, namely 40, 48 or 56 Wm^{-2}, with thermal-neutrality having previously been established to correspond to a total heat loss of 47.2 Wm^{-2}. Three different thermal gradient conditions used were zero, two, or four $K\ m^{-1}$. Over 200 subjects, aged between 18 and 65, were subjected to the nine thermal combinations possible using the heat loss and gradient conditions described above. The results of the study showed that local thermal discomfort could be experienced by 20-40 per cent of a randomly selected group. Furthermore, discomfort was due to individual differences in thermal neutrality. If subjects have individual control of the equivalent temperature, then the percentage of people dissatisfied can fall to five per cent. Wyon and Sandberg (1996) also concluded, however, that thermal gradients due to displacement ventilation could be as high as 4ºC, if individual control of whole-body heat loss was provided for some sensitive individuals. This conclusion is relevant to the CH_2 design because the displacement technique[7] will be used for fresh air delivery and some control over supply air registers will be provided. No control over individual supply air temperature is possible, however, in the current CH_2 design[8].

[3] City of Melbourne note: One of the main requirements of the overriding design brief for CH_2 was to pursue the Property Council of Australia's A-Grade office criteria. Although CH_2's heating and cooling systems are non-conventional, indoor environment and comfort standards had to meet or exceed conventional standards to satisfy industry and tenant expectations.

[4] City of Melbourne note: The primary reason for not using natural ventilation during the day is related to the depth of floor plate and the problems associated with ensuring suitable uniform air flow throughout the space. In addition, windows lack individual control by all the users within an open plan workspace. This lack of control prevents the application of adaptive comfort standards to widen acceptability ranges. It should also be noted that air conditioning was required to meet the PCA grading included in the design brief and to meet commercial market expectations.

[5] City of Melbourne note: CH_2 is designed to maintain the office at a resultant temperature of 21-23º C, which is the mean of air and radiant temperatures. As highlighted in footnote 1, the thermal comfort of occupants in CH_2 is to be achieved primarily by radiant cooling rather than by cooling with chilled ventilation air.

[6] City of Melbourne note: This section does not explicitly consider the influence of chilled ceiling panels or swirl diffusers on the formation of thermal gradients or stratification within the office space. Thermal gradients in relation to thermal comfort, heat sources and wall surfaces are, however, discussed. In response to this gap, the City of Melbourne has commissioned a supplementary technical paper that specifically considers the influence of chilled ceiling panels in conjunction with under-floor air supply through swirl diffusers on thermal and ventilation performance.

[7] City of Melbourne note: CH_2 does not apply the displacement technique therefore the conclusion is not relevant. Ventilation in CH_2 is provided by an under-floor air supply using occupant-controlled swirl diffusers (UFAD). Swirl diffusers have been used to ensure rapid removal of moisture form the space during the morning start-up mode. Any attempt to use the displacement ventilation techniques in CH_2 has been prevented by the formation of convection currents introduced by the chilled ceiling panels. Refer to the following web link, www.cbe.berkeley.edu/underfloorair/glossary.htm, for detailed definitions of UFAD, which is summarised here: "An under-floor air distribution 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 (AHU) 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 draught discomfort is minimised, as supply air temperatures are higher than those for conventional ceiling-based systems and occupants have some amount of control over their local air supply conditions."

[8] City of Melbourne note: Although occupants do not have direct control over the supply-air temperature, people will be able to request changes to the levels of cooling supplied to each chilled ceiling panel control zone.

The position of heat sources will also influence the vertical temperature profile within a room using a displacement ventilation (DV) system, or similar as in the CH_2 building. Li et al. (1992) found that there was a greater variation in temperature at head height for a 600 W heat source placed 0.11 m above floor level compared to the same heat source located at 0.56 m or 1.06 m. The difference between the room and supply temperatures was nearly 1.5ºC greater when the heat source was at 0.11 m. This variation is significant considering that the recommended maximum difference should not exceed 3.0ºC. The horizontal location of the heat source only had a minor influence. This finding has relevance to offices such as CH_2 because heat sources such as printers are usually mounted on desks.

The same authors investigated the impact of various wall surface emissivities (Li et al., 1993). The same test room used in their earlier work was used to investigate the impact of thermal radiation from the internal surface of the walls[9] on air stratification within the room. Surfaces with a high (black paint) and a low (aluminium) emissivity were tested. Larger stratification was found to occur with the aluminium coated wall because there was less thermal transfer from the walls to the ceiling and floor. Normal room surfaces have a high emittance, even for light coloured paints, so the possibility of suppressed thermal radiation transfer (and increased stratification) is unlikely to occur in the CH_2 building.

Relative Humidity

The fresh air delivered into the offices of the CH_2 building is designed to have a dry bulb temperature of 19ºC[10] and a relative humidity level below 65 per cent[11] (AEC, 2003a). Under these conditions, the absolute humidity ratio of the air is approximately 0.009 kg kg^{-1} of dry air. Using hourly climatic data for a typical meteorological year in Melbourne (Morrison, 1990), ambient relative humidity levels exceed this level for 48 hours a year, i.e. less than one per cent of the total hours. In one third of those hours, the temperature exceeds 19ºC and in the remaining hours the temperature is below the desired supply temperature. Sensible heating or cooling of the air to meet the design conditions will not remove water vapour. It is therefore possible that on a small number of occasions, the inlet air will exceed 65 per cent RH[12]. No details of any method to reduce the water vapour content from incoming fresh air when its absolute humidity level is too high were available at the time of preparing this paper.

There does not appear to be a large body of literature evaluating the impact of relative humidity on thermal comfort. In the relevant studies available, the effect of humidity on thermal comfort is measured by the subjects' tolerance of air temperature, rather than humidity per se. For example, the impact of high relative humidity on thermal comfort has been studied by Palonen et al. (1993). The study was carried out in an office building in Finland during winter, when the mean daily outdoor temperature varied between -16ºC and 6ºC. Air temperature levels ranged from 20ºC to 24ºC, with 22ºC regarded as the optimum level. Relative humidity levels were increased from 12-28 per cent to 28-39 per cent by steam humidification. The study population was 169 workers, who were asked to judge their degree of thermal comfort at various combinations of the above conditions. The researchers found that more humid air increases the tolerance of low temperature air and decreases tolerance of high temperature air. They also found the average percentage of workers who were dissatisfied with their room thermal climates was 40-45 per cent, even though these conditions were within the requirements of ISO 7730. It was concluded that the temperature range of 20-24ºC during wintertime may be too wide without individual temperature control.

The impact of higher levels of temperature and relative humidity on indoor air quality as perceived by sedentary subjects in climate chambers was investigated by Fang et al. (1998). In this study, air temperature and relative humidity levels varied in the ranges of 18-28ºC and 30-70 per cent respectively. Air polluting odours were also introduced into the chambers in the forms of polyvinyl chloride and acrylic sealant. The study found that there was a strong impact by temperature and humidity on the acceptability of the air, but the climatic factors had little impact on the perception of odours. Acceptability was linearly correlated with the increase in enthalpy of the air.

Air Movement and Drafts

Air movement is important in a closed environment for a number of reasons, including replenishment of oxygen and the removal of odours. However, air movement is not essential for thermal comfort, if a thermally neutral environment is provided in terms of temperature and relative humidity. For air speeds of 0.25 ms^{-1} or less, thermal acceptability is unaffected in neutral environments (Berglund and Fobelets, 1987, cited in ASHRAE, 2001). Excess air movement, on the other hand, can be experienced as draughts.

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[9] City of Melbourne note: Most of the space in CH_2 is not expected to be influenced by the internal surface of the perimeter walls due to the deep floor-plan, however, in other buildings this may be more critical.

[10] Author note: In the design study of chilled panel ceiling performance AEC (2003e), the inlet air supply temperature is stated to be 20ºC.

[11] City of Melbourne note: The use of cold surface elements, such as chilled ceilings and chilled beams, introduce sensible cooling within the space (refer to footnote 33 for description of sensible and latent heats of cooling). Therefore, if the humidity in the space is left uncontrolled, the moisture content may rise and condensation will start forming on the chilled surfaces whenever the dewpoint of the air rises above the surface temperature of the chilled element. Active humidity control is therefore a fundamental aspect of a chilled ceiling or chilled beam system design and is incorporated in CH_2. Refer footnote 12.

[12] City of Melbourne update: CH_2 has active humidity control of the primary air via a wet cooling coil and reheat. Therefore it is not possible for the RH to exceed 65 per cent as suggested by the authors as a mechanically controlled process will ensure that humidity limits are not exceeded. The active humidity control employed for CH_2 will provide a better moisture-controlled environment than traditional heating, ventilation and air-conditioning systems used in Australian buildings. Low relative humidity and high supply temperatures will limit opportunities for mould growth in air supply duct work. This is in contrast to the low temperatures and near-saturated supply-air conditions of normal variable air volume (VAV) systems that have the potential to create an excellent environment for the growth of mould in ductwork. Mould growth has been found to be a primary cause of sick building syndrome and therefore the approach of CH_2 is expected to have health benefits for occupants. In addition, swirl diffusers have been selected in place of displacement diffusers due to their ability to help remove moisture from the areas near the chilled ceiling panels in the quickest time.

Widespread human perceptions of air movement were found possible by Toftum (2004), who found that at temperatures up to 22-23ºC there was some danger that sedentary workers might find air movement to be unacceptable, but this decreased as the temperature was increased. Overall, whether air movement was perceived to be good or bad depended not only on the thermal environment, but also on personal factors such as activity level and thermal sensation. Toftum (2004) also suggests that other factors such as the degree of fatigue, clothing habits and gender of the subject may complicate the problem. Similar widespread responses to air movement were reported by Xia et al. (2000). These researchers investigated the effect of turbulent air movement for the temperature and relative humidity ranges of 26-30.5ºC and 35-65 per cent respectively using an environmental chamber. Subjects were able to adjust the air movement to suit their requirements. A wide variation of preferences was found but most subjects were able to achieve comfort after adjusting the air velocity. In the CH_2 building, one manually adjustable air supply diffuser is to be fitted per desk (AEC, 2003b)[13]. This facility should therefore increase the potential for occupant thermal comfort.

Heating and Cooling Systems

Passive and active systems are used to achieve thermal comfort in the CH_2 building. The main hardware components of CH_2's active conditioning systems are shown schematically in Figure 1, followed by general overviews of the heating and cooling systems. A more detailed description and review of the individual components used in the cooling system is then presented because the proposed design combines a number of novel features. Their expected performance in Melbourne is discussed with regard to international experience.

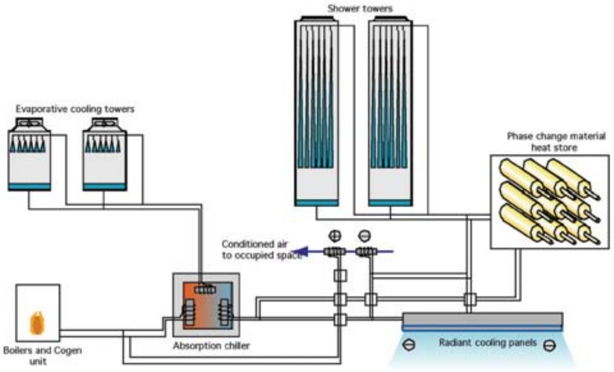

Figure 1: Schematic of proposed heating and cooling system in CH_2 Building. (Source: Kenton, 2004)[14]

Heating System Overview

Thermal modelling of the CH_2 building by consultants indicated that heating should not be required (AEC, 2003c)[15]. The passive design principles adopted plus the heat generated by the people, equipment and lights have been predicted to produce a cooling load even in winter, rather than a demand for heating[16,17]. However, the fresh air introduced into the building via the ventilation system will need to be heated on days when the outside air temperature is below 200C. For this reason and to cover any small direct heating requirements, a heating system is to be installed, which uses heat from the co-generation plant or natural gas fired boiler.

The cogeneration system, using a natural gas-fired micro-turbine[18], is to be installed primarily to produce electricity for the CH_2 building[19]. It has been estimated that approximately 100kW of the heat generated by the plant will be recovered and used either for direct heating or to drive the vaporisation process in the absorption chiller. Despite the potential to operate with a high overall efficiency (85-90 per cent), the use of small combined heat and power (CHP) systems in buildings is relatively new. Alanne and Saari (2004) have reviewed the status of small-scale CHP systems for this application. Operational experiences over long periods are not yet available, according to these authors, because of the relative newness of the technology.

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13 City of Melbourne note: The CH_2 design team gave careful attention to the effect of the passively cooled vaulted ceiling on generating convection currents, and the form and location of the chilled ceiling elements. This was to ensure excessive draughts were avoided and air movement around workers stayed within acceptable minimums. Tests were carried out on the convectively driven movement of air across the ceiling panels, the emissivity of the concrete vaulted ceilings and the positioning of the panels on the curved roof profiles. This included testing the material finish of the chilled ceiling panels in a test chamber in Germany to determine the impact of anodised and un-anodised surfaces.

14 City of Melbourne note: This diagram was not provided by the design team and is not representative of the system as designed, tendered or constructed. It does not convey correctly the use of centrifugal chillers, separate chilled water circuits for primary air and chilled ceiling panels, linage of the cooling towers to the phase change materials or the incorporation of dehumidification control. Refer to the Study Outline for a current image of the system.

15 City of Melbourne note: The report concluded that space heating is not the predominant driver for system design. Primary air heating and reheating is required and perimeter heating convectors are provided to northern and southern facades to provide skin heating for early morning warm-up in winter.

16 Author note: The energy required annually for space and water heating for most of a surveyed 31 commercial buildings in Melbourne was found to be between 130-310 MJ m^{-2} (PCA, 1997), so this modeling prediction may be overly optimistic.

17 City of Melbourne note: Re Author note 16, Property Council of Australia 1997 survey figures are for a total base building heating load. The energy range quoted is to provide for primary air heating demand in addition to space and water heating, so the figures do not indicate energy required for space heating in isolation. In Melbourne office buildings primary air heating is the biggest component of heating load when compared with space and other heating loads. The author's comparison and conclusion therefore appear misplaced.

18 City of Melbourne note: The natural gas micro-turbine will reduce pressure on electricity supply infrastructure during peak-demand periods, while using an energy source with a lower greenhouse gas emissions coefficient. Hence less greenhouse gas will be emitted per unit of electrical energy produced.

19 City of Melbourne note: The electrical load provided by the co-generation plant will meet the requirements of the computer room servers and its support systems, including air conditioning, light and power. This is estimated to be in the order of 60 kVA. Installation of the micro-turbine will ensure uninterrupted supply if Melbourne's electricity grid fails.

In their assessment of micro-turbines, high costs[20] and low electrical efficiency, particularly in the part-load condition[21], are the main disadvantages of the technology. Their low noise, weight and vibration level, together with small space requirements are the main advantages. In a comparison with other small CHP technologies, namely fuel cells, reciprocating and Stirling engines, gas micro-turbines were not considered to be the most technically compatible with office buildings. Reciprocating engines and fuel cells were considered to be superior. According to a government funded study in Australia, small (up to 300kW) high-speed reciprocating gas engines were likely to be the most efficient and financially viable way to provide power and heat to buildings (SKM, 2001).

In the CH_2 building, heat will also be recovered from the air exhausted from the offices using a heat exchange system[22]. It has not been possible to assess the heat recovery system, since no details were available at the time of the study. However this is a conventional technology and should work effectively if properly designed and operated. Waste or recovered heat will be distributed into each level by finned convective heaters[23] "set into the floor near the windows" on the north and south sides of the building. The warm air from these heaters is conceived to create "a barrier of warmth around the external walls" (AEC, 2003d). Assuming that some convective heating of the inside surface of the window also occurs, the adverse radiant effect of cold windows will also be reduced[24].

Cooling System Overview

During the daytime, it is proposed that chilled beams and ceiling panels provide cooling for the occupants in the main office zones (Figure 2). The intention is that the cooling and 'shower' towers will primarily produce the cool water for these panels at night[25]. This 'coolth' will be stored in phase change material (PCM) and used to chill the water circulated through the beams and ceiling panels during the day. An absorption chiller will be used as a back-up cooling system, in the event of insufficient capacity in the primary system[26].

During the night-time, it is proposed that heat accumulated in the building fabric be removed by 'night purging'. This technique uses the diurnal temperature difference of the outside ambient air to flush unwanted heat stored in the building's thermal mass during day with cooler night-time air. This purging will be achieved by natural ventilation only, induced by cross ventilation and the stack effect, assisted by extraction cowls mounted on top of the north facade.

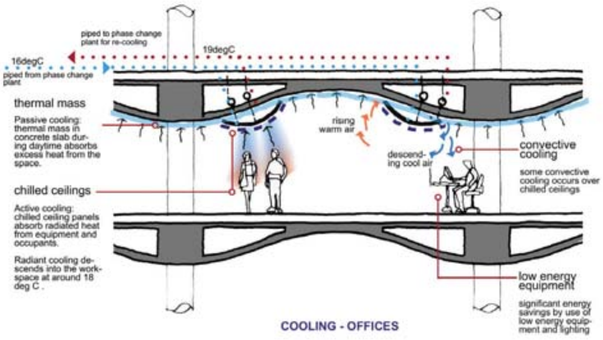

Figure 2: Schematic overview of cooling system operation in CH_2 building. (Source: CoM, 2004)

Cooling System Components

Some elements of the cooling system and their combination are unusual. Therefore, the individual technologies proposed are described below together with an evaluation of their likely effectiveness in the light of both Australian and overseas experience.

Phase Change Material

A critical component of CH_2's cooling system is the PCM. Its function is to store 'coolth' transferred from the exit water of the shower-cooling tower combination at night[27].

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[20] City of Melbourne note: Micro-turbine generators have a higher upfront cost but considerably lower maintenance and running costs when compared with an equivalent-sized diesel generator, the most common type of small-scale standby generation plant in use.

[21] City of Melbourne note: The natural gas micro-turbine, when operating, will run at full capacity as it supplies less than 15 per cent of the building's average electricity demands.

[22] City of Melbourne update: In the final CH_2 design, an air-to-air heat-recovery system on the exhausted air stack outlet was not included. There are several reasons for this. First, it would create significant resistance to the natural flow of air up the thermal exhaust stacks and would require additional electrical energy to push or draw air out of the building using fans. Second, energy recovery from ventilation air is less beneficial in temperate climates such as Melbourne than in climates where significant cooling or heating is required. Third, and most significantly, in the case of CH_2 the primary heating and cooling loads are transferred to the office space by water that flows in a recirculating path and thus conserves retained heating or cooling potential. Since CH_2 does not use air to fulfil its primary cooling or heating needs, the potential to recover energy from exhausted air is concomitantly reduced.

[23] City of Melbourne note: This is not reflective of the original heat recovery design presented. Recovered heat from the relief air was originally to be used to preheat primary air, not for the convective heaters on the office floor. Perimeter hydronic heating convectors are included in the final design on the northern and southern facades to provide 'skin' heating for early morning warm-up in winter

[24] City of Melbourne note: This approach is used extensively in Europe and is considered a well-tested way of managing unwanted heat loss through glass in winter. In summer, the reverse occurs, when cold air from chilled beams at door height is produced in front of the windows and allowed to fall down the glass, in the process absorbing heat directly from the surface.

[25] City of Melbourne note: Standard electric chillers, in combination with the shower towers and cooling towers, will satisfy daytime cooling loads by operating at night to create a 'heat sink' in the form of the charged Phase Change Material (PCM). Of these systems the majority of heat rejection will be performed by the cooling towers, not the shower towers. At night cooling and shower tower effectiveness is greatest because outdoor temperatures are cooler compared with warmer daytime temperatures Also, at night the electric chiller unit can draw on off-peak power, which is useful when ambient conditions, in summer periods, are not sufficient to charge the PCMs using the low-energy cooling capability of the cooling and shower towers exclusively. In addition, standard electric chillers will operate more efficiently during cooler night-time temperatures. The combination of these systems, night-time operation and night purge will all contribute to saving energy, money and reducing overall greenhouse gas emissions.

[26] City of Melbourne note: The absorption chillers will use excess heat from the gas-fired micro-turbine unit, which will operate at capacity during daytime peak energy demands. Operation of natural-gas-driven cooling systems not only reduce pressure on electricity supply infrastructure during peak demand, but also use an energy source with a lower greenhouse gas emissions coefficient.

[27] City of Melbourne note: There are two ways to look at the operation of the PCMs, depending on thermodynamic perspective. CH_2's PCM can be viewed as absorbing excess heat generated during the day, which can then be removed during off-peak energy periods and the cooler nights. Alternatively, the PCMs can be viewed as storing the cooling potential ('coolth') of the chilled water generated by the shower and cooling tower combination, which is the approach taken by the authors. Refer also to footnote 25.

In the storage process, it is intended that the PCM will be cooled sufficiently to change phase and solidify from its previous liquid state[28]. During the daytime, a closed loop will circulate water through the PCM to the chilled beams and ceiling panels, thus providing cooling to occupants. Throughout the day, the PCM will release its 'coolth' through this process[29] and be returned to a liquid state by the evening, so that the process may be repeated the following night[30].

The use of PCMs in buildings is not new. Solar researchers (such as Morrison and Abdul-Khalik, 1978) have investigated their potential as an alternative to the traditional, but more bulky, thermal storage media i.e. water and rock. A number of buildings have been built using PCMs and Duffie and Beckman (1991) describe some of the results of these installations. In recent times, phase change research has focussed on the impregnation of building materials themselves to overcome the problem of the large areas required if the PCM is to be melted by direct solar radiation (Khudhair and Farid, 2004). In general, PCMs have been used to store excess heat and thus experience of the method proposed for the CH$_2$ building is limited[31]. Zalba et al. (2004) evaluated an air-based PCM cooling system designed for a residential building[32]. The PCM used had a phase change temperature interval of 20-240C. Although their simulations and experiments indicated the feasibility of using PCMs for cooling, the difference in operating temperature, heat transfer medium and application limits the relevance of this research to the CH$_2$ application.

A phase change system, which shows some promise for low energy office cooling has been reported by Turnpenny et al. (2000 a & b). In their system, warm air is drawn up from the room continuously during the day by a typical ceiling fan and moved past a series of heat pipes mounted above the fan. PCM has been embedded in the heat pipes and heat in the air is transferred to the PCM, melting it and simultaneously cooling the air, which is then forced back down into the room. During the night, shutters adjacent to the PCM are opened and cool outside air is drawn across it, which is subsequently cooled and solidified. Warmed air is expelled through a second set of shutters. The PCM is thus recharged with 'coolth' ready for the next day. In the testing of a full-scale prototype in a 16 m^2 room, ten units each containing eight litres of PCM achieved heat transfer rates of 800-2000 W, depending on melting time, which is a function of the difference between the room and PCM temperatures. According to New Scientist (2001), the researchers have found the system to be "as effective as air conditioning but costing only one-sixteenth as much to run."

The PCM to be used in the CH$_2$ building is currently being developed by the supplier (Environmental Process Systems Ltd, UK) and will be a low (15ºC) melting point material. The PCM is reportedly a mixture of non-toxic salts and organic compounds (AEC, 2003e). The CH$_2$ system has been designed to supply a daily cooling load of 4539 kWh, i.e. 25 per cent greater than the estimated cooling load. The PCM will have a latent[33] heat value of approximately 210 MJ m^{-3} and therefore at least 78 m^3 of PCM encapsulated in the (proposed) 0.1 m diameter polypropylene tubes will be required[34]. The life expectancy and chemical stability of PCMs are the critical factors, which determine their viability. The PCM to be used is a new material under development and therefore no long-term operating experience is available[35]. Hawlader et al. (2002) found no deterioration in the energy storage capacity of encapsulated paraffin after 1000 cycles, but this represents only three years of daily phase change. Much longer cycle times are required for the financial viability of PCMs in the CH$_2$ building.

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28 City of Melbourne note: The most analogous storage system to the one proposed for CH$_2$ is the ice storage system that has been widely applied internationally in industrial and commercial buildings and in a few Australian locations. The primary difference in the PCM system is that unlike water, which has a fixed freezing point of zero degrees, the chemical formula of the phase change material can be designed so that its freezing or phase change temperature matches the desired operating temperature of the radiant cooling ceiling panel system. This ability to specify the chemical formula of the phase change material also allows the temperatures to be matched with cooling temperatures achievable with low energy cooling systems such as the shower and cooling towers, which operate effectively for many months of the year in ambient conditions. Thus, the ability to select a preferred temperature of phase change for the thermal energy storage system enables the effectiveness of radiant cooling panels and shower/cooling towers to be combined in a low energy performance system.

29 City of Melbourne note: The function of the PCM in the CH$_2$ design is to absorb heat during the day and thus 'time shift' the demand for energy for cooling to night-time off-peak energy charging periods and cooler outdoor conditions. During cooler temperatures, low-energy evaporative cooling can occur using the cooling and shower towers. When evaporative cooling alone is inadequate, due to warmer ambient conditions, the electric chiller will fulfil cooling requirements under the most efficient operating conditions.

30 City of Melbourne note: The size of the PCM cooling storage tanks is designed to satisfy the cooling requirements of the building for about three consecutive days. This allows operation even when dissipating the heat stored during daytime operation is not possible immediately, for example when warm nights persist for several days.

31 City of Melbourne note: As stated in the text, "In general, PCMs have been used to store excess heat", which, in the building sector, has typically been for the purposes of providing low energy heating in residential buildings. While it is acknowledged that the configuration of the CH$_2$ design is novel, considerable industry experience and knowledge, which may not appear in the academic literature, has been developed in the use of PCM for storing cooling potential or heat over a range of different phase change temperatures from 164ºC to -114ºC. Thermal energy storage systems for cooling have been applied internationally on a commercial scale in many settings, including office buildings, banks, hospitals, prisons, colleges, schools, exhibition centres, breweries and industrial plants. Refer to project documentation, included by the following PCM manufactures on their websites: France: http://perso.wanadoo.fr/cristopia/english/products/documentation.html, England: www.epsltd.co.uk/ and Australia: www.teappcm.com. To supplement the content of this paper the City of Melbourne has commissioned a paper by an Australian PCM specialist to provide further detail on the use of PCM systems internationally and the design used in CH$_2$.

32 City of Melbourne note: The PCM thermal energy storage system in CH$_2$ uses water as the heat transfer medium. Research cited in the paper, which refers to systems that use air as a medium for transferring the heat from the PCM's are expected to perform significantly differently to the system proposed for CH$_2$.

33 City of Melbourne clarifying note: Latent heat refers to the amount of thermal energy that is absorbed during a change in phase from, for example, a liquid to a solid or released when changing from solid to liquid. Sensible heat complements latent heat and is the amount of energy required to change a specific amount of material by a specific unit of temperature. When latent heat is absorbed or released the material does not change temperature, compared with sensible heat where the amount of heat (thermal energy) released or absorbed correlates directly to a change in the materials temperature.

34 City of Melbourne update: Encapsulating the PCM thermal store in a bank of tubes is an early design proposal. The final design incorporates the PCM material in spheres, suspended in a tank. This new detail, although a factual change, does not substantially change conclusions about the overall operational design. Refer to images contained in the Outline for this paper for details of the configuration of the final design.

35 City of Melbourne note: In addition to requiring the company supplying the PCM material to demonstrate significant performance testing, the CH$_2$ team has secured insurance to cover the cost of failure of the PCM and interconnected cooling system for a period of 10 to 15 years.

Displacement Ventilation[36,37]

A key element in the cooling system of the CH_2 building is the use of the displacement technique to deliver fresh tempered air[38]. In a DV system, ventilation air is introduced at ground level and the natural buoyancy effect, generated by the heat sources (human and non-human) within the space, drives this fresh air to the occupants' breathing zone[39]. DV systems have been widely used in Europe for several decades. Writing in 1989, Svensson stated that DV systems had a 50% share of the market for industrial applications in Scandinavia. The author also provides a useful table (reproduced here as Table 1) listing the advantages and disadvantages of DV systems.

Advantages	**Disadvantages**
Low turbulence intensities in the occupied zone reduce risk of draught problems.	Large vertical temperature differences can cause draught problems.
Higher average velocities can be accepted without any risk of draught problems.	Only small heat loads can be removed without draught problems.
Air exchange efficiency rates of between 50 per cent and 60 per cent are obtained in practical operations.	Metering points for airflow measurement are often lacking, due to small pressure drops.
Better prospects of achieving high ventilation efficiency than mixing systems.	Only cool air can be supplied.

Table: 1 Advantages and disadvantages of displacement ventilation systems. (From Svensson, 1989)

Lin et al. (2005) have compared displacement and mixing ventilation[40] (MV) systems for a variety of buildings in Hong Kong, including a three-room 'office'. Their study is of particular relevance to designers in Australia because it considers higher heat loads than experienced in the cooler climates of northern Europe. These researchers used computational fluid dynamics software to study the differences between DV and MV systems for the office, which assumed an occupancy level of 10 persons, and was provided with cooled air at the rate of 10 $l\ s^{-1}$ per person. Office loads (human, solar and equipment) were over 7 kW. No chilled beams or ceilings were used with the DV system. The temperature variation in the horizontal direction was found to be greater in the MV system than in the DV system. Vertical distributions were found to be similar. Temperature gradients were within 3ºC, as recommended by various standards.

The percentage dissatisfied (PD), due to draughts, was lower (10 per cent) for the DV system than the 20 per cent for the MV system, while the predicted percentage dissatisfied (PPD) was similar for both systems. The study indicates that DV systems can perform satisfactorily in sub-tropical climates and so should perform adequately in the range of climatic conditions experienced in Melbourne.

The Nordic experience after nearly two decades of DV systems was that they were well suited to industrial applications, department stores and large public buildings (Svensson, 1989). However, when no additional cooling power is provided by chilled ceilings, the use of DV systems for comfort ventilation was restricted to low cooling loads. Once cooling loads exceeded 30-40 W m^{-2}, draughts can become a problem in comfort installations, if air supply velocities are increased. The location and type of supply air terminal device used will be an important factor in ensuring that occupants do not experience drafts.

Researchers at the UK's Building Research Establishment (BRE) believe that the maximum allowable cooling load is even lower (20-25 W m^{-2}) than in the Scandinavian countries for simple DV systems with conventional diffusers supplying air at 19ºC (Butler and Swainson, 2002). To raise the cooling capacity, these authors investigated increasing the volumetric air supply using two alternative forms of fabric diffuser, which would maintain air movement levels and temperature variations within the limits specified by the British Standard (BS, 1995). The maximum recommended air velocity is 0.15-0.2 m s^{-1} and the maximum recommended temperature difference between ankle and head height is 3ºC.

A sock and a bin diffuser were investigated in the BRE study. The sock was 4.25 m long and could fit into the skirting board location at the bottom of a long wall. The bin diffuser was 700 mm in diameter and stood 740 mm high. Their designs permitted a higher airflow (230 $l\ s^{-1}$) capable of meeting a cooling load of 48 Wm^{-2} without causing unacceptable drafts. The bin diffuser outperformed the sock diffuser, which generated a vertical temperature gradient close to the middle of the sock. Although airflow velocities were within the range specified in the British Standard, an unacceptable ankle-to-head difference was measured in regions close to the diffusers. It was also acknowledged that these diffuser designs would take up valuable office space.

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[36] City of Melbourne note: This section cites research that considers the use of DV or MV systems for providing cooling. The ventilation system in CH_2 is not fundamentally a key element of the building's cooling system. The chilled ceiling provides cooling along with chilled beams. The under-floor supply system provides fresh air at sufficient volume and moisture content to maintain comfort within the space, while removing pollutants and ensuring sufficient oxygen. Refer also to footnotes 7, 37 and 38.

[37] 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 like a horizontal layer. The objective of DV is not only to ensure better ventilation and less pollutants, it is also aimed at maintaining stratification with warmer air layers lying above people's heads, which means that the air supplied 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. Refer also to footnotes 7, 36, 38 and 39.

[38] City of Melbourne note: Ventilation of CH_2 is not by true thermal displacement, as indicated in footnote 7, 36, 37 and 39.

[39] City of Melbourne note: In the CH_2 system, it is the momentum generated by the mechanical ventilation system and the swirl diffusers that provide the driving force to move air to occupants breathing zone, not natural buoyancy as stated in this paper. Refer also to footnotes 7, 36 and 37.

[40] City of Melbourne note: Mixing ventilation systems are also called dilution systems.

However, some preliminary work on the use of fabric inserts with conventional floor tiles gave similar performance results to the sock and bin diffusers.

In the CH_2 building, the floor air diffusers are located between work stations (AEC, 2003f) and the air delivery rate is 1.5 l s^{-1} m^{-2} to suit an occupancy level of one person for every 15 m^2. Occupants are able to adjust the diffuser to minimise draughts. The minimum fresh air requirement in the CH_2 building has been set at 22.5 l s^{-1} per person. No study of the impact of diffuser type, number or their position was available at the time of writing this paper and thus further comment on the type and location of CH_2 diffusers is not possible. The study by Butler and Swainson (2002), however, demonstrates that the position and type of diffuser influences both draught and ankle-to-head temperature differential. Furthermore, their study demonstrated that higher airflows to meet higher cooling loads could be met if fabric diffusers were used.

Chilled Ceilings and Beams

Chilled ceiling panels, fixed to the curved ceiling in the office spaces, have been sized to cater for the internal cooling loads generated by occupants, lighting and equipment. These chilled panels cover 35 per cent of the curved ceiling. Chilled beams are to be located in front of the windows around the perimeter of each office zone. Their function is to cater for the loads generated by direct solar gain and heat conducted through the windows. The radiant temperature of the panels is designed to be 18ºC, achieved by pumping water at 16ºC through the panels. The shower/cooling tower-PCM combination will provide this chilled water. The internal cooling loads in the central office zone are estimated to be 35.5 Wm^{-2} for 95 per cent of the time. The air temperature design criterion for this zone is 21-25ºC, but since the panels will provide radiant cooling, the objective of the system is to achieve a maximum resultant temperature of 23ºC.

In the UK, chilled ceiling panels are generally believed to be capable of dealing with cooling loads[41] of 40-50Wm^{-2}. When cooling loads exceed these levels, perimeter chilled beams are recommended and this combination is then capable of handling loads up to 80 Wm^{-2} (DLE & MGW, 2001). Chilled ceilings and beams are used in combination with displacement ventilation in 60-80 per cent of UK applications (DLE & MGW, 2001). The effectiveness of this cooling strategy on occupant comfort has been demonstrated at BRE by Alamdari et al. (1998). These authors introduced air at 190C into a test cell at the rate of 3.5 air changes per hour (ACH^{-1}) or 2.6 ls^{-1} m^{-2} at ground level. The air temperature and airflow rate were determined by thermal comfort rather than air quality requirements. Some downward convection was determined, but upward convection was dominant in the vicinity of the occupants. A 90 per cent or better occupant satisfaction was predicted.

Similar positive results in terms of occupant comfort were obtained in other experiments conducted in the UK using a 16.2 m^2 and 2.8 m high test room (Hodder et al., 1998). In this case, the supply air mass flow rate was set at 3 ACH^{-1} and its temperature was set at 19ºC, as in the BRE experiments. The air supply rate in the CH_2 building is to be 1.5 l s^{-1} m^{-2} or 1.9 ACH^{-1}, assuming a 2.9 metre average ceiling height, and the supply air temperature is to be 20ºC. Based on the UK experiences, the chilled ceiling-displacement ventilation combination may not be able to meet comfort requirements[42] because the displacement airflow rate is lower and supply temperature is higher.

Butler (2001) summarising some of the work of BRE on novel office cooling systems states that “displacement ventilation and chilled ceiling cooling systems are particularly sensitive to location and proximity to other physical objects that may influence airflows”. The systems can also be hard to control in perimeter zones subject to solar gains, as proposed in CH_2, because air buoyancy effects drive them. Achieving the correct airflow pattern and behaviour in the perimeter zone of an office using a chilled beam is particularly important, if the beam is to perform effectively. Butler (2004) reports the results of testing chilled beams at BRE. Since the room air is driven only by natural convection, it is crucial that the air can circulate freely through the device. This prerequisite means that the chilled beams must be installed either below the soffit or, if they are installed above a suspended ceiling, there should be a large free open area below the chilled beam. Architects and/or clients seeking a continuous ceiling with a uniform appearance may oppose this design requirement[43].

The use of blinds may also affect the performance of the chilled beam. BRE found that a closed slatted venetian blind constrained the thermal plume on the window side of the blind. If the slats were partially open the plume could pass through. . The degree of opening determined how much the air was able to interact with the beam. A roller blind pulled down constrained the plume even more than a closed slatted blind. If there is a gap at the top of the blind, then a narrow jet of hot air will exit at this point and can be directed to the beam.

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[41] City of Melbourne note: The number cited refers to total floor area, which is a useful guide. It is however, important to consider a variety of factors, which significantly influence the performance of chilled panels, especially: metal pan design; surface finish; and chilled water temperature.

[42] City of Melbourne note: Comfort requirements in this context refer to thermal comfort, which in CH_2 is primarily being met by radiant cooling systems (chilled beams, panels and thermal mass of concrete ceilings). As stated earlier, the author indicates that “internal cooling loads in the central office zone are estimated to be 35.5 Wm^{-2} for 95 per cent of the time”. The figure, 35.5 Wm^{-2} is well below the cooling load of 40-50 Wm^{-2} that chilled ceiling panels are generally believed to be capable of dealing with. CH_2, however, uses chilled beams and panels in combination, which the author cites is capable of handling loads of up to 80 Wm^{-2}. This information suggests CH_2 will achieve the required thermal comfort requirements. As indicated, in footnote 1 and 36 the ventilation system does not play a key role in the cooling of the building. Consequently, setting the air supply at a lower or higher flow rate and/or supply temperature does not greatly influence the building’s ability to meet thermal comfort requirements. It is, however, possible to calculate the influence of the lower air flow rate, of 1.9 ACH-1 at 20ºC, for CH_2 will have on the cooling provided by the ventilation air, when compared with the BRE experiment conditions of 3 ACH^{-1} at 19ºC. By assuming a 25ºC exhaust temperature and equivalent relative humidity for the supply air and the same atmospheric pressure condition, the contribution of CH_2’s ventilation air to overall cooling will be approximately 9 Wm^{-2} and 17 Wm^{-2} for the BRE building.

[43] City of Melbourne note: The need for a free open area below chilled beams is acknowledged by the CH_2 design team, however, chilled beam system designers suggest a perfectly acceptable result can be created by placing beams above a perforated metal pan CH_2.

Roller blinds are recommended in preference to venetian blinds (Butler, 2004). In the CH_2 building, external timber shutters are proposed to reduce the penetration of solar radiation on the western face of the building, but since details about the use of blinds or mounting of the chilled beams were not available at the time of this study, comment on their possible efficacy is not possible.

Shower Towers[44]

A novel feature of the cooling system is the five shower towers[45]. These are lightweight fabric tubes, 1.4 m in diameter and 8 m in height, fixed to the outside facade of the south side of the building. In theory, when fine droplets[46] of water are sprayed vertically down the towers, the momentum of the falling water entraps a certain volume of air, which establishes an air flow of air down the towers[47]. Any evaporation of the droplets cools the air, water and internal surfaces of the towers. It is intended that during the daytime the cooled and humidified air will be directed into the ground level retail spaces. At night-time, any cooled water collected at the base of the shower towers will be directed to the cooling towers, where it will be further cooled and conveyed to the PCM storage tanks to solidify the phase change material.

Givoni (1994) claims to have developed the shower tower to cool outdoor rest areas for the '92 EXPO in Seville, Spain. A search of the literature, however, indicates that the concepts employed in the shower towers are not new. Bahadori (1985) provides an analysis of Baud-Geers, which are the traditional wind towers used in Iran[48]. The traditional Baud-Geer had a number of disadvantages and Bahadori (1985) lists these and analyses a system modified to overcome these drawbacks. One of the modifications is the provision of a wetted surface to evaporatively cool the induced air[49]. The author provides charts estimating the dry bulb temperature of the air leaving the evaporative cooling column for given inlet conditions (ambient dry bulb, relative humidity and wind velocity) at various tower heights. Figure 5 in Bahadori (1985) shows that for a wind velocity of 5 ms^{-1} and ambient conditions not dissimilar to a summer day in Melbourne (25ºC and 33 per cent RH), the dry bulb temperature leaving the evaporative cooling column is approximately 16ºC for a 10 m high tower. The condition of the air at 35ºC for a 9 m high tower is likely to be 90 per cent RH and approximately 20ºC.

The flow of air down the modified Bahadori towers is a function of the pressure differential at the tower opening and the exit point. Given that the air velocities used in Bahadori's analysis are greater than those likely to be experienced regularly in Melbourne, it is difficult to see how the pressure differential for reliable flow will be regularly achieved[50]. Badran (2003) investigated the use of cool towers, as proposed by Bahadori, but with lower wind velocities (3.5-5.0 ms^{-1}). Badran concluded that any increase in tower height above 9 m did not significantly increase performance in terms of the dry bulb temperature or velocity of air leaving the tower. In the low wind velocity region, the tower inlet conditions were 38ºC and 39 per cent RH and the analysis indicated that a 4 m tower of cross-section 0.32 m^2 would produce air at 25ºC with a flow of 0.3 $m^3\,s^{-1}$.

Pearlmutter et al. (1996) provide a theoretical analysis and experimental experience with a direct evaporative cool tower (DECT) used to cool a 500 m^2 glazed courtyard located in the middle of a multi-use complex in Israel. Following some prototype testing, the authors found the cooling potential for a natural draft system was low and hence they chose a mechanically draughted system. The effective height of the tower was 10 m and had a diameter of 3.75 m. The fan-forced airflow induced in the tower was 20,000-25,000 $m^3\,h^{-1}$, i.e. it had a velocity of 0.5-0.63 $m\,s^{-1}$. It was found that the maximum cooling power of the system was just over 100 kW. Water consumption was 1-2 $m^3\,d^{-1}$.

The ability to cool the water as well as the air depends on a number of factors. The diameter of the drops sprayed into the tower and the length of time they spend there (i.e. the height of the tower being) is a key parameter. Pearlmutter et al. (1996) found that when large droplets (62 mm) were used, the air temperature only reduced gradually and needed a full 15 m of height to evaporate. With smaller droplets (14 mm), a fall of 12ºC in air temperature was achieved within the first metre of the tower. Large drops are required to achieve maximum cooling of the water, while smaller drops are required for maximum air cooling. No final water temperatures were reported in their paper but the authors noted "the excess water collected in the pool beneath the tower is cooled considerably, and if more efficiently utilized could potentially increase the system's effectiveness" (Pearlmutter et al. 1996).

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[44] City of Melbourne note: The majority of heat rejection will be performed by the cooling towers, not the shower towers.

[45] City of Melbourne note: The shower tower is based on the Passive Downdraught Evaporative Cooling (PDEC) concept. Refer also to footnote 50.

[46] City of Melbourne note: Fine droplets in this context should not be interpreted to mean mist. For the shower tower system to work effectively, the water must be released at the top of the tower as small droplets.

[47] City of Melbourne note: The air is also evaporatively cooled, which provides additional downward movement due to buoyancy related forces caused by an increase in the density of the air.

[48] City of Melbourne note: The design of traditional Iranian wind towers are significantly different from that proposed for the CH_2 shower towers. Traditional Iranian wind towers are either rectangular or octagonal, with multiple openings to catch wind from any direction. At the centre of these towers a baffle wall is normally positioned to direct the wind downwards, preventing it from blowing right across the tower. In conventional wind towers, this baffle wall works to a certain degree but there is a considerable loss of wind through the openings in the leeward side of the tower, partly because of the positive pressure of the windward side of the tower, but also because of the negative pressure on the leeward side of the tower sucking air out of the tower.

[49] City of Melbourne note: The flow of air down the wetted-wall wind tower example cited is primarily induced by the wind with some evaporative air cooling creating decreased buoyancy. In contrast, the downwards flow of air in the CH_2 shower towers is primarily driven by the drag forces generated by the falling water shower and the decreasing buoyancy caused by evaporative cooling of the air.

[50] City of Melbourne note: The CH_2 shower tower is based on the Passive Downdraught Evaporative Cooling (PDEC) concept. Research and literature relevant to the PDEC concept has not been referenced here. The PDEC concept does not rely on wind or pressure differentials at the opening and exit points to induce flow of air down the tower. Air flow in the tower is induced as described in footnote 47 and 49.

In Australia, shower towers have been installed at the 1500 m^2 Interactive Learning Centre at Charles Sturt University on its Dubbo Campus in NSW (CADDET, 2002). Located in the central space of the building[51], the four 8.8 m high towers use two water spray systems. Large droplets are sprayed into the tower at the top and smaller water particles are then misted into the air just prior to its entry into the occupied space. Some measurements taken at the building suggest the system is performing poorly[52] (Yeo, 2004). Flow into the building at the time of the measurements was only eight per cent of the design flow, resulting in much reduced cooling capacity. This occurred on calm days. On windy days, airflow direction in the towers was upward, i.e. reversed and consequently provided no cooling at all.

The literature on 'cool' or shower towers predicts that natural ventilation can produce appreciable cooling power with wind velocities and tower heights as low as 3.5 ms^{-1} and 4 m respectively. However, practical experience with towers indicates that natural draught is inadequate. To date all installations and analysis has been performed for climates with high dry bulb temperatures and low relative humidities. In the three summer months (December, January and February) in Melbourne, the average dry and wet bulb temperatures during office hours (8am to 6pm) is 21.9ºC and 15.9ºC respectively (Roy and Miller, 1981). The exit air temperatures and airflow rate from an 8 m shower tower with a 15 lm^{-1} can be predicted using the expression developed by Givoni (1994). For the above dry and wet bulb a value, an exit air temperature of 16.5ºC is predicted, which will be adequate to cool the retail space on the ground level, as proposed. The predicted airflow rate would provide approximately 4 ACH^{-1} for the retail spaces. During the night, the function of the shower towers is to precool the water entering the cooling towers. A 0.5-1.00C reduction in temperature is anticipated. As mentioned, no data could be located to substantiate this expectation, but according to Pearlmutter et al. (1996) considerable cooling occurs and so this estimate appears to be reasonable.

Cooling Towers

There will be two Baltimore Air Coil RCT series counter-flow cooling towers installed at the CH_2 building. Their main purpose is to reduce the temperature of water at night to the level where freezing of the PCM occurs. In the three summer months (December, January and February) in Melbourne, the average dry and wet bulb temperatures during non-office hours (7pm to 7am) is 17.9ºC and 14.5ºC respectively (Roy and Miller, 1981). The manufacturer has claimed that an exit water temperature of two degrees above the ambient wet bulb temperature can be expected. To freeze the PCM a temperature of below 15ºC is required and therefore it appears the cooling towers will not achieve this temperature, even if the water has been pre-cooled by the shower towers. This conclusion agrees with the consultant's analysis, which found that the cooling towers could only be used for nine days over the three main summer months to freeze the PCM[53] (AEC, 2003e). The absorption chiller[54] will therefore be the main source of cooling during the summer months. The cooling load in the three summer months is estimated to represent approximately 36 per cent[55] of the total annual cooling load of the building (AEC, 2003c).

Night Purging

Night ventilative cooling or night purging has the potential to reduce cooling loads where there is sufficient diurnal difference in ambient air temperatures. Outside air is drawn into the building at night and heat is transferred to the moving air as it circulates through the building. The effectiveness of night purging is a function of the airflow rate, surface area and thermal effusivity, the final factor being the root of the product of the conductivity, density and specific heat of the building material (van der Maas and Roulet, 1991). In the CH_2 building, movement of air is to be induced by natural means[56]. When the outside air temperature is below the concrete ceiling temperature, windows on the north and south facades will be opened automatically to allow outside air to be drawn in.

[51] City of Melbourne note: In the Dubbo system "the evaporative shower towers protrude into the sky to catch the dry hot outside air and funnel the cooled air through the central atrium providing cooling to all perimeter rooms as well as the core", source: AIRAH Journal – February 2003. As indicated in this extract the configuration of this system is different to the CH_2 shower tower system.

[52] City of Melbourne note: The exact explanation for the poor performance of this system is not known and comparison with the CH_2 shower tower system is difficult due to the significant difference in overall configuration. However, Marci Webster-Mannison explained in a recent article (Cooling Rural Australia – Passive Downdraught Evaporative Cooling, Dubbo Campus, Charles Sturt University, published in AIRAH Journal – February 2003), that "some parts of the system need to be improved". "The wind deflectors and baffles to the high-level louvres have not provided sufficient back draught protection, resulting in some overheating of the perimeter rooms. The main problem appears to be that the ingress of outside air, due to wind, causes a positive pressure in the room that prevents the movement of cool air from the central space, through the vents to the perimeter rooms. Modification of the wind deflectors and baffles has been prototyped, first in cardboard, to determine the most effective solution. Selected baffles, to windows with different orientations and eave conditions, were then modified to test the effectiveness of the proposed solution. These tests showed a dramatic decrease in the ingress of outside air, and the creation of negative pressure in the room that allowed air to move from the central space through to the perimeter rooms."

[53] City of Melbourne note: When ambient conditions in summer are not sufficient to charge the PCM using the cooling and shower tower systems alone, an electric chiller unit, using off-peak power, will be used to bring the water for cooling the PCM below its phase change charging temperature of 15ºC.

[54] City of Melbourne note: In addition to the absorption chiller, an electric chiller, operated at night, also will provide cooling in summer.

[55] City of Melbourne note: This figure indicates that 64 per cent of the building's annual cooling load will be met by the low energy cooling systems of the shower and cooling towers, which is significant.

[56] City of Melbourne note: Also, the flow of air through the CH_2 building will often be assisted by wind-driven extraction turbines on the top of the exhaust ducts on the north façade.

The thermal mass of the exposed concrete ceilings will absorb some of the daytime heat gains and the cooler outside air will remove some of this heat at night as it moves through the building. It is believed that the use of night purging can reduce the daily cooling load requirement of the CH_2 building by approximately 14 per cent in summer (AEC, 2003c).

Blondeau et al. (1997) conducted a series of experiments in a three-storey office building in France to investigate the impact of nocturnal cooling on energy consumption and occupant comfort. In their building, outside air was induced by mechanical, rather than natural, ventilation. Purging began at 9 pm and continued until 8 am. The required airflow rate was the equivalent of 8 ACH^{-1}, which agreed with the finding of Agas et al. (1991). As in the CH_2 building, the windows were kept closed and shutters restricted thermal gains during the daytime. Internal temperatures could be reduced to within 2-4ºC of the minimum ambient temperature and the temperature of the air in purged rooms was 1.5-2.0ºC lower than the reference room. These results were obtained for an average outdoor temperature range of 8.4ºC, which Blondeau et al. (1997) believed was unfavourable[57]. When translated into cooling energy needs, savings of 25 per cent were predicted for a set point temperature of 24ºC.

Similarly high air exchange rates were used by Birtles et al. (1996). In a simulation study, rates of 5-15 ACH^{-1} were used. It was found that the higher the air exchange rates the lower resulting internal temperature. Increasing from five to 15 ACH^{-1} reduced the internal temperature by 1.5ºC during the daytime. At the lowest ACH^{-1}, the internal temperature was at least 2.0ºC lower than the 'no purge' case. Purging temperature was set at 16ºC. The effect of thermal mass on peak temperatures was also investigated. High mass interiors reduced peak daytime temperatures by 1.5-2.0ºC.

Ventilation by natural means, i.e. the stack effect can be achieved but obviously without the reliability of a fan-forced system. Van der Maas and Roulet (1991) carried out an experimental study of natural ventilation on a three storey building and developed a simple algorithm to predict exit air velocities knowing the inside-outside air temperature difference, the inlet-outlet opening area ratio and the height between inlet and outlet. Application of this algorithm, however, may be inappropriate in this case because of the indirect air path in the CH_2 building. Van der Maas and Roulet's model did predict that heat removed from a building could be maximised by increasing the surface area and the thermal effusivity of the exposed materials.

In the case of the CH_2 building, the surface area of the ceiling has been increased by approximately 10 per cent by adopting a undulating profile. Surprisingly, however, the consultants found little difference in cooling loads when external walls of concrete, aerated concrete and plasterboard were compared (AEC, 2003c)[58]. The thermal effusivity of concrete is approximately 1864 J m^{-2} K-1 $s^{-0.5}$, which is over five times higher than plasterboard. Their finding appears to contradict the research relevant to night purging[59]. The fresh air entering a typical perimeter zone was calculated to be 4.2 kg s^{-1} (on average) or 12600 m^3 h^{-1} (AEC, 2003c), which is the equivalent to approximately 4.1 ACH^{-1}. This level of ventilation is lower than the cited overseas researchers believe is appropriate for effective night purging[60].

Thermal Mass

Although the designers of the CH_2 building do not believe the thermal mass of the external walls would contribute to any reduction of cooling load, the inclusion of thermal mass internally was considered very important to the thermal performance of the building. Approximately 70 per cent of the concrete ceilings in the office spaces have been left exposed so that, in combination with the night purging, there would be the dual benefits of cooling energy reduction (20 per cent) and a beneficial radiant effect for the occupants.

Balaras (1996) provides an overview of the benefits of thermal mass in the cooling of buildings. Properly placed and utilised, thermal mass can reduce summer peak cooling loads by absorbing heat produced during the day and dampening internal air temperature rises. By maintaining internal conditions within acceptable limits for longer period, overall energy consumption can also be reduced. Balaras (1996) cites research that reports a reduction of 20 per cent in cooling energy consumption in a commercial building, which is in line with the estimates made for the CH_2 building. Kolokotroni et al. (1998) have also demonstrated in the UK that a combination of thermal mass and night ventilation can usually be beneficial. Field measurements were taken in a four-storey office building, which contained exposed concrete columns and other thermal storage elements. Cross ventilation was provided at night between 6pm and 8am. The temperature data shows that the night-ventilated spaces were generally lower than equivalent unventilated spaces, especially during the early hours of the working day.

[57] Author note: In Melbourne, it is 7.5ºC, based on the long-term average temperatures at 5am and 3pm in the three summer months (December, January and February).

[58] City of Melbourne note: The findings of the CH_2 project team consultants referenced here is based on modelling predictions and is indicative of the relative impact of the perimeter wall area compared with the ceiling area, which covers a large area due to the deep floor plan,

[59] City of Melbourne note: The findings of the CH_2 design team is based on computational fluid dynamics modelling for the building, which considered different wall materials and found that due to the low proportion of wall area compared with ceiling area the type of wall material was found to have little effect on the overall cooling loads.

[60] City of Melbourne note: In order to determine if the consultants (refer Footnote 58) findings do in fact contradict the relevant research, the authors of this paper would need to evaluate the ratio of the surface area of internal thermal mass to the volume of the building and the thermal effusivity of thermal mass materials for the studies cited. Computational fluid dynamic modelling by the CH_2 design team consultants has determined the air change rate for night purging to be sufficient. Modelling to determine an effective rate has also taken into account the resistance to air flow caused by the fly screened night purge windows, convoluted air flow path through the building, thermal mass exposed area and effusivity of ceiling material.

Becker and Paciuk (2002) caution that in some instances, i.e. non-loaded buildings, night purging can increase overall energy consumption and night-time peak power loads. In the case of the CH_2 building, night purging is to be achieved by natural ventilation and therefore this problem is avoided.

Comfort and Productivity

The value of better buildings from a business perspective is increasingly acknowledged. Small improvements in work productivity by the building's occupants far outweigh other costs associated with improving the built environment. The building should perhaps no longer be seen just as a place of work, but rather as one of the components that determine the productivity of the enterprise. Using data from a variety of sources, Clements-Croome (2003) illustrates that staff costs are 100-200 times the cost of energy and therefore a 0.5 per cent to one per cent increase in productivity offsets related energy costs. According to this author's field study research, the three main factors influencing productivity are crowded work spaces, job dissatisfaction and the physical environment. "The most common complaints about unsatisfactory environment were those connected with high or low temperature variations; stale and stuffy air; and dry and humid air" (Clements-Croome, 2003).

While avoiding uncomfortable internal environmental conditions would appear to be commonsense and may produce a happier workforce, the direct productivity gains made from making marginal changes in those conditions are hard to quantify and not universally accepted. The weak link between thermal comfort and productivity is acknowledged by the designers of the CH_2 building (AEC, 2003g). In assessing the potential productivity gains resulting from CH_2's indoor thermal environment, only the research conducted in offices has been used in this paper. Similarly, only aspects of the indoor thermal environment, i.e. temperature, humidity and air movement are considered here.

In a discussion following a series of papers investigating the impact of the building environment on indoor productivity (Lorsch and Abdou, 1994b), the first author stated that "there is no direct link between worker satisfaction and productivity, nor is discomfort (emphasis added) always linked to nonproductivity." The authors also state that "although there is a preponderance of opinion that improving the work environment leads to productivity, quantitative proof of this statement is sparse and controversial." A sample of the research literature confirms this view.

Fisk and Rosenfeld (1997) review the literature "on the linkage between thermal environment (primarily air temperature) and selected indices of work performance." These authors state that although there is substantial evidence of an association between work performance and air temperature, …not all studies found such associations" and not all studies showed a positive association between comfort and productivity. For example, one study cited found that 18-49 per cent more typewriting work was performed at 20ºC compared to 24ºC. Other studies of mental work performance (but not necessarily in offices) showed that reading speed, memory and learning performance also might improve at temperatures outside of the traditional comfort range. Slight thermal discomfort appeared to increase arousal, according to Fisk and Rosenfeld (1997).

A study of call centre workers, however, showed a reduction in workers' talk time i.e. an increase in their productivity could be achieved by increasing the airflow rate from 5 to 10 litres $s^{-1}p^{-1}$ at an air temperature of 24.5ºC. This result indicates that the adverse effect of higher temperatures on this activity could be overcome by increasing air movement[61] (Tham, 2004). Other studies (such as Fang et al., 2004) of office workers, while "confirming the observed impact of temperature and humidity on perceived air quality…" found that "performance of office work was not significantly affected by indoor air temperature and humidity".

Leaman and Bordass (1999), using occupant surveys from 11 UK buildings over a 15-year period, arranged possible factors affecting productivity into four clusters. Only the first of these clusters, i.e. 'personal control' includes factors relevant to this study. Perceptions of personal control were measured by the average of five variables, namely heating, cooling, lighting, ventilation and noise. Of these, noise was most strongly associated with productivity, which perhaps confirms the decision to keep the windows of the CH_2 building closed during the day. Leaman and Bordass (1999) state that in "study after study, people say that the lack of environmental control is their single most important concern, followed by lack of control over noise." In the CH_2, building, occupants have direct control over air movement via the displacement air inlet vents[62], so by this measure it may be concluded they will not perceive significant productivity benefits from the heating and cooling systems[63].

[61] City of Melbourne note: CH_2 airflow rate is designed to operate at 22.5 litres $s^{-1}p^{-1}$.

[62] City of Melbourne note: Occupants, as groups, will be able to control the radiant cooling provided to each chilled panel cooling zone. Individually, occupants will be able to control their local lighting environment.

[63] City of Melbourne note: This conclusion should be considered in the context of the limited palette of productivity indicators taken into account in this study, such as thermal comfort. . Although outside the bounds of this paper, it is relevant to consider the influence of providing 100 per cent outside air under conditions that protect from the growth of mould, as these factors have both been shown to have a high correlation to productivity. In the context of the range of factors expected to contribute to improved productivity in CH_2, the design team does not expect thermal comfort to have a significant influence in comparison to other contributing factors.

Conclusions

The heating and cooling system for the CH_2 building will use some novel technologies and concepts such as shower towers, PCM and natural night purging. However, these innovations will be backed up by more conventional technologies such as an absorption chiller, evaporative cooling towers and waste heat recovery[64]. Properly engineered, these latter systems should ensure that thermally comfortable environmental conditions are achieved in the CH_2 building.

A review of the technologies proposed to provide cooling against previous experience indicates that the displacement ventilation airflow rate is low compared to overseas experience, although the cooling loads[65] predicted are in the same range. While evaluation of the shower towers using empirical formulae indicates that useful temperatures and airflow rates may be obtained, Australian and overseas experience indicates that reliance on natural ventilation is inadequate[66]. The shower-cooling tower combination cannot be used to produce useful temperatures in summer so the absorption chiller must be used[67]. Although design calculations indicate that approximately 64 per cent of the cooling load occurs in the non-summer months, the wisdom of incorporating unproven cooling technologies that cannot be used during the main period of continuous and peak cooling demands is questionable[68]. Natural ventilation for night purging, while effective in favourable ambient conditions, does not achieve the air exchange rates found necessary in overseas studies[69].

Because the indoor conditions chosen for CH_2 are within the accepted range of comfort zones for a climate controlled building, productivity is unlikely to be increased by the air temperature and humidity. The small level of control offered by the vents in the displacement ventilation system does not constitute significant control over individual environments, which has been cited as the single biggest concern of workers. Finally, it should be remembered that in terms of office worker productivity… “HVAC and IAQ are rated well below such items as privacy, interpersonal communications and relationships, office arrangement and managerial attention” (Lorsch and Abdou, 1994b).

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64 City of Melbourne update note: An electric chiller, configured to operate at night during off-peak energy supply periods, has also been installed and waste heat recovery has been removed for the reasons explained in footnote 22.

65 City of Melbourne note: As discussed in footnote 1, 36, 42 the ventilation system in CH_2 has not been designed to satisfy cooling loads, so the air flows for achieving cooling are not relevant. Cooling loads in the building are intended to be met using chilled ceiling panels and beams.

66 City of Melbourne note: Refer to footnotes 48, 49, and 50 for notes relevant to evaluating this conclusion.

67 City of Melbourne note: Or electric chiller depending on day or night operation and cooling requirements.

68 City of Melbourne note: The decision by the CH_2 design team to incorporate the shower and cooling towers has been made in the context of the whole year. Energy reductions gained from these technologies, for 64 per cent of the year and the contribution they make to reducing cooling loads beyond the summer period, were considered a worthy investment.

69 City of Melbourne note: Refer to footnotes 56, 58, 59, and 60 for notes relevant to evaluating this conclusion.

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Project Funding and Support

Significant funding for the technical papers has been provided through an AusIndustry Innovation Access Program grant and supported by cash and in-kind contributions from the City of Melbourne, Sustainable Energy Authority Victoria, Building Commission of Victoria, the Green Building Council of Australia and the CH_2 Project, Design and Consulting Team. The Innovation Access Program is an initiative of the Commonwealth Government's *Backing Australia's Ability* action plan.

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