**CHILLED CEILINGS & BEAMS** for AIRAH Energy 2003 Conference

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## Abstract

Radiant chilled ceilings and chilled beam systems offer potential for overall capital savings, which may be achieved by lowering slab-to-slab heights, reducing cooling capacity requirements, and minimising ducting. These systems also provide significant energy efficiency advantages due to fan energy savings and improved chiller COP, thereby reducing life-cycle building costs. Additionally, improvements in occupant thermal comfort and IAQ are achieved.

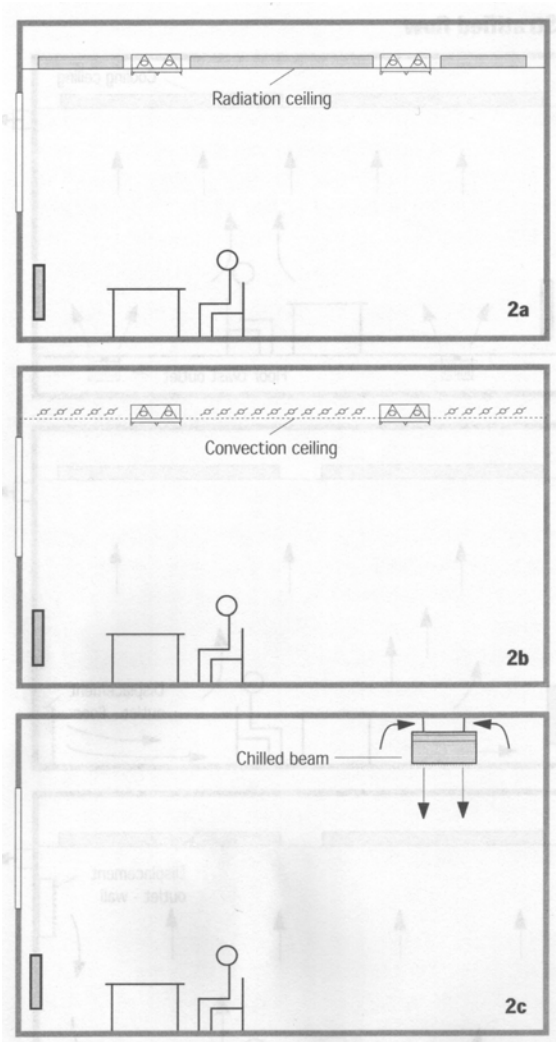
## Key Words

Radiant chilled ceilings, cooled ceilings, cooling ceilings, chilled beams, air diffusion, mixed flow, thermal displacement, swirl diffuser, twist outlet, air grille, aspiration, induction, cold air distribution, draught, draft, thermal comfort, indoor air quality, IAQ, sick building syndrome, SBS, energy efficiency, free cooling, economiser cycle, coefficient of performance, COP, green building, HVAC, heating ventilation air conditioning, airconditioning

## 1.0 INTRODUCTION


Chilled ceilings (fig 1a) and chilled beams (fig 1b) have been successfully used in Europe for more than 15 years. Their use in Australasia has, by comparison, been extremely limited and has faced significant resistance, with engineers, architects, contractors, developers and owners arguing that such systems are unsuitable for our climate and buildings due to high first cost, low cooling capacity, local comfort requirements and the threat of condensation. Similar criticisms were initially made in Europe, however a general acceptance of this technology has since developed in Europe since significant advancements have been made with the technology and important advantages have been realised, such a enhanced draught-free comfort, uniform temperature distribution, low noise, reduced operating costs, improved indoor air quality, and reduced space requirements.

## 2.0 OVERVIEW OF CHILLED CEILINGS & BEAMS




*Chilled ceilings* are surfaces, usually of metal or plaster board, that have chilled water piping running through them or in contact with them to provide a combination of convective and radiant sensible cooling from above the space. Installation heights typically range from 2.5 to 8 m, though higher installation heights are possible.

Chilled ceilings have either large, unbroken surfaces, that are known as *radiant chilled ceilings* (fig 2a), or slatted surfaces, known as *convective chilled ceilings* (fig 2b). Convective chilled ceilings provide significantly enhanced capacity, due to the increased convective component through the air gaps between the slats.

Chilled ceilings can be fabricated to form the ceiling surface, eg as a plaster board ceiling or as metal panels suitable for use in traditional T-grid suspended ceiling systems, or are suspended as panels above the space. In the latter, this is often done above an open false ceiling system (eg a perforated metal ceiling with at least 20% free area).

Where acoustical absorption is required, perforated or slatted surfaces are used with either acoustically absorptive tissue sandwiched between the chilled ceiling system and the visible perforated ceiling surface, or with acoustical matting behind the slatted chilled ceiling system.

*Chilled beams* (fig 2c) are convectors (heat exchangers) that essentially only provide convective cooling. This is done passively or actively. Passive chilled beams use the convection forces of cooled air falling through the cooling coil to provide air circulation. Active chilled beams use an induction system in each chilled beam, powered by air supply (usually of outdoor air only) ducted to each chilled beam, to draw room air across the coil to boost chilled beam performance.

Chilled beams are either integrated into the ceiling as a convector, whose discharge surface is flush with the visible ceiling surface, or are freely suspended above an open-grid ceiling or in a space without a ceiling.

Water piping is typically made of copper thermally bonded with an aluminium absorber, for chilled ceilings, or an aluminium coil, for chilled beams. Panel piping generally has a serpentine pattern.

## 2.1 Cooling Capacity

Metal chilled ceilings provide extremely rapid response of only a few minutes to changing loads in the space, due to their lightweight construction and low thermal inertia, which typically allows them to pull down to operating temperature within 15 minutes of being turned on. Plasterboard chilled ceilings are far more sluggish and take four to five times longer to respond to changing loads than their metal counterparts.

Specific sensible cooling capacity of the <u>active (ie cooled) ceiling surfaces</u> varies significantly. For plasterboard radiant ceiling systems it is typically 70 $W/m^2$, for metal panel radiant ceiling systems 90 $W/m^2$, and about 150 $W/m^2$ to 180 $W/m^2$ for convective ceiling systems (based on tests according to German standard DIN4715). These specific sensible capacities are for <u>active surfaces</u>, based on $\Delta T_{chilled\ ceiling - room} \approx -10$ K. This temperature differential equates to a supply water temperature of, for example, 12 °C with 14 °C return at a room temperature of 23 °C. Supply water temperature of less than 12 °C is not recommended, due to the threat of condensation, and minimum supply water temperatures as high as 16 °C are often used in offices that also have openable windows. Typically, 50% to 60% of the ceiling surface is active, which means that resultant room specific cooling capacity, as a function of floor area, is generally a little more than half of the above specific active values.

It should be noted that chilled ceiling cooling capacities specified by manufacturers are not always comparable, since test methods vary. Tests conducted in Nordic countries result in capacities that are 5% to 25% higher[i] than tests conducted in Germany according to test standard DIN4715. This is because the Nordic chilled ceiling test standards allow heat loads to include the walls, which significantly increases convective air motion in the space, thereby boosting chilled ceiling or passive beam performance. The Nordic tests also locate some of the heat load in the walls of the ceiling void above the chilled ceiling, thereby increasing radiant capacity. By comparison, German test standards require walls to be insulated and clearly define the manner in which heat loads are to be evenly dispersed in the space, to reduce capacity boosting through increased convective currents.

Due to asymmetric heat loads in practice, laboratory testing and on site testing have shown that actual cooling capacity in rooms is 3% to 17% higher, when no air is supplied into the space, than capacities realised by the German test standards, with the highest differences being for convective chilled ceilings[ii]. When high-level mixed flow is present with evenly spread loads in the space, at least 5% increase in capacity is realised relative to German test standard results.

## 2.2 Outdoor Air Supply & Latent Heat Removal

Chilled ceilings provide only sensible cooling. A parallel, dedicated outdoor air system (DOAS) must be used to remove latent loads and to ensure acceptable air quality in the space (fig 3). The DOAS should have a dry bulb temperature at least 2 K to 3 K less than the supply water temperature of the chilled ceiling, to prevent condensation on the chilled ceiling surface. This parallel DOAS system also removes some sensible loads from the space.

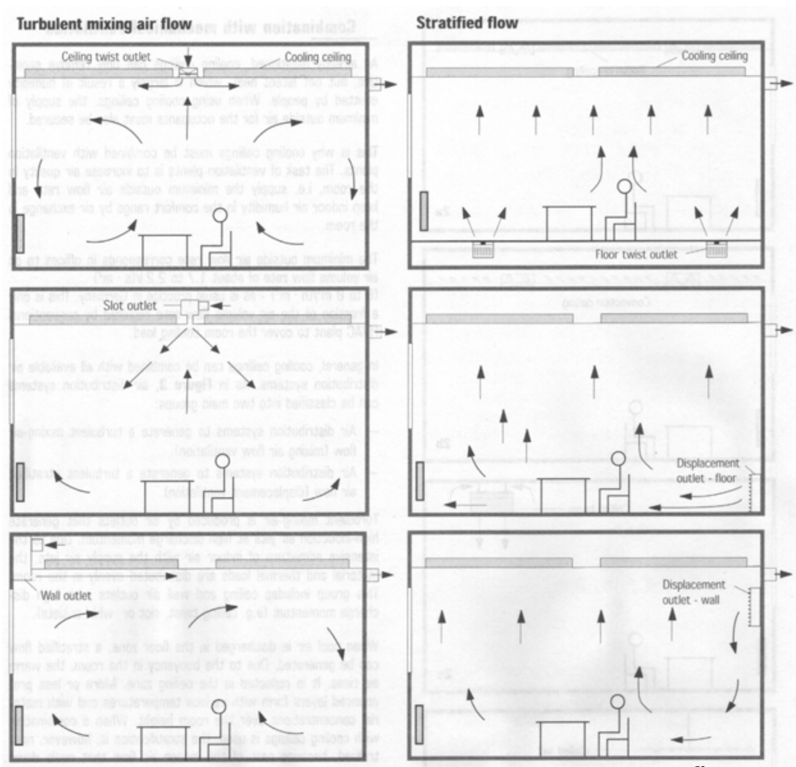



fig 3

The DOAS can supply air by means of high-level mixed airflow, or as displacement supply, typically at a rate of at least 1 to 2 L/s/m$^2$.

If *low-level displacement* diffusers are used, then this air is supplied at 1 to 3 K less than room temperature, so as to create a “lake” of cool outdoor air that spreads across the floor. Displacement air supply improves the indoor air quality in the occupancy microclimate, on condition that chilled ceiling/beam cooling capacity is not much greater than that of the displacement system.

By comparison, *high-level mixed airflow* offers three advantages that are especially important for Australia’s high heat load conditions:

1) The air movement across the chilled ceiling surface typically boosts chilled ceiling performance by at least 5%.
2) The benefit of an occupancy microclimate of enhanced indoor air quality that is typically realised by a displacement system cannot be achieved if such a system is combined with a chilled ceiling that provides more than 50%[iii] or 60%[iv] of total room sensible cooling capacity (the chilled ceiling surface destroys the layer of concentrated contaminants and heat that would otherwise stratify to a high level, mixing this back into the occupied space). For reasons of comfort, displacement sensible cooling capacity is typically limited to 40 W/m$^2$ to 60 W/m$^2$ in typical offices. Combined chilled ceiling and displacement systems are therefore extremely limited in the total sensible cooling capacity that they can provide.
3) Larger supply-to-room temperature differentials can be employed with mixed flow systems. This is especially so if high aspiration ceiling diffusers are used, such as swirl diffusers, in combination with chilled ceilings or passive chilled beams. For example, ceiling swirl diffusers may be used at a temperature differential of -15 K (eg 23 °C room temperature and 8 °C supply air temperature). This is demonstrated by Hu et al[v] where an extremely high level of comfort is achieved by the high aspiration of a swirl diffuser at 2.8 m height, delivering 1.6 L/s/m$^2$ airflow at a supply-to-room temperature differential of -16K, resulting in an ADPI of 97% as opposed to 58% from a multicone circular diffuser operating under the same conditions. (In general, an ADPI of at least 80% is required for acceptable comfort). Such cold air supply from high aspiration ceiling diffusers allows effective dehumidification to be achieved without the need for reheat, allows chilled ceiling or passive chilled beam performance to be boosted by through lower supply water temperature (eg 12°C) without the threat of condensation, and increases the sensible cooling capacity from the DOAS system (which reduces the capacity requirement from the chilled ceiling system, thereby reducing cost). The high induction effect of swirl diffusers also increases the effective number of air changes per hour in the space, which is important when chilled ceiling/beam cooling capacity is off due to low loads, as the air movement created by the diffusers ensures sufficient space air motion without the threat of stagnation or a feeling of stuffiness in the space.

In contrast to high aspiration ceiling diffusers, the induction supply air system in active chilled beams is not able to sustain supply-to-room temperature differentials greater than –10 K in cooling mode. This is since supply air is discharged into the space through slots, which are not highly inductive. Instead of using strong mixing to prevent dumping, the supply air stream relies on Coanda-effect suction of the supply air stream to the ceiling surface. At temperature differentials greater than –10 K this air stream becomes unstable and may detach from the ceiling, causing dumping and draughts.

## 2.3 Chilled Ceiling Heating

Chilled ceiling panels can be used to provide heating to the space, on condition that the following parameters are adhered to:

1. Maximum specific room heating, based on floor area, should not exceed 50 $W/m^2$ for heating when no air is supplied into the space (eg at night or over weekends) or when air supply is by means of a displacement system, or 100 $W/m^2$ if high level mixed flow air supply is present[vi]. These limitations exist, due to the formation of a strong vertical temperature gradient in the space, which should not exceed 2 K/m.

2. Inner glass surface temperature should not drop below 13°C to 14°C (ie $k_{glass} \leq 2.0\ W/m^2/K$ for $T_{ambient} = 0°C$), so as to prevent draughts from cold air cascading down the cold glass surface (eg for less than 0.2 m/s velocity along the floor at 1 m distance from a 3 m high window) and to prevent discomfort from excessive asymmetric radiant temperature differentials in the space between the surrounding room surfaces at about 21 °C to 22 °C and the cold glass surface.

3. Heating should form a strip of 0.8 to 1.0 m wide along the perimeter ceiling of the space, so as to effectively counteract the cold radiant perimeter surfaces of the space and reduce the asymmetry of the radiation temperatures. Supply water temperature typically ranges from 30°C to 40°C, with return water temperature 2 to 4 K lower than the supply[vii].

Alternatively, or in addition to the above, the DOAS may be used for heating.

While both the air side and water side of active chilled beams can be used for heating, passive chilled beams cannot be used to provide heating via the water system, since this heat would simply short-circuit as convective currents into the ceiling void.

## 2.4 System & Controls

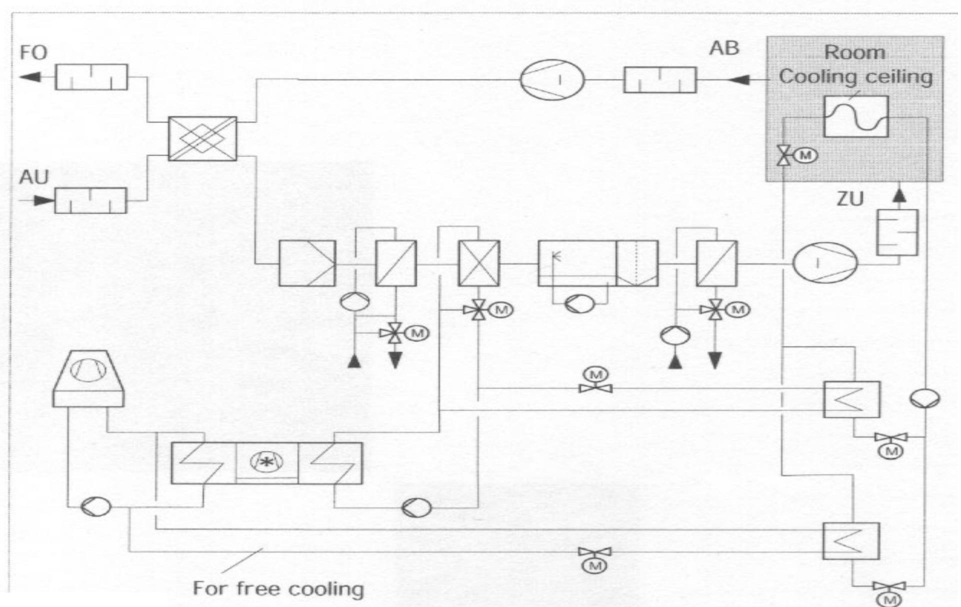


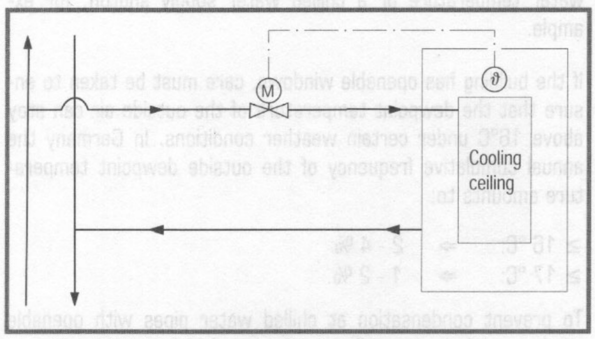

Fig 4 Principle of a cooling ceiling system + mechanical ventilation

In order to maximise energy efficiency, chilled ceiling design in Europe is typically based on the water and mechanical ventilation systems shown in fig 4, inclusive of indirect free cooling of the chilled water by the cooling towers.

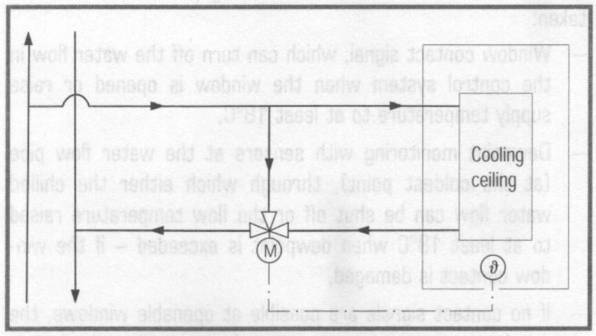
Room temperature (fig 5) is controlled by the cooling capacity of the chilled ceiling or chilled beam system, by:

- Altering chilled water flow through
    - o Stop valves with servomotor
    - o Cross valves with servomotor
- Altering the chilled water flow temperature with stop valves, servomotor and separate water pump.

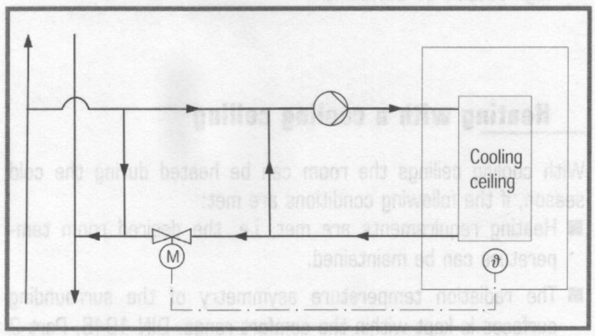
Plant control should also include dew point monitoring, by means of dew point temperature sensors on the coldest supply water piping to each chilled ceiling zones, so as to either turn off zone chilled water supply or raise supply water temperature if the threat of condensation is encountered.




Alteration of chilled water flow rate with stop valve and servomotor




Alteration of chilled water flow rate with cross valve and servomotor




Alteration of chilled water flow temperature with stop valve, servomotor and separate water pump

Fig 5

## 3.0 ADVANTAGES OF CHILLED CEILINGS & BEAMS

### 3.1 Enhanced Comfort

Comfort levels are especially high for chilled ceilings. Due to the high radiant cooling capacity of chilled ceilings, room air motion is typically draught free, and is generally less than 0.10 m/s for specific sensible capacity of 100 W/m$^2$ active surface, less than 0.15 m/s for specific sensible capacity of 150 W/m$^2$ active surface, and less than 0.20 m/s for specific sensible capacity of 200 W/m$^2$ active surface. These values assume that there is no air supply into the space, or that air supply is by means of a displacement system. Where high-level mixed airflow is used, air movement is governed by the air supply system, though due to the extremely low airflow rates, room air velocities are generally less than 0.2 m/s if high aspiration diffusers, such as swirl diffusers, are used.

Room air velocities resulting from chilled beams are significantly higher than for chilled ceilings. As a rule of thumb, maximum air velocities directly beneath passive chilled beams, as a function of specific capacity, are twice as high as those mentioned above for chilled ceilings. This is due to the lack of radiant capacity and the highly concentrated nature of the convective capacity from a chilled beam. Consequently, passive chilled beams should not be located above chairs and desks.

Active chilled beams result in maximum room velocities somewhat lower than their passive counterparts, since the induction system discharges air to spread by means of Coanda effect suction across the ceiling. However room air velocities are not as low as with chilled ceilings and the threat of dumping exists if supply air temperature is too low.

### 3.2 Reduced Operating Costs

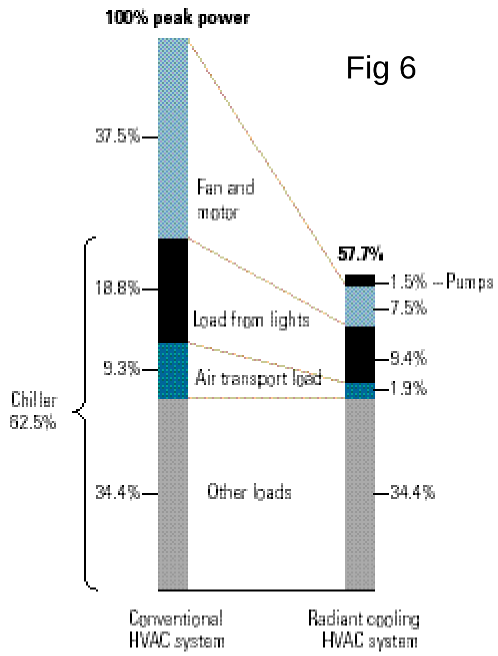


Fig 6

For room sensible loads greater than 50 W/m$^2$, chilled ceilings typically provide lower operating costs than comparable VAV systems[viii]. This is primarily due to the significant savings realised in reducing energy requirements of the transport medium (fans, pumps, etc), and is the case even though chilled ceilings are less able to benefit from free cooling than conventional VAV systems. (Chilled ceilings are only able to use indirect free cooling of the chilled water system from the cooling towers plus direct free cooling of the significantly reduced airflow required for outdoor air supply to the space). Typically fans, etc. account for 50% of the operating cost of a VAV-type HVAC system. In comparison to air, water, inclusive of pumping, requires 1/60 the amount of energy to remove the same amount of heat from a space[ix]. Chilled ceiling systems do not waste energy recirculating air in the building. Depending on building and system design and ambient conditions, operating cost savings of about 30% can be realised in comparison to VAV systems[x]. Fig 6[xi] shows how radiant cooling systems achieve savings. Components of peak HVAC energy use in a typical California office buildings are shown for conventional and radiant cooling, with about 62.5 % of energy usage for the former consisting of cooling load that the chiller must remove. Note that the cooling load from lights decreases because the radiant system's 100% outside air ventilation directly vents half of the lights' heat to the outdoors. In conventional buildings, most of that heat stays in the building with recirculating supply air. In the example, energy savings exceed 42%. In comparison to allair VAV systems, Stetiu[xii] found for the above load profile that on average for nine American cities, radiant cooling systems save 30% on overall energy for cooling and 27% on demand. Energy savings ranged from 17% in cold moist areas (humid areas required substantial dehumidification by both systems) to 42% in warmer, dry areas.

### 3.3 Reduced Space Requirements

Since only primary air ducting and water piping are required, significant space savings are realised, reducing slab-to-slab heights as well as service shaft areas, thereby increasing usable space and often allowing an additional floor to be slotted into a building of restricted height. Space savings range between about 35% to 45% in risers and false ceilings, and 40% to 60% in central stations.

### 3.4 First Cost

Initial cost of chilled ceilings or beam systems, when viewed in isolation from the building as a whole, are typically higher than of comparable VAV systems. However, the benefits of space savings, as outlined above, dramatically impact on the initial cost of the building as a whole, which for many designs is less than initial building cost with a conventional VAV system.

### 3.5 Other Advantages

In addition to the above advantages, radiant chilled systems provide:

- Improved indoor air quality (IAQ). This is because ventilation air is not recirculated and there are no wet surface cooling coils, thereby reducing the likelihood of bacterial growth, a major contributor to sick building syndrome.

- Better user comfort, even at room temperatures closer to outside air temperatures, than is possible with conventional space conditioning. This is because about 50% of the heat transfer is radiant, which is direct and draught-free. Also, there is virtually no noise from a radiant chilled system.

- Better efficiency and possibly smaller sizes of chillers boilers, because delivery temperatures are closer to room temperatures.

- Lower maintenance costs, due to the inherent system simplicity. No space conditioning is needed in outside walls, and a common central air system can serve both interior and perimeter zones.

## 4.0 CONCLUSIONS

Chilled ceilings and chilled beams should be considered for buildings where high levels of energy efficiency are to be designed for, where significant advantages can be realised by decreasing space requirements for services or by decreasing slab-to-slab heights, or where high levels of occupant comfort are desired. Initial cost of the chilled ceiling or beams, when viewed on their own, is typically higher than for VAV systems, however the initial cost of the building as a whole is often lower due to significant space savings. Additionally, ongoing advantages accrue not only due to increased energy efficiency, but also due to increased usable space.

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*AIRAH is the Australian Institute of Refrigeration, Airconditioning and Heating.*

**References**

[i] Selker T, Finkelstein W: Erfahrungen mit Kühldeckenmessungen nach DIN 4715 – Vergleich mit der Nordtest-Methode, Trox, 2000
[ii] Gräff B, Hirschfeld U: Leistungsbestimmung von Kühldecken: Untersuchyunhg der Übertragbarkeit von Norm-Messungen in Prüfbusen auf Originalräume, Institute für angewandte Thermodynamik und Klimatechnik, Fachhochschule Giessen-Friedberg, 2000
[iii] Fitzner K: Displacement systems and cooled ceilings, results of laboratory tests and practical installations, Hermann-Rietschel-Institute of Heating- and Air-Conditioning, Technical University of Berlin, Paper for Indoor Air '96 Conference, Nagoya
[iv] Fitzner F, Krühne H: Displacement Flow and Cooling Ceilings, Hermann-Rietschel-Institute für Heizungs- und Klimatechnik, Technical University of Berlin, Healthy Buildings 95
[v] Hu S C, Barber, J M, Chiang, H: Full-Scale Thermal Performance Tests of Alternative Diffusers when operating with Cold Air, ASHRAE Transactions 4251, 1999
[vi] Nickel J: Heizen und Kühlen mit Decken, TAB, Seite 41-48Nr. 05/97.
[vii] Sodec F: Heizen mit Kühldecken, Krantz-TKT, E-Bericht Nr. 86, 1996
[viii] Cooling and Heating Systems, Krantz-TKT Technical Brochure, DS 4076 e, 10-2001
[ix] Makulla D: Energetischer Vergleich einer Luftkühldecke mit einer Wasserkühldecke und Quellüftung, Ki Luft- und Kältetechnik, 7/1997
[x] Mumma S A: Ceiling Panel Cooling Systems, ASHRAE Journal, November 2001
[xi] Design Brief: Radiant Cooling, Energy Design Resources, Financial Times Energy, Boulder Colorado, 2002
[xii] Stetiu C, VAV and radiant cooling systems comparison, Lawrence Berkeley National Laboratory, 2002