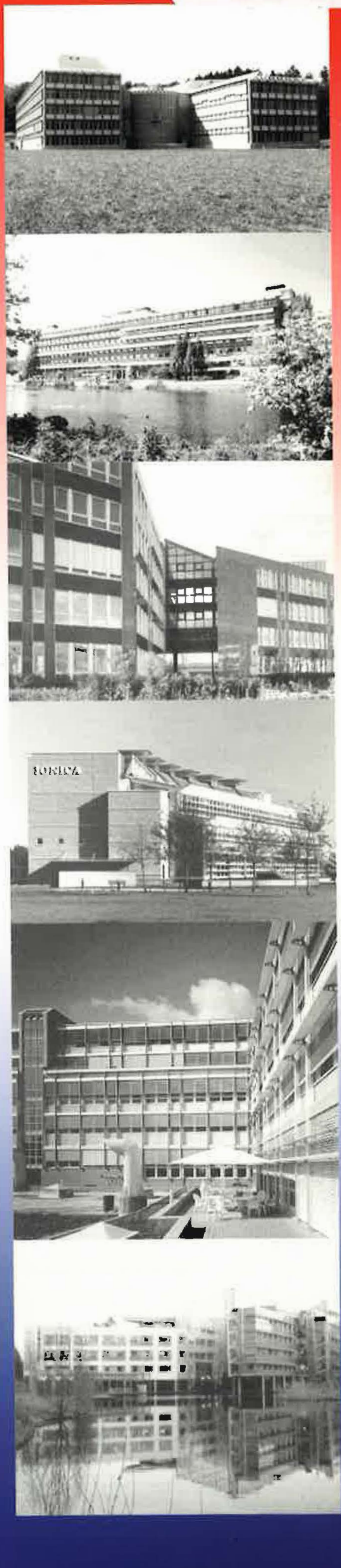
International Energy Agency

Low Energy Cooling



Technical Synthesis Report
IEA ECBCS Annex 28

Energy Conservation in Buildings and Community Systems

Low Energy Cooling

Annex 28 Technical Synthesis Report based on:
Review of Low Energy Cooling Technologies, contributing authors:
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Selection Guidance for Low Energy Cooling Technologies by N. Barnard and D. Jaunzens.
Low Energy Cooling, Early Design Guidance by J. Huang, J-R. Millet, J. L. Alexandre,
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July 2000

Design and layout: Lockhart-Ball Associates

Keywords: Cooling; Passive cooling; Night cooling

Published by: ESSU (ExCo Support Services Unit), Coventry, U.K.

ISBN: 1 902177 16 3

Code: Ann 28 TSR07

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-one IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems (ECBCS)

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the Executive Committee has initiated the following (completed projects are identified by *):

1 Load Energy Determination of Buildings *
2 Ekistics and Advanced Community Energy Systems *
3 Energy Conservation in Residential Buildings *
4 Glasgow Commercial Building Monitoring *
5 Air Infiltration and Ventilation Centre
6 Energy Systems and Design of Communities *
7 Local Government Energy Planning *
8 Inhabitant Behaviour with Regard to Ventilation *
9 Minimum Ventilation Rates *
10 Building HVAC Systems Simulation *
11 Energy Auditing *
12 Windows and Fenestration *
13 Energy Management in Hospitals *
14 Condensation *
15 Energy Efficiency in Schools *
16 BEMS - 1: Energy Management Procedures *
17 BEMS - 2: Evaluation and Emulation Techniques *
18 Demand Controlled Ventilating Systems *
19 Low Slope Roof Systems *
20 Air Flow Patterns within Buildings *
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36 Retrofitting in Educational
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Annex 28 Low Energy Cooling

Summary

The aims of Annex 28 are to investigate the feasibility and provide design tools/guidance on the application of alternative cooling strategies to buildings. Outputs of the Annex include a review of the technologies, detailed design tools and case study descriptions. The scope is limited to the technologies included in the Annex. The information provided reflects the state of technologies in a country or countries participating in the Annex and should not be taken as representative of the situation on a worldwide basis.

Scope

This report contains a summary of ECBCS Annex 28 Low Energy Cooling. It is primarily aimed at building services practitioners, designers and policy makers who require background knowledge of practical low energy cooling approaches. It is designed to be accessible to the non-expert and to give an introduction to the benefits of low energy cooling. Other key Annex Reports are:

Review of Low Energy Cooling Technologies
Selection and Guidance for Low Energy Cooling Technologies;
Early Design Guidance for Low Energy Cooling Technologies;
Detailed Design Tools for Low Energy Cooling Technologies;
Case Studies of Low Energy Cooling Technologies.

Participating Countries

The participating countries in this task were: Canada, Germany, Finland, France, Netherlands, Portugal, Sweden, Switzerland, United Kingdom, and United States of America.

Operating Agent

The Operating Agent was shared between the UK Department of Environment, Transport and the Regions (DETR) and Oscar Faber Group Ltd (UK).

Low Energy Cooling

1. Annex 28 Technical Synthesis Report

Introduction

The refrigerative cooling of buildings contributes significantly to energy demand, and hence greenhouse gas emissions, of non-domestic buildings. In addition, demand for good thermal comfort is resulting in the wider use of air conditioning. In response to concern over the resultant impact on greenhouse gas emissions, the IEA's Future Building Forum held a workshop on Innovative Cooling in 1993. This identified a number of technologies with the potential to reduce the need for conventional cooling. As a follow-up, Annex 28 (Low Energy Cooling) was established.

Objectives

The primary objectives of this Annex were to identify cooling approaches and to demonstrate their performance. The emphasis was on 'passive' and 'hybrid' cooling strategies. Primary considerations included ensuring that:

- The life cycle costs (including energy and maintenance etc.) were less than conventional systems;
- The level of thermal comfort is comparable with conventional systems;
- The technologies are sufficiently robust to changes in building occupancy and use;
- The design concepts of such systems are well defined and that good guidelines are available for all stages;
- The necessary design tools are available in a form which designers can use in practice;
- The cooling system is shown to integrate with the other systems (e.g. with heating and ventilation) as well as with the building and control strategy.

Sublasks covered:

- Description of Cooling Methods;
- Development of Design Tools;
    - Selection Guidance;
    - Early Design Guidance;
    - Detailed Design Tools;
- Case Studies.

Fundamental to this activity was an evaluation by demonstration. The evaluation of case studies presents a unique opportunity to exchange and gain experience from technologies tested under scientific conditions. The aim was to select prestige buildings in which substantial energy savings had been made over conventional technology and in which good thermal comfort was secured. These case study buildings are located in various countries representing a very diverse range of climatic conditions from hot and humid to dry and cool. The various climate conditions give markedly different prerequisites for the studied technologies. The suitability of a technical alternative is thus often dependent on the location of the building.

Activities and Products

The project was divided into three subtasks relating to the three phases of researching and documenting the various cooling strategies; these are:

Subtask 1: Description of Cooling Strategies

The aim of this subtask was to establish the current state of the technologies in the participating countries. These details are reported in:

Review of Low Energy Cooling Technologies

This report also contains national data for climate, building standards, heat gains, comfort criteria, energy and water costs for each participating country.

Subtask 2: Development of Design Tools

Different complexities of numerical tools are required throughout the design process. To reflect these requirements, three different levels of tools have been developed as described in the following reports:

1. *Selection and Guidance for Low Energy Cooling Technologies;*
2. *Early Design Guidance for Low Energy Cooling Technologies;*
3. *Detailed Design Tools for Low Energy Cooling Technologies.*

Copies of source codes executable files (where appropriate) are provided on disk.

Subtask 3: Case Studies

The third element of this work was to illustrate the various cooling technologies through demonstrated case studies. Eighteen such case studies are documented and are reported in:

Case Studies of Low Energy Cooling Technologies.

These case studies give feedback on performance and operation in practice and include design details and monitored performance data.

2. Low Energy Cooling Technologies

The following low energy cooling strategies have been evaluated in this study:

- Night Cooling by Natural Ventilation;
- Night Cooling by Mechanical Ventilation;
- Slab (Foundation) Cooling by Air and Water;
- Evaporative Cooling;
- Desiccant Cooling;
- Chilled Ceilings and Beams;
- Displacement Ventilation;
- Ground Cooling (Air);
- Aquifer Cooling;
- Ground Cooling (Water);
- Sea/River/Lake Cooling.

An overview of these technologies and their application in this programme is presented in Table 1.

Technology	Subtask 1	Subtask 2			Subtask 3
	Review of Technology	Selection Guidance	Early Design Guidance	Detailed Design Tools	Case Studies
Night Cooling (natural ventilation)	•	•	•	•	•
Night Cooling (mechanical ventilation)	•	•	•	•	•
Slab cooling (air)	•	•		•	
Slab cooling (water)	•	•	•	•	•
Evaporative cooling	•	•		•	•
Desiccant + evaporative cooling	•	•		•	•
Chilled ceilings and beams	•	•			•
Displacement ventilation	•	•			•
Ground cooling (air)	•	•	•	•	•
Aquifer	•	•		•	•
Sea/river/lake water cooling		•		•	•

Table 1 An Overview of Technologies and their Applications

2.1 Night Cooling by Natural Ventilation and/or Mechanical Ventilation

'Night' cooling by ventilation is used to lower the temperature of the thermal mass of the building at night when the outdoor air temperature is substantially below that of the midday air temperature. When correctly designed and controlled, this enables the daytime peak (dry bulb) temperature to be reduced. Latent cooling (dehumidification) does not take place therefore indoor moisture loads should be minimised. Also, as cooling occurs the relative humidity of the air will rise. It is important that this rise should not result in discomfort (i.e. the relative humidity should be maintained at less than ~ 60%).

To accomplish night cooling effectively several measures must be introduced; these include:

- Preventing solar heat gain by incorporating external solar shading over windows;

- Minimising internal heat gains (e.g. by using low energy appliances, switching off any electrical equipment which is not in use and taking advantage of natural daylighting;
- Ensuring that ventilation air is in direct contact with the thermal mass of the building (i.e. there should be no insulated coverings, false ceilings or suspended floors etc.);
- Ensuring that the mean of the daily maximum and minimum outdoor air temperature is at or below acceptable comfort temperature;
- Providing good thermal insulation to the building envelope;
- Avoiding anything above the basic ventilation rate needed for air quality requirements during any part of the day when the outdoor air temperature is greater than that of the surface temperature of the thermal mass;
- Plan a control measure to prevent excessive cooling at start of day.

These conditions and requirements make night cooling appropriate for moderate conditions in which high midday dry bulb temperature is not common (e.g. usually < 31°C and where high outdoor relative humidity is not common (i.e. where dry bulb rather than latent cooling is the primary issue). The key to night cooling is the thermal mass of the building since it stabilises diurnal variations in temperature. Essentially two mechanisms are involved. First there is the daily inertia of the building which provides daytime cooling (based on the night cooling of the thermal mass that was achieved during the previous night). Secondly is sequential inertia in which the building structure gradually warms up (or cools down) over a period of several days (e.g. two weeks). To take full advantage of the daily inertia, the thermal mass must be in direct contact with the indoor air. Thermal insulation such as carpeting and false ceilings and false floors substantially reduces the effectiveness of the thermal mass in providing the desired daily cooling cycle.

Natural Ventilation

Both residential and non-residential buildings can be cooled by this approach although needs vary according to type. Office buildings, for example are largely unoccupied at night so that relatively high rates of ventilation, draughts and, hence, discomfort can be created. In residential buildings, cross flow between one side of the building and the other should be promoted and windows should have fixed opening positions. Intruder protection such as louvre systems should also be considered. Typical night air change rates needed for cooling are between 5-20 air changes/hour (ach). In non-residential buildings, similar concepts may be applicable. Other solutions include wind-towers, passive stack ventilation, and ventilation through atria and solar chimneys.

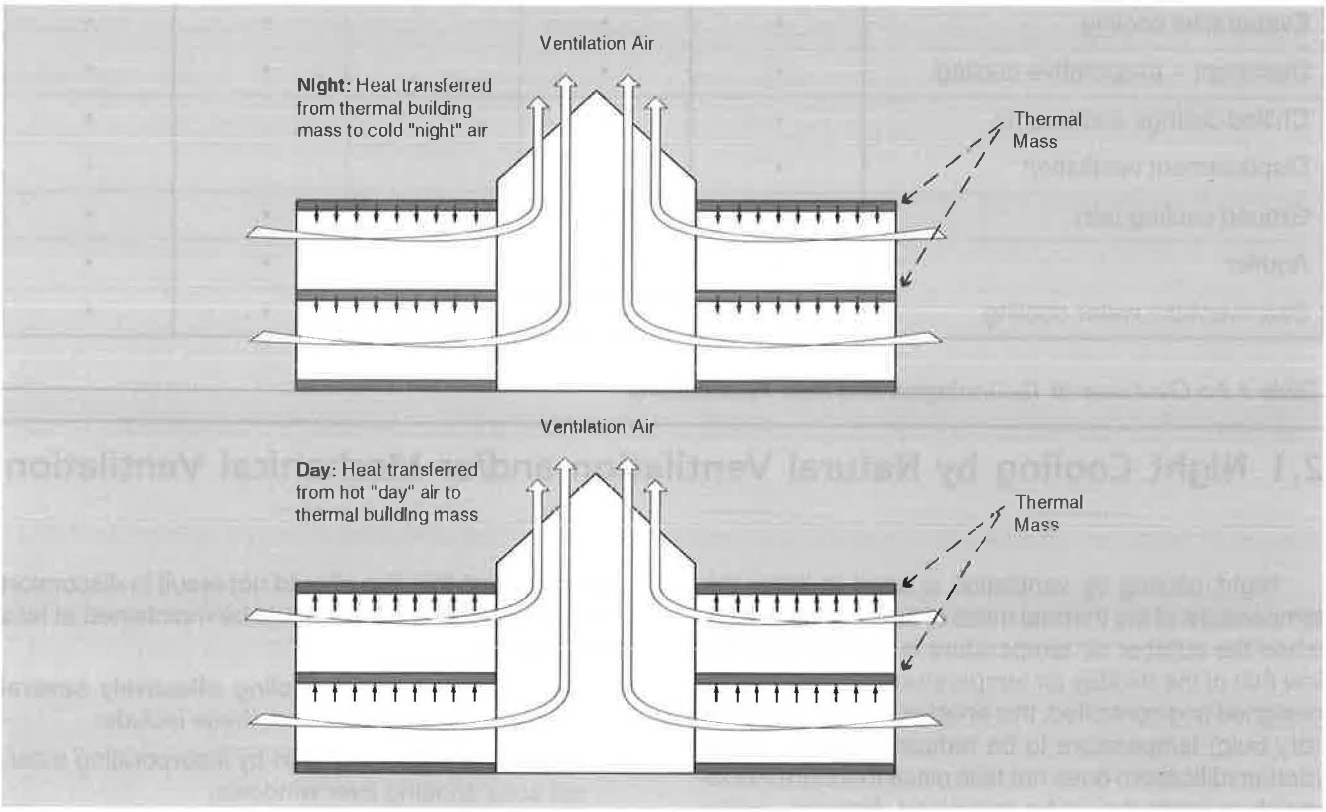


Figure 1 Principles of Night Cooling

Mechanical Ventilation

Night cooling by mechanical ventilation follows the same principles as that for natural ventilation except that mechanical ventilation is used to provide all or part of the 'night' cooling air. This provides for improved control and relatively smaller (and secure) air intakes but cooling benefits must be balanced against the use of fan energy.

Night Cooling by Ventilation Check-List

Favourable Factors:

- Cool climate;
- Average between Summer day and night dry bulb temperature falls within acceptable 'comfort' temperature;
- Periodic heat loads.

Unfavourable Factors:

- Hot/humid Climate;
- External noise and/or air pollution;
- Limited floor/ceiling height (e.g. <2.75m);
- Deep plan/cellular space (e.g. >2.5 times ceiling height);
- High heat gains;
- A requirement for precision; temperature and humidity conditions.

Design Aims:

- Cross ventilation and/or stack driven air flow;
- Control strategy to avoid over-cooling;
- High efficiency fans and low-pressure drop needed for mechanical systems otherwise primary energy consumption could exceed cooling performance.

Design Requirements:

- Good thermal contact between ventilation air and thermal mass;
- Solar shading;
- Reduced internal heat loads;
- Openable windows or equivalent;
- Security and privacy.

Cooling Performance:

- Night cooling for heavyweight construction will offset ~20-30W/m^2 of heat gain;
- Internal peak spaced (dry bulb) temperature is reduced by 2-3K;
- There must be good air contact with the thermal mass, flow paths must be unobstructed.

2.2 Slab (High Thermal Mass) Cooling (Air)

As with the above night cooling approach, 'slab' cooling takes advantage of the thermal mass of a building. However, wall and floor sections have a honeycomb of ducts cast into the slab material or prefabricated in false floors through which ventilation air is passed. In summer, the principles of night cooling are applied by ventilating the slab with cool outdoor air to reduce fabric temperature. During the daytime, advantage is then taken of the depressed thermal mass temperature to pre-cool the supply air. If necessary, additional conditioning can take place at the supply air diffusers.

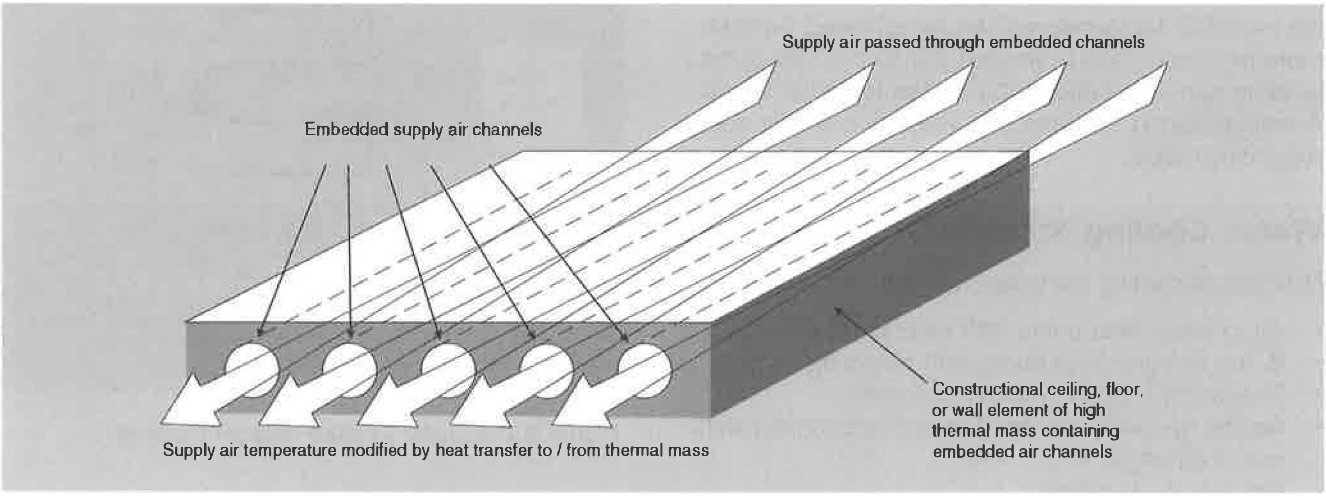


Figure 2 Principles of Slab Cooling (Air)

Slab Cooling Check-List

Favourable Factors:
- Cool climate;
- Periodic heat loads.

Unfavourable Factors:
- Hot/humid climate;
- High heat gains;
- A requirement for precision temperature and humidity conditions (see control strategy).

Design Aims:
- Minimise pressure drop;
- Control strategy to avoid over-cooling;
- Use slab for heat storage in winter.

Design Requirements:
- Good thermal contact between ventilation air and thermal mass;
- Solar shading;
- Reduced internal heat loads;
- Access for the cleaning and maintenance of Airways;
- Space for ventilation system.

Cooling Performance:
- 40 W/m^2 without exposed lower slab surface;
- 60 W/m^2 with an exposed lower slab surface;
- Could be combined with displacement ventilation to reduce temperature in occupied zone;
- 'Top-up' mechanical cooling to meet peak loads.

A Control Strategy

A careful control strategy is needed to optimise cooling and to avoid other problems such as overcooling and condensation. In the Annex 28 study the following cooling strategy was applied:

Maximum (night) ventilation rate when indoor – outdoor temp > 4K;

Minimum (night) ventilation rate when indoor – outdoor temp < 1K;

To avoid condensation, the slab temperature must not be cooled to less than 1K above the lowest dew point temperature expected during the day.

2.3 Slab Cooling (Water)

Floor/ceiling sections are cast with water piping embedded into the concrete. Cooling and heating sources are then used to maintain the temperature of the slab and hence optimise comfort temperature within the building. By applying substantial thermal mass combined with a comprehensive piping network, very stable indoor air temperatures can be achieved. Furthermore high heat gains from one room or one side of the building can automatically be shifted to cooler areas. A well-designed systems can work in a wholly self-regulating mode.

Water Cooling Strategies

Methods of cooling the water vary but can include:

- Air to water heat pump with reversing cycle;
- Water to water heat pump with reversing cycle;
- Evaporative cooling (adiabatic tower);
- Aquifer (groundwater table) or lake/sea cooling with heat exchanger;
- Refrigerative cooling.

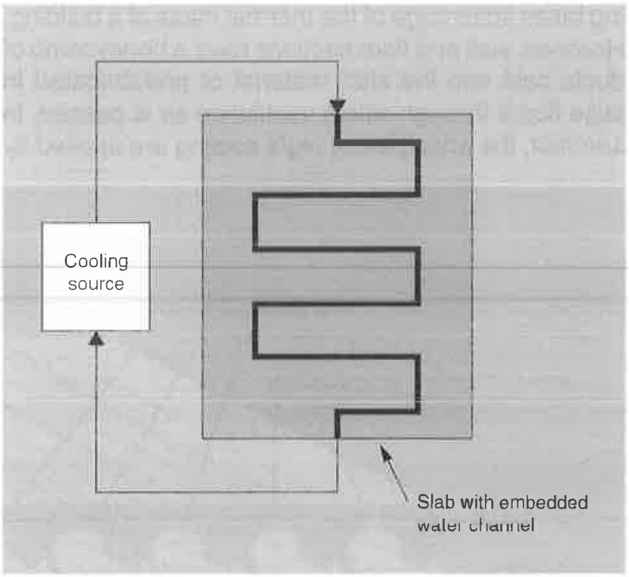


Figure 3 Principles of Slab (Water) Cooling

Slab Cooling (Water) Check-List

Favourable Factors:

- Low energy/quality source of cooling;
- Ability to use system for heating in winter.

Unfavourable Factors:

- Hot/humid climate;
- High heat gains;
- A requirement for precision temperature and humidity conditions.

Design Aims:

- Avoidance of condensation problems (slab temperature > room air saturation temperature);
- Surface/air temperature, 4K.

Design Requirements:

- Good thermal contact between ventilation air and thermal mass;
- Solar shading;
- Reduced internal heat loads;
- Pipe-work connections accessible;
- Space for central cooling and distribution system.

Cooling Performance:

- Cooled Floors: 30 to 40 W/m² with cooling water at 22°C, occupied space at 26°C;
- Cooled Ceilings: 40 to 50 W/m² with cooling water at 22°C, occupied space at 26°C;
- Could be combined with displacement ventilation to reduce temperature in occupied zone.

2.4 Evaporative Cooling

Energy is 'taken' from the air to evaporate water, which is provided as a spray or sometimes as a wet, porous media. This results in a depression in dry bulb temperature and a rise in humidity. Available modes are:

Direct: The ventilation supply air is passed directly through the water spray and then enters into the space to be cooled;

Indirect: The ventilation supply air is passed through a heat exchanger, which, itself has been cooled by being located in the path of direct cooling. The advantage is that cooling of the supply air takes place without the air absorbing any of the extra humidity. Unfortunately, though, the efficiency of cooling is much reduced.

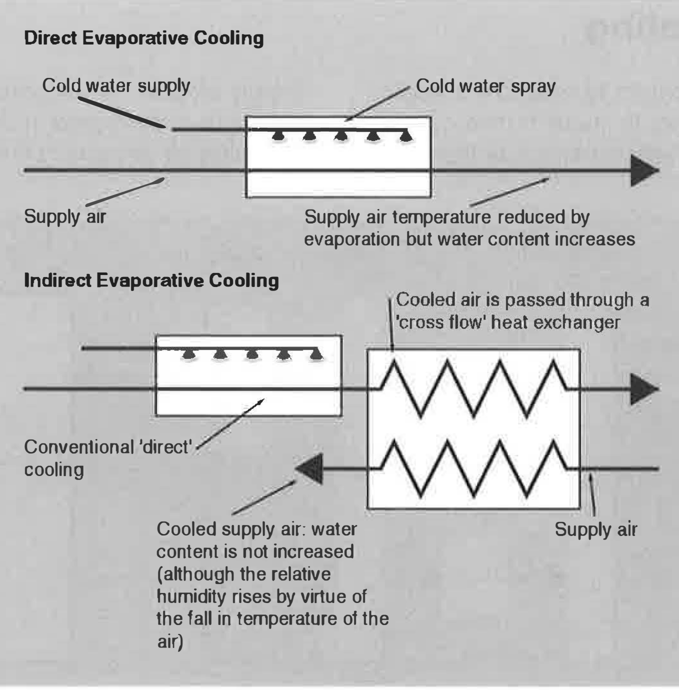


Figure 4 Principles of Evaporative Cooling

Two Stage Indirect/Direct: direct cooling follows indirect cooling. The intention is to maximise cooling potential while minimising the increase in moisture absorption of the supply air.

Allowing for the need for fan and water pump energy, typical coefficients of performance (COP's) are:
COP = 4 for direct/indirect coolers
COP = 6-7 for direct coolers.

They can only be used where the resulting rise in relative humidity (due to both dry bulb temperature depression and increase in moisture content arising from direct evaporation) does not exceed comfort level (e.g. 60%) or any requirement that may otherwise be specified for the space to be cooled. Evaporative cooling only works efficiently when the air to be cooled is relatively dry (i.e. substantially less than the dew-point temperature), and there can be considerable water consumption etc.

Evaporative Cooling Check-List

Favourable Factors:

- Dry (not humid) climate.

Unfavourable Factors:

- Humid climate;
- High heat gains;
- Specification of close temperature/humidity control;
- Possible Legionella concern although the risk is limited by low water temperatures.

Design Aims:

- Heat recovery using heat exchanger to preheat outdoor air in winter.

Design Requirements:

- Space for ventilation system.

Cooling Performance:

Direct Systems:
- Ratio of cooling delivered to energy for generation and distribution ~ 7;
- Water consumption ~ 1.3 litres/MJ of cooling.

Indirect/Direct systems:
- Ratio of cooling delivered to energy for generation and distribution ~ 4;
- Water consumption ~ 1.5 litres/MJ of cooling.

Combination with other technologies:
- Night cooling;
- Displacement ventilation;
- 'Top-up' mechanical cooling to meet peak loads.

2.5 Desiccant Cooling

Desiccant cooling endeavours to extend the applicability of evaporative cooling to more humid conditions by using a desiccant to extract moisture from the supply air prior to evaporative cooling. A typical cooling cycle is illustrated in Figure 5. In this example the incoming air stream, (1), is first dried by passing it

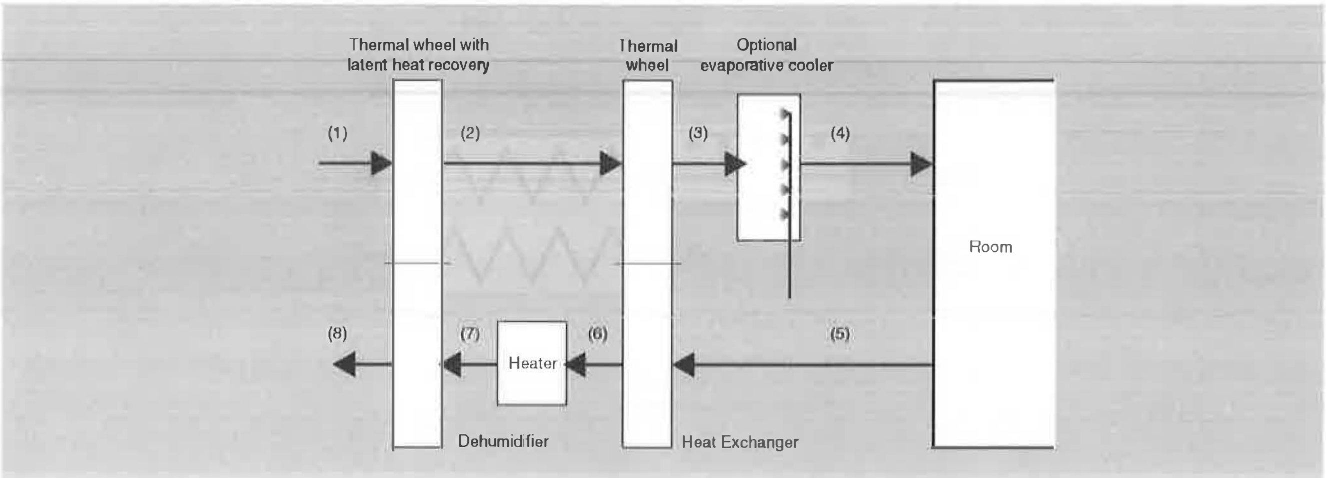


Figure 5 Principles of Desiccant Heat Recovery (with Optional Evaporative Cooler)

through a latent heat recovery wheel. The action of dehumidification raises the dry bulb temperature of the supply air and therefore it must be passed through various stages of cooling. Firstly it is passed through a conventional thermal wheel heat exchanger, (2), (which has been pre-cooled) and then it is passed through a direct evaporative cooler, (3), where it loses temperature but gains humidity. From here it enters the space that needs to be cooled. The outgoing (heated exhaust air stream) is evaporatively cooled , (4), and then passed through heat exchanger, (5), to assist cooling of the supply air stream. The resultant air is further heated and used to dry the latent heat recovery wheel to prepare it for drying the supply air.

A by-pass is placed at the heater stage and further controls are needed to ensure that the system does not function in reverse mode except in winter when both heat wheels are used for direct heat recovery from the exhaust air for pre-heating the supply air.

Two types of desiccant exist: solid and liquid based.

Desiccant cooling systems have the following benefits:

- Improvement to indoor air quality – in addition to desiccant cleaning the air as it dehumidifies it, some desiccants also act as bactericides;
- Capability of producing very low humidity levels;
- Ability to use alternate energy sources and waste heat;
- Minimal electrical consumption;
- Capacity for demand side management by shifting electrical consumption to a thermal source;
- Separate control of humidity and temperature.

Desiccant Cooling Check-List

Favourable Factors:

- Waste heat or cheap thermal source available.

Unfavourable Factors:

- A requirement for precision temperature and humidity conditions;
- Dry Climate.

Design Aims:

- Air filters to increase life span of dehumidifier.

Design Requirements:

- Space for ventilation system;
- Supply and extract airstreams normally adjacent.

Cooling Performance

- Ratio of cooling output to energy input ~1 at present. Anticipated improvements should give ratio of > 1.7;
- Examples of delivered cooling performance are:
  Gas: CoP 2.6
  Electrical: CoP 11.6

Combination with other technologies:

- Night cooling;
- Displacement ventilation;
- Evaporative cooling.

2.6 Chilled Ceilings and Beams

Cold water is run through coils in ceiling panel units or along beams located just beneath the ceiling. This water is supplied at an inlet temperature of between approximately 16°C - 18°C. To avoid condensation the

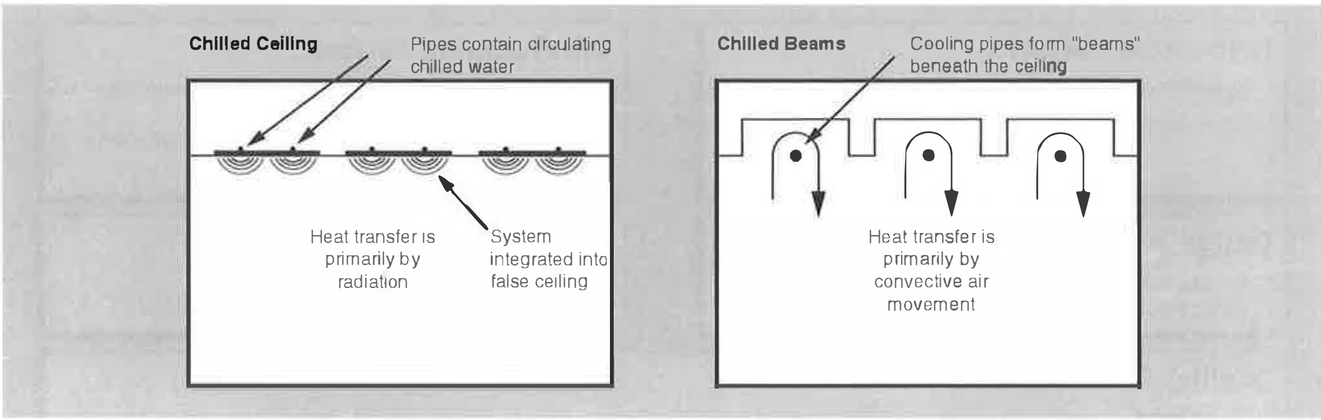


Figure 6 Principles of Chilled Ceilings and Beams

water temperature should not fall to less than 1.5K above the dew temperature of the room air.

Chilled ceilings provide 'sensible' (dry bulb) cooling. Typically, they are used in conjunction with displacement ventilation systems, in which case any latent cooling (and further dry bulb cooling) is achieved by dehumidifying the ventilation supply air. Because large temperature reduction is not needed, low 'quality' cooling sources such as the outdoor air, aquifer sources or heat pumps can be used, thus reducing the need for conventional refrigerative cooling.

Chilled ceilings have a construction of flat panel units that primarily transfer cooling to the space by radiation. Chilled beams have a more open structure and tend to rely on convective transfer (air movement) as the principle mechanism of heat transfer.

Chilled Ceilings/Beams Check-List

Favourable Factors:

- Low energy/quality source of cooling.

Unfavourable Factors:

- A requirement for precision temperature and humidity conditions.

Design Aims:

- Avoidance of condensation problems.

Design Requirements:

- Space for cooling elements;
- Space for central cooling and distribution system.

Cooling Performance:

- Up to 100W/m^2 of sensible cooling. Further sensible (dry bulb) and latent cooling can be obtained from the displacement system (see displacement ventilation).

2.7 Displacement Ventilation

Conditioned air at approximately 2K below ambient room temperature is emitted at low level and at very low velocity (0.1 – 0.3m/s) into the space. The air gradually spreads close to floor level until it reaches a thermal source such as an occupant or electrical equipment. It then plumes around the source, rising to ceiling level where it is captured and extracted. Unlike more conventional mixing ventilation systems, this approach is, designed to avoid the mixing of air supply air with room air. Instead it 'displaces' the room air. Displacement ventilation, therefore, provides a precision means for effectively meeting the air quality needs of occupants. Furthermore emissions from heat sources are rapidly carried away from the occupied zone. For these reasons, efficient cooling can be introduced. In a conventional office building, cooling capacity is restricted to approximately 30-40W/m^2 by the temperature at which air must be introduced and the volume flow rate of the ventilation air.

Displacement Ventilation Check-List

Favourable Factors:

- Surface temperature of heat sources > 35°C.

Unfavourable Factors:

- A requirement for precision temperature and humidity conditions;
- Strong disturbances to air flow (e.g. movements or downdraughts).

Design Aims:

- Supply air temperature = 18°C;
- Vertical temperature gradient < 1.5K.

Design Requirements:

- Ceiling to floor height of >2.7m needed;
- Space for large low velocity terminals at low level.

Cooling Performance:

- 30 – 40 W/m^2.

2.8 Ground Coupling (Air Cooling and Heating)

A matrix of piping is placed under the foundations of the building (typically at a depth of 6m where the temperature of the ground is essentially uniform throughout the year). This network is connected to an outdoor air intake at one end and to the building ventilation system at the other. Ventilation air is drawn through the matrix for pre-cooling in the summer and preheating in the winter. In cooling mode, it will usually be used to supplement another technology (typically night cooling) and will therefore not operate until needed.

This system is suited to all mechanically ventilated buildings provided the installation of the piping system is feasible. Normally it is most applicable to the non residential sector and where there is a moderate cooling demand (i.e. the system has good peak performance but limited seasonal performance because the ground source will gradually heat up).

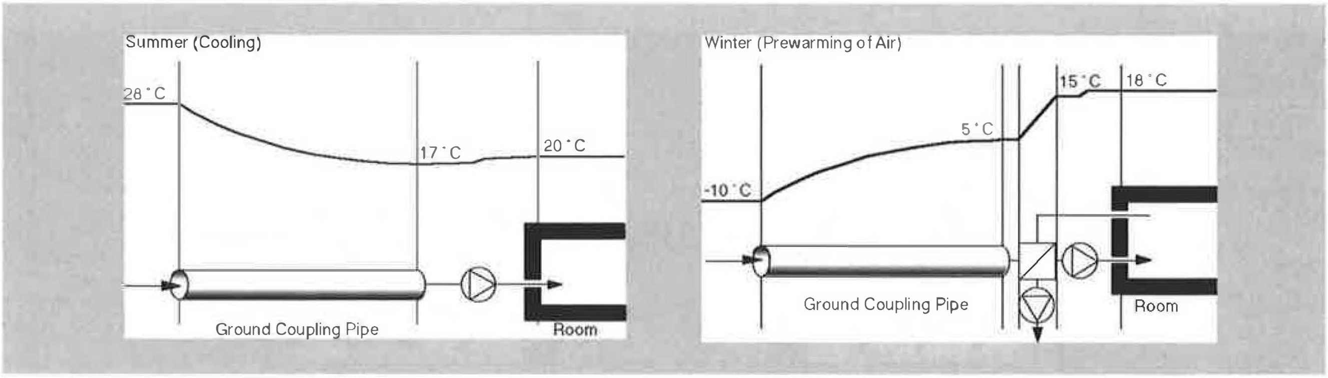


Figure 7 Principles of Ground Cooling and Heating

Ground Coupling Check-List

Favourable Factors:

- Ground temperature at 12°C or below;
- Located in sand or gravel and below water table;
- Flowing groundwater.

Unfavourable Factors:

- Hot climate;
- Solid (rock) ground;
- Ground pollution (e.g. radon);
- High heat gains;
- Need for close temperature/humidity control.

Design Aims:

- Protect the building from heat gains (solar, internal etc.);
- Minimise piping system pressure drop.

Design Requirements:

- Space requirement for piping system;
- Access requirements for maintenance;
- Effective sealing in wet ground).

Cooling Performance:

- 45W/m^2 of ground coupling area.

2.9 Aquifer (Groundwater) Cooling

Groundwater (aquifer) systems can be used in both heating and cooling modes. During the summer, cold water is abstracted from one part of the aquifer system (the 'cold' well) (typically at 2°C-12°C but depending on the aquifer and location) and is used via a heat exchanger (Figure 8) for cooling the building. The resultant heated water is then recharged into the aquifer at a different location (the 'hot' well). In winter, the process is reversed with 'warm' water (typically at 8°C-15°C) being taken from the 'hot' well and used to preheat the ventilation air. The resultant cooled water is returned to the 'cold' well. The output from the heat exchanger may be connected to a heat pump to extend the conditioning capability of the system.

Although the basic principle of energy storage is simple, it is necessary to perform accurate and specialised investigations of the aquifer and of the intended performance of the store before starting to design the building. To avoid progressive heating or cooling of the aquifer, it is important that the energy input and abstraction are approximately in balance.

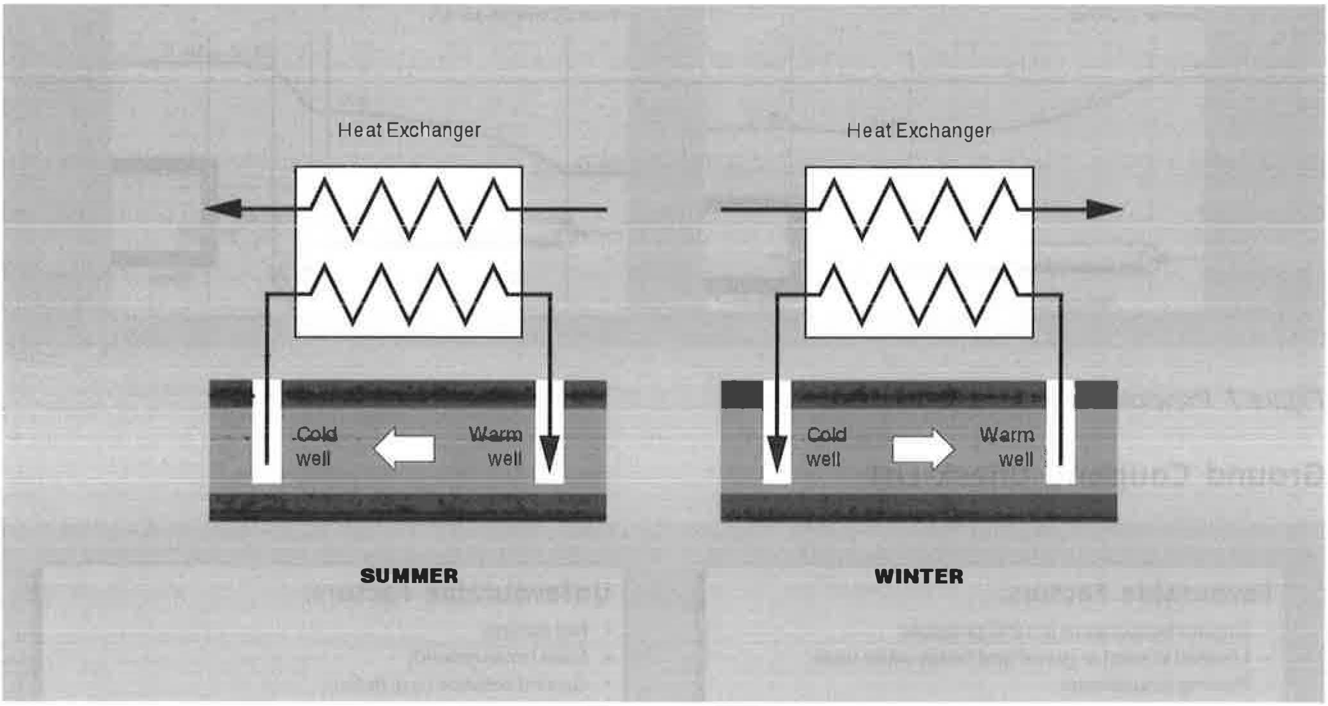


Figure 8 Using Aquifer for Cooling and Pre-Heating

Aquifer Check-List

Favourable Factors:

- Sand or limestone aquifer, bounded by clay or similar impermeable boundary;
- Climates with balanced heating and cooling season for inter-seasonal storage.

Unfavourable Factors:

- Hot climate (e.g. cooling only);
- Restrictions or costs on groundwater uses;
- Moving groundwater compromising seasonal storage.

Design Aims:

- Balance between heat and cool extraction.

Design Requirements:

- Cold and warm wells should be spaced 100 – 150m apart;
- Space for heat exchanger.

Cooling Performance:

- Typical design cooling load 50 – 100 W/m² (e.g. based on peak of 900 kW cooling for 25l/s water abstraction/recharge).

2.10 Sea/River/Lake Cooling (Water)

Based on similar principles to groundwater cooling, water is taken from a lake or from the sea. The closed loop can either be used to provide direct cooling or indirectly as a condenser. Seawater is corrosive, therefore the sea water loop may require special protection such as a titanium heat exchanger.

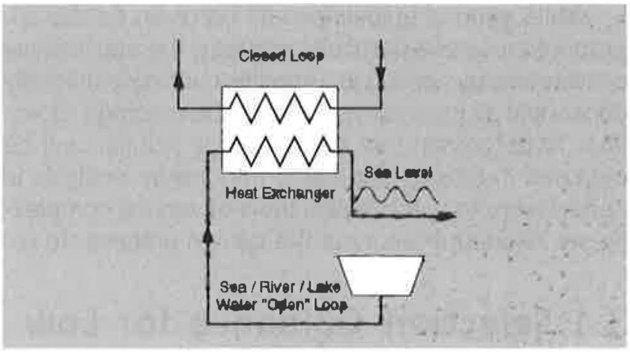


Figure 9 Lake or Sea Water Cooling

Sea/River/Lake Cooling Check-List

Favourable Factors:

- Proximity to water source.

Unfavourable Factors:

- Hot climate;
- Great depth required to reach cold water;
- Salinity in sea water encouraging corrosion.

Design Aims:

- Minimise cold water source pumping costs;
- Eliminate corrosion and fouling possibilities. If brackish or sea water is used a titanium heat exchanger may be necessary;
- Compatibility with mechanical cooling.

Design Requirements:

- Space for heat exchanger, pumps etc.

Cooling Performance

- Intake temperature should be below 10°C; Indirect cooling of condensers in conjunction with mechanical cooling can be effective with intake temperatures up to 13°C. Fortunately large water bodies do not reach maximum temperature until after the Summer.

2.11 Sea/River/Lake Cooling

Water is abstracted from a local water source and circulated through a heat exchanger before being returned in an 'open' loop. A closed loop branch from the heat exchanger is then used to provide either direct cooling or indirectly as a condenser for a heat pump.

Sea/River/Lake Cooling Check-List

Favourable Factors:

- Proximity to cold water sources.

Unfavourable Factors:

- Hot climate;
- Great depth may be required to reach cold water;
- Salinity in seawater may cause corrosion.

Design Aims:

- Minimise cold water pumping costs;
- Eliminate corrosion and fouling possibilities;
- Compatibility with mechanical refrigerative cooling.

Design Requirements:

- Water temperature <13°C (indirect condenser cooling); <10°C for direct cooling;
- Space for heat exchanger and associated plant.

Cooling Performance:

- ~ 80W/m² (combined direct and indirect).

3. The Numerical Design Tools

While general guidelines can be given on the appropriateness of a particular strategy, the applicability of a low energy cooling to a specific building is uniquely dependent on the circumstances of the building in question. To be certain that a low energy solution will be obtained it is essential that a full energy analysis is undertaken. To achieve this, tools of varying complexity are needed throughout the design process. To reflect these needs, three different levels of tools have been developed by the Annex. These are:

- Selection Guidance for Low Energy Cooling Technologies;
- Early Design Guidance for Low Energy Cooling Technologies;
- Detailed Design Tools for Low Energy Cooling Technologies.

3.1 Selection Guidance for Low Energy Cooling Technologies

Figure 10: Selection Chart (Template)

Steps:

1. Delete non-applicable parameters.

2. Determine rating of each technology:

negative F= low feasibility
no F, negative S = low suitability
no F, zero / no S = medium suitability
no F, positive S = high suitability

Input parameters
(see notes opposite)

Technologies		Daytime natural ventilation	Daytime mechanical ventilation	Night cooling (natural ventilation)	Night cooling (mechanical ventilation)	Slab cooling (air)	Slab cooling (water)	Evaporative cooling (direct & indirect)	Desiccant + evaporative cooling [1]	Chilled ceilings / beams	Displacement ventilation	Ground cooling (air)	Aquifer [2]	Sea / river / lake water cooling [3]	Mechanical cooling
F / S Rating		-F	-S	-F		+S	+S			+S			+S	+S	+S
Temperature	Hot	-F	-F	-F	-F	-F						-S	-S		+S
	Warm	-S	-S	-S	-S										
	Cool					+S	+S	+S				+S			
Humidity	Humid							-F							+S
	Semi-humid														
	Dry							+S	-S						
Noisy / Polluted air		-F		-F											
Ground Pollution												-F			
Residential		+S[4]		+S[4]						-S			-S	-S	
Retrofit						-F[6]	-S[7]					-S[6]			
Limited floor-ceiling height		-S		-S							-S				
Deep Plan / Cellular Space		-F		-F											
Heavyweight				+S	+S	+S	+S[8]								
Limited Solar Protection / High Solar Gains		-S	-S	-S	-S	-S	-S	-S		+S		-S	+S	+S	+S
High Internal Gains		-S	-S	-S	-S	-S	-S	-S		+S		-S	+S	+S	+S
Close Temperature Control		-F	-F	-F	-F	-F	-F	-F	-S	-S	-S	-S			+S
Close Humidity Control		-F	-F	-F	-F	-F	-F	-F	-F	-S	-S	-S			+S

The objective of this task was to produce a simple selection guide that would be suitable at the pre-design stage in identifying the most promising cooling technologies for a particular type of building and climate zone. The aim was to filter out unsuitable choices at an early stage, thus preventing costly mistakes or unnecessary design calculations at a later stage.

Selection guidance is presented in the form of the chart illustrated in Figure 10. It is based on a 'Feasibility' (F) and 'Suitability' (S) rating which reflects the impact of key building parameters on each of the technologies. The intention of the selection chart is to:

- Highlight the parameters and associated ratings;
- Eliminate from a particular design, technologies that are unlikely to be suitable (i.e. those with a '-F' rating);
- Add the suitability ratings (+S,-S) for the remaining technologies to give an overall rating. A positive rating is favourable whereas a negative rating is unfavourable. A net 'zero' rating implies that the technology has no significant impact. Hence a positive 'S' rating indicates the potential suitability of a technology to a particular application, whereas a negative value indicates low suitability.

Daytime natural and mechanical ventilation options are included in the chart to represent the lower boundary of the selection process, in which no need for cooling is implied. Mechanical (refrigerative) cooling is placed at the upper boundary.

Notes for Input Parameters

Input Parameters

Temperature	Hot	STD [9] > 28°C and SNT [10] > 20°C
	Warm	STD [9] > 28°C and SNT [10] < 20°C
	Cool	STD [9] < 28°C and SNT [10] < 20°C (e.g. UK)
Humidity	Humid	MC [11] > 0.014 kg / kg
	Semi-humid	MC [11] < 0.014 kg / kg and WBD [12] <8 K (e.g. UK)
	Dry	MC [11] < 0.014 kg / kg and WBD [12] >8 K
Noisy / Polluted air		Relative to desired internal environment
Ground pollution		e.g. Radon
Residential		Less stringent comfort criteria likely to apply, smaller scale of development
Retrofit		Space restrictions probable
Limited floor / ceiling height		Reduces effectiveness of natural ventilation and displacement ventilation (~2.7m minimum)
Deep plan / cellular space		Depth reduces effectiveness of natural ventilation (maximum ~7.5m for single sided ventilation, ~15m for cross ventilation). Cellular arrangement impedes air movement.
Heavyweight		e.g. exposed soffit or floor
Limited solar protection / High solar gains		Window solar factor x window area / floor area > 0.15 (typical solar factors; clear glazing ~0.8; solar control glass ~0.5; external shading ~0.2)
High internal gains		Internal design gains from occupants + equipment + lighting > 30 W/m^2
Close temperature control		e.g. design criteria 22 +/- 2°C
Close humidity control		e.g. design criteria 40-70 %RH

Note 1: *Applications limited by availability of low cost heat source.*
Note 2: *Geographic restrictions regarding presence of aquifer.*
Note 3: *Geographic restrictions regarding location near sea / river / lake.*
Note 4: *Natural ventilation is particularly suited to residential applications due to low cost.*
Note 5: *Applies to hollow core systems. Other approaches suitable for retrofitting are under development.*
Note 6: *Applies to ground cooling systems installed under buildings. In some applications it may be possible to install the system beneath adjacent ground.*
Note 7: *Not applicable if system already installed for heating.*
Note 8: *Use of slab cooling - water requires exposure of the slab and so the space will be heavyweight.*
Note 9: *SDT is the summer peak design temperature (°C).*
Note 10: *SNT is the summer night minimum design temperature corresponding to summer peak design temperature (°C).*
Note 11: *MC is the summer design moisture content (kg / kg dry air).*
Note 12: *WBD is the wet bulb depression, the difference between the summer design ambient dry and wet bulb temperatures.*

3.2 Early Design Guidance for Low Energy Cooling Technologies

The report on early design guidance provides a compilation of guidance for low energy cooling technologies intended for use during early design. Guidance is presented in terms of design charts, tables and practical information. Details included in the main report are summarised in the Table below:

Early Design Guidance	Summary
A. The applicability of evaporative cooling in commercial office buildings	Tabulated maximum temperatures, percentage hours under-cooled and electrical consumption (fans and cooling). Information is generated from DOE software.
B. Evaporative cooling in office buildings	Tabulated peak temperatures/cooling coil loads under Summer design conditions plus annual energy (heating, cooling and fan) and water consumption per annum for French climates of Trappes, Carpentras and Nice. Information generated by COMET thermal software.
C. Slab cooling system with water	Charts for estimating the cooling provided in combination with a cooling tower based on indoor plus outdoor dry and wet bulb temperatures.
D. Night cooling ventilation in UK commercial buildings	Design temperatures to predict peak temperatures, free cooling provided and fan energy consumption for south-east UK climate. Information generated using FACET software.
E. Night cooling in residential buildings	Tabulated data to establish minimum solar protection required to limit peak temperatures for four French climates. Information generated using COMET thermal software.
F. Ground coupled air systems	Design curves for capacity and sizing of simple systems based on the detailed design tools contained in the Annex 28 detailed design report.

3.3 Detailed Design Tools for Low Energy Cooling Technologies

This part of the study focused on developing a set of design tools. Where possible they are based on a common structure following the ASHRAE toolkit format, i.e.:

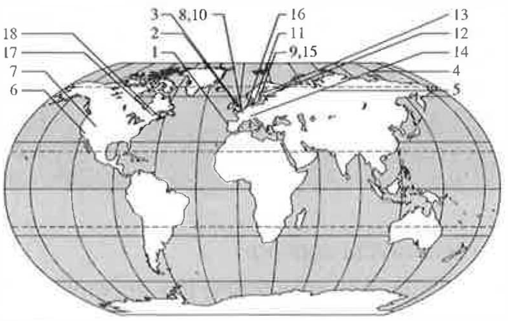
1. **Technology Area**: Specification of the area to which the tools relate;
2. **Developer**: Contact address etc.;
3. **General Description**: An explanation of the purpose of the tool, typically incorporating a schematic showing the system elements and their interaction plus an information flow diagram with algorithm inputs, outputs and parameters;
4. **Nomenclature**: Definition of the mathematical variables used in the mathematical description and the code variables used in the source code;
5. **Mathematical Description**: Base equations for the algorithm describing the relationships between the variables;
6. **References**: The source of empirical or non-standard mathematical equations and other data used;
7. **Algorithm**: Definition of the structure of the algorithm as a step by step procedure detailing the order in which these base equations are calculated;
8. **Flow Chart**: Flow charts illustrating the calculation procedures are presented;
9. **Source Code**: This is provided for most tools. Software versions of the source code and executable files are presented on a disk enclosed in the detailed design tools report;
10. **Sample Results**: Input and output data are provided to give users an illustration of how each tool is intended to be used and what results to expect.

A list of the detailed design tools is presented below.

1. Night Cooling (Natural Ventilation);
2. Night Cooling (Mechanical ventilation);
3. Slab Cooling (Air);
4. Slab Cooling (Water);
5. Evaporative Cooling (Direct and Indirect);
6. Desiccant + Evaporative Cooling;
7. Displacement Ventilation;
8. Ground Cooling (Air);
9. Ground Cooling (Water).

4. The Case Study Buildings

Fundamental to this Annex was an evaluation by demonstration. The purpose was to take advantage of a unique opportunity to exchange and gain experience from technologies tested under scientific conditions. Above all, these buildings were selected because they demonstrated substantial energy savings over conventional technology while securing good thermal comfort was secured. A total of eighteen buildings were analysed, their location and the applied technology are summarised in Table 2 below. The various climate conditions give markedly different pre-requisites for the studied technologies and hence the suitability of a technical alternative must be considered in relation to the location of the building.



	Night Cooling (Natural)	Night Cooling (Mechanical)	Slab Cooling (Water)	Evaporative Cooling	Desiccant Cooling	Chilled Ceiling/Beams	Displacement Ventilation	Ground Cooling (Air)	Aquifer	Ground Cooling (water)	Sea/River/Lake Water Cooling
1 Vila Nova de Gaia, Porto, Portugal	❄										
2 The OU Design Studio, Milton Keynes, UK	❄										
3 The IONICA Office Building, Cambridge, UK		❄									
4 The Dow Building, Horgen, Switzerland			❄								
5 Sarinaport Office Building, Fribourg, Switzerland			❄								
6 The ACT² Stanford Ranch House, Rocklin, California, US			❄	❄							
7 The One Utah Center Building, Salt Lake City, US				❄							
8 Gaz de France Research Centre, Paris, France				❄							
9 Infracity Commercial Centre, Stockholm, Sweden					❄						
10 The Nestlé-France Head Office, Noisiel, France						❄	❄				
11 Hamburg Regional Bank, Hamburg, Germany						❄	❄				
12 The Granlund Office Building, Helsinki, Finland						❄					
13 The Wärtsilä Diesel Building, Vaasa, Finland						❄					
14 The Schwerzenbacherhof, Zurich, Switzerland		❄						❄			
15 SAS Frösundavic, Stockholm, Sweden									❄		
16 The Groeene Hart Hospital, Gouda, Netherlands									❄		
17 The Advanced House, Laval, Canada										❄	
18 The Purdy's Wharf, Halifax, Canada											❄

Table 2: Location of Buildings and the Applied Technology

These case studies offer guidance based on experience but do not give any guarantee for the suitability of a technology. The particular aspects analysed in the case studies included:

- **Energy**: In most cases, energy consumption is reduced when compared to a conventional refrigerative cooling system. The studied technologies can either be used solely or as a first step in combination with conventional cooling strategies (e.g. to reduce refrigerative cooling load and plant size).
- **Cost**: The intention is that total (life cycle cost) should be lower than with conventional methods. Costs vary from country to country, therefore this must be taken into account. Nevertheless, each case study is supported with a comparative cost analysis.
- **Performance**: Ultimately performance in terms of occupant well-being and thermal comfort must be satisfactory. The studies have therefore made an evaluation of conditions and occupant reactions.

4.1 Night Cooling with Natural Ventilation

Vila Nova de Gaia, Single Family Dwelling, Portugal

Project Data

Location:	Vila Nova de Gaia, Portugal
Altitude	200m
Year of Construction	1991/1992
Heated Floor Area	316m²
Unheated Floor Area	96m²
Number of Floors	4
Total Volume	920m³
Cooling Degree Days	118 Kd
Heating Degree Days	1979 Kd
Heating Load	12.3 kW
Cooling Load	7.7kW

This building is an example of how to obtain comfortable indoor conditions in a moderately mild climate based on natural ventilation for night cooling combined with good thermal insulation to minimise winter heating needs. The principle building details and performance results are summarised in the following text and tables. Construction costs at US$ 560 or 505 ECU per m² were no different to comparable construction techniques of similar quality.

The climate in this region is mild, both in winter (average temperature of 8°C) and in summer (average temperature of 12°C). Cooling has been aimed, therefore, at minimising internal and solar gains and maximising the use of thermal mass. The main design principles are:

- High level of insulation (U-values, W/m²K are: external walls 0.65, floor 0.5, windows 3.9, roof 0.5-0.7);
- Solar protection (external shades, overhangs and external and internal blinds);
- High thermal mass;
- Airtight design (0.3 air changes/hour at 50Pa);
- Natural night cooling ventilation using cross flow by window opening at night;
- Restricted ventilation in the day time when the outdoor air is hotter than the indoor air;
- Gas central heating;
- No mechanical cooling.

During summer monitoring the maximum dry bulb temperature (measured upstairs) did not exceed 27.5°C with a corresponding black bulb temperature maintained between 24°C - 26°C. The ground floor was generally 1-2 K cooler than the upstairs temperature.

Winter heating consumption is summarised below:

Monitoring period	Winter 96/97
Gas (propane)	315 kg
Electricity	450 kWh
Wood (fireplace)	2000 kg
Specific heating consumption	160 MJ/ m²a

Table 3 Winter Heat Consumption

Practical Experience

Experience over five years of occupancy has demonstrated good summer cooling performance. This example has been used as an argument to improve Portuguese Building Regulations as well as European CEN Standardisation. The underlying design principles are firmly accepted as the most adequate for Portuguese buildings and the regulations will be revised accordingly.

The Open University Design Studio, Milton Keynes, UK

This case study has focused on retrofit to improve comfort and reduce energy demand. The main design features are:

- Reducing summer over-heating that results from thermal emission from electronic drawing equipment;
- Refurbishment to reduce heat gains and to enhance natural cooling (no mechanical cooling);
- Night cooling by opening upper windows close to ceiling level (i.e. the thermal mass). This is based on individual user judgement combined with security guarding and manual closing of windows by security guards in adverse weather conditions;
- Upgrading thermal insulation, especially of glazing (from single to triple glazing);
- Use of mid-pane blinds to replace internal blinds.

Project Data

Location: .... Milton Keynes, UK
Altitude 50m
Year of Construction 1970
Refurbished 1993
Conditioned Floor Area .... 400 m²
Conditioned Volume .... 1080 m³
Heating Degree Days .... 2478 Kd

- Exposing the thermal mass of the ceiling by removing ceiling tiles and replacing with acoustic plaster;
- Installing controls and low energy lighting.

The combination of effective techniques to reduce internal heat gains combined with the selection of an appropriate window system allowing effective night cooling has produced a comfortable and well liked working environment. During monitoring, over an exceptionally hot period, reduced indoor air and black bulb temperatures were maintained. This has been achieved at a comparable cost to installing a mechanical cooling system but has the benefit of reduced maintenance and operating costs.

Practical Experiences

External pollution and security are important urban issues. There was evidence of the ingress of particulate matter entering the building and causing staining. Some occupants experienced draughts in the middle of the space when windows were open. The control of lighting and blinds was not always at an optimum. It was important for the occupants, security guards and cleaning staff to have training in the operation of the building.

4.2 Night Cooling (Mechanical and Natural Ventilation)

The IONICA Office Building, Cambridge UK

Project Data

Location: .... Cambridge, UK
Altitude 10m
Year of Construction 1993/1994
Conditioned Floor Area 4000m²
Number of Floors 3
Cooling Degree Days (18°C) 104Kd

This building has incorporated a wide range of low energy options. The main design features include:

- Natural ventilation by window opening, atrium and wind towers;
- Night cooling;
- Maximising use of natural daylighting;
- Individual user control of perimeter windows combined with automated night control;
- Hollow slabs to enhance thermal storage capacity;
- Top-up mechanical cooling utilising indirect evaporative cooling and heat pump cooling;
- Thermal wheel heat recovery.

The building incorporates a comprehensive control strategy based on the procedure outlined in the table below. This strategy is subject to fine tuning and override is also possible.

Conditions	Time	Operation
Zone temperature < 19°C at night	Any Time	All heating plant full on unless cooling has been in operation.
External air temperature < 14°C	Day	AHU runs with all plant enabled to supply air into slab at 21°C.
External air temperature < 14°C, zone temperature < 26°C	Day	Natural ventilation in southern zones, mechanical ventilation (21°C) in northern zones.
External air temperature < 14°C, zone temperature > 26°C	Day	AHU runs with all plant enabled to supply air into slab at 21°C.
Minimum zone temperature <20°C	Night	AHU runs with the thermal wheel only (to redistribute heat in the slab).
Minimum zone temperature > 19°C at night and <24°C the previous day	Night	All plant off.
Minimum zone temperature > 19°C at night and > 24°C the previous day	Night	Night cooling with natural ventilation in southern zones, mechanical 'free' cooling in northern zones.

Table 4 Control Modes of Ventilation System

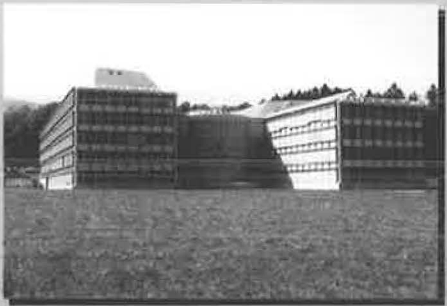
Practical Experiences

- Although the south side of the building was largely naturally cooled, monitoring showed that the indoor temperature could be maintained below peak out door temperatures. For the indoor temperature to exceed a threshold level of 27.5°C, the outdoor temperature needed to peak at above 30°C;
- Draughts sometimes occurred due to high velocities created by the wind towers;
- Late night and 24 hour use of some parts of the building restricted night cooling potential;
- Insect ingress occurred during passive night cooling;
- Occupants tended to allow overheating before opening windows. It would be preferable for occupant windows to be opened before becoming to warm.

4.3 Slab Cooling (Water)

The DOW Building Headquarters, DOW Europe, Horgen, Switzerland

Project Data



Location:	Horgen, Switzerland
Altitude	437m
Year of Construction	1991/92
No of Working Spaces	300
Heated Floor Area	14400m²
Slab Cooling Area	7500m²
Number of Floors	5
Cooling Degree Days	198Kd (18°C)
Heating Degree Days	3616Kd (20/12°C)
Heating Load	213MJ/m²
Cooling Load	17MJ/m²
Heating Capacity	510kW
Cooling Capacity	400kW
Ventilation	120kW
Ventilation Rate	3m³/m²

Basic Design Features

Design and construction of this building followed Swiss Energy Regulations that permits active cooling only in exceptional cases. The building takes advantage of high thermal mass combined with embedded water channels to provide effective cooling and heating. By utilising 'free' cooling for two thirds of the time, the building is very energy efficient when compared to a conventional fully mechanically cooled building. Principal design features include:

- Concrete slabs stores heat gain from day to night when it is removed via air coolers connected to water loops in the slab;
- Mechanical ventilation provides displacement ventilation through supply air inlets integrated into suspended lamp support frames in the rooms. This results in cool air descending to the floor with low turbulence;
- Solar protection by automatic (and occupant) controlled independent external solar shading for each facade;
- Heat recovery;
- High thermal insulation (walls 0.3W/m^{2}K, glazing 1.7 W/m^{2}K);
- No increase in investment (capital) costs;
- Openable windows for optional use;
- Daylighting and energy efficient lighting.

Control Strategy

A simple control strategy has been implemented in which supply air is kept at 19°C (thus avoiding condensation) all the year round. The ventilation flow rate is reduced to 50% at night. Cooling water flow is also set at 19°C. Water circulation starts at midnight and is continued until the temperature difference on the water side of the cooler is less than 1K. Circulation is then shut down for an hour before the process is restarted. This cycle continues until the temperature of the water returning from the cold slab falls below a set value. This method enables cooling water circulation to match the slow rate of heat discharge from the concrete slab.

Practical Experiences

- Very efficient energy savings were demonstrated while good thermal comfort conditions were maintained;
- A lengthy control optimisation period was needed (two years) to establish a good control mechanism;
- Mass storage technology gives excellent performance;
- 'Free' cooling was most effective at an average night outdoor temperature of between 15°C - 18°C. At higher temperatures cooling potential reduces rapidly and falls to zero at 20°C. At lower temperatures cooling demand is lower and usually falls to zero at 13°C. The maximum night free cooling capacity was 100Wh/m^2 and has approximately the same magnitude as the thermal load during the day.

The Sarinaport Office Building, Fribourg, Switzerland

Project Data

Location:	Fribourg, Switzerland
Altitude	677m
Year of Construction	1993/94
No. of Working Spaces	380
Heated Floor Area	9500m^2
Number of Floors	4
Heated Volume	27000m^3
Cooling Degree Days	198Kd (18°C)
Heating Degree Days	3616Kd (20/12°C)
Installed Heat Capacity	150kW

Basic Design Features

This building is designed to minimise daily changes in the energy flow through the building. This is achieved by ensuring that only a small variation of energy flow can pass through the building envelope. Advantage is then taken of the very high thermal capacity but low transfer rate of the thermal mass. Daily compensations in energy flow are compensated by storing or releasing energy from the thermal mass by circulating water through the embedded channels.

The design is based on three mutually dependent principles; these being:

- Airtight, highly insulated building envelope;
- Thermoactive ceiling for heating and cooling;
- Displacement ventilation.

The main design concepts incorporate:

- Heavy concrete/ceiling mass containing embedded water channels;
- No thermal bridging across envelope insulation;
- Openable but high U value windows;
- Automatically controlled external sun shading with occupant override;
- Sound insulated floor/ceilings with perimeter air ducting and air grilles for displacement ventilation;
- Optional solar heating;
- Gas boiler although an intermittent heat pump should be considered;
- Evaporative cooling.

Control Strategy

A water temperature of 26°C maintains a ceiling surface temperature of 22°C. For cooling, a temperature of 20°C is maintained. Because of the very high thermal mass and measures to restrict daily variations in energy flow, the system is largely self-regulating and contains heating and cooling in a single circulation system. The temperature of the ceiling is kept at 22°C all the year round. Should the room temperature fall to 21°C, the ceiling automatically transfers heat to the space. Above 22°C, the ceiling takes heat from the space. This is largely self-regulating and also distributes heat from rooms with high loads to adjacent cooler rooms.

Practical Experiences

- Summer monitoring demonstrates that an essentially uniform temperature is maintained, reaching no more than 24°C, even when the outdoor temperature peaks at 34°C;
- Cooling performance is 15-20 W/m^2 with a maximum of 30W/m^2. For small areas (one to two rooms, a peak of 50 W/m^2 is acceptable);
- Capital investment cost is about 10% less than a comparable building of conventional design. Energy consumption is about half;
- Occupant satisfaction is very high.

4.4 Evaporative Cooling

The ACT^2 Stanford Ranch House, Single Family Dwelling, Rocklin, California, USA

Project Data

Location: .... Rocklin, California, USA
Altitude 73m
Year of Construction 1994
Conditioned Floor Area .... 153m^2
Number of Floors 1
Cooling Degree Days .... (18°C) 1746Kd
Heating Degree Days .... (18°C) 648Kd
Cooling Load 7kW

Basic Design Features

The building slab is night cooled direct evaporation using embedded plastic coils (350m in length and 50mm in diameter). The building is also cooled by evaporative pre-cooling of room air during the night. Other features include high thermal mass, good thermal insulation (windows 2.1 W/m^2), low emissivity glazing and energy efficient appliances. At night the building is simultaneously pre-cooled while providing 15°C chilled water to the plastic coils for thermal storage. On average summer days the radiant cooling provided by the floor slab provides sufficient cooling. However, on peak summer days, additional cooling is obtained by circulating water from below the slab to a fan coil unit.

Control Strategy

The evaporative cooler is controlled by a time clock to operate at night during the coolIng system. Occupants open windows to remove any excess moisture. The fan coil units for cooling (and heating) are controlled by a proportional thermostat. That senses the difference between the zone temperature and thermostat setting and adjusts the fan speed accordingly. In the heating season the load is sufficiently small to meet space heating and domestic hot water needs by means of a single, high efficiency, hot water heater of 29.3kW. A condensing gas system is used with an efficiency of 94%.

Practical Experiences

The system could maintain comfort conditions despite outside temperatures reaching up to 40°C for three consecutive days. It is estimated that 81% of the cooling need was delivered directly by the evaporative cooling unit, first by flushing and pre-cooling the house from 10pm – 7am and then by passive cooling through the floor slab. Initially there was some problem with rising humidity but this was solved by shutting off the water supply to evaporative cooler thirty minutes before shut off and allowing the fan to flush moist air out of the house.

The 'One Utah Center' Building, Salt Lake City, USA

Project Data

Location:	Salt Lake City, USA
Altitude	1768m
Year of Construction	1991
Conditioned Floor Area	38925m^2
Number of Floors	24
Conditioned Volume	148000m^3
Cooling Degree Days	(18°C) 3409Kd
Heating Degree Days	(18°C) 550Kd
Cooling Capacity	2816kW

Basic Design Features

Utah has very dry and hot summer conditions which is very suited to evaporative cooling. In Utah, the design condition is 35°C at 15% relative humidity rising to 35%. Under these conditions, dry bulb evaporative cooling down 15°C is possible. The main design features include:

- Single pass (100% air supply) ventilation system;
- 3-stage chiller and direct evaporative cooling system;
- Identical supply air conditions as would be provided by a conventional HVAC system;
- Good indoor air quality;
- Heat recovery in winter.

Cooling is achieved by means of a 3-staged system consisting of an indirect evaporative cooler, conventional chilled water coils and a direct evaporative cooler. By putting the chilled water coils before the direct evaporative allows the chiller to provide only sensible cooling without competing with the humidity added by the evaporative cooler. On an annual basis, the evaporative coolers provide 80% of the total cooling load. The two chillers (880kW and 1936kW) are used on the few days when the outdoor wet bulb temperature reaches 20°C or more.

Control Strategy

100% outdoor air is supplied whenever the outdoor temperature is above 12°C. Outdoor air is first indirect evaporatively cooled. If needed, the mechanical cooling is used to bring the wet bulb temperature to 12°C. Direct evaporative cooling is then used adiabatically to cool the air to the supply temperature. Since the discharge air temperature is always maintained at 12°C, the absolute humidity of the supply air is identical to a conventional chilled water system. The indirect evaporative cooler sensibly cools the supply air to within 4K of the outdoor wet bulb temperature. When the wet bulb temperature exceeds 20°C the chiller is required to lower the temperature of the supply air a few degrees before it enters the direct evaporative cooler.

Practical Experiences

The system has operated successfully since installation. From practical experience, payback for this type of system is estimated at 3-4 years for a 25,000 l/s system down to 2 years for a 50000l/s or larger system. During 1994, a record hot summer for Salt Lake City, the chiller load did not exceed 1478 kW despite the outside temperature reaching 41°C on several days. During the period of use, the chillers have averaged only 450 hours/year (not at full load) compared to 1500 hours for a typical mechanical cooling system in a commercial office in the same area. Similarly, electricity use is reduced by typically a third to 5.98 kWh/m^2 per year. Total annual savings are $51000 (pay back < 4 years).

The 'Industry Division Office' Gaz de France Research Centre, Paris, France.

Project Data

Altitude 70m
Year of Construction 1991/92
Number of Working Spaces 35
Heated Floor Area .... 1000m^2
Number of Floors 2
Total Volume .... 3000m^3
Cooling Degree Days .... (18°C) 144Kd
Heating Degree Days .... (18°C) 2600Kd
Heating Capacity 80kW

Basic Design Features

Main design features include:

- High level of insulation (0.7W/m^{2}K);
- 25% façade area glazed;
- Internal shading (mainly north facing);
- Central daylighting;
- Electrical heat gains < 20W/m2 or less;
- Hot water (radiator) heating;
- Balanced ventilation with rotary (thermal wheel) heat recovery and indirect evaporative cooling to pre-cool/heat supply air;
- Forced mechanical night cooling in summer.

Control Strategy

An automated BEMS approach is used with four operating modes, i.e. winter/summer, occupied/unoccupied. Indoor temperature is measured in two rooms located on the north and south sides. Sensors in and around the air handling units monitor the outside, supply and exhaust air characteristics. The control conditions are:

- When direct outside air is sufficient (no heating/ cooling needed), the heat exchanger is bypassed;
- Indirect cooling when estimated humidified temperature is less that the outdoor air temperature (with a two hour 'run on');
- Night cooling in summer when the outside temperature is less than the inside temperature (4 air changes/hour);
- No heating and ventilation when the building is unoccupied (except for night cooling);
- Steam humidifier to maintain RH above 30%.

Practical Experiences

Experiences included the following:

- Summer electricity consumption was 11 kWh/m^2 (15% for hot water);
- Acceptable payback period;
- 4K reduction in peak outdoor temperature;
- No mechanical cooling;
- Insufficient solar protection of south facing and daylighting glazing.

4.5 Desiccant Cooling

The 'InfraCity' Commercial Centre, Stockholm, Sweden

Project Data

Location: ...... 30 km North of Stockholm, Sweden
Year of Construction 1972
Year of Renovation 1994
Number of Office Rooms 250
Heated Floor Area .... 7000m^2
Heated Volume .... 18900m^3
Cooling Degree Days .... (18°C) 42Kd
Heating Degree Days .... (20/12°C) 5480Kd
Heating Capacity 300kW
Cooling Capacity 130kW

Basic Design Features

In Sweden, many buildings have to be renovated to incorporate cooling to respond to increased thermal gains and comfort expectations. During the renovation of this building, desiccant cooling combined with evaporative cooling was introduced as an alternative to conventional refrigeration. The main design and conceptual features include:

- Desiccant combined with evaporative cooling;
- Single pass (no return) airflow;
- Simple ventilation system;
- High peak load performance;
- Low operational cost;
- Cooling and heating combined in a single unit;
- Existing ductwork incorporated into the design;
- Heat recovery;
- No refrigeration.

Control Strategy

- By using a desiccant wheel in conjunction with energy recovery and evaporative humidifiers, a supply temperature of 12°C – 19°C (depending on climate) and a supply moisture content close to ambient conditions is maintained;
- Basic minimum ventilation for the whole building is $5m^3/s$. This is increased up to $10m^3/s$ in cooling mode;
- In winter the system operates in heat recovery mode at 86% efficiency and $5m^3/s$ single pass ventilation.

Practical Experiences

- During monitoring, despite day temperatures at 30°C - 35°C and warm nights, the supply air temperature remained fairly constant at 15°C - 18°C, while the extract temperature remained at 24°C - 25°C;
- Power supplied to the driving fans varied according to load between 5kW – 35kW;
- The system provided good comfort to occupants and more are being installed.

4.6 Ventilated Chilled Beams

The 'Granlund' Office Building, Helsinki, Finland

Project Data

Location:	Helsinki, Finland
Altitude	46m
Year of Construction	1989/91
Number of Working Spaces	300
Heated Floor Area	$6998m^2$
Number of Floors	4/5
Heated Volume	$35850m^3$
Heating Degree Days	(17/12°C) 4366Kd
Heating Capacity	1370 kW
Cooling Capacity	400kW

Basic Design Features

For this building, calculations showed that cooling would be needed for long periods throughout the year. This need was provided by extending, for as long as possible, periods of 'free' cooling combined with top up cooling by means of chilled beams. Essential features included:

- Efficient mechanical chilled beam cooling;
- High thermal insulation (U-value of 0.28 W/m^2K) combined with high thermal mass (concrete);
- Triple glazed windows (U value of 1.8 W/m^2K);
- Electrical load of no more than $28W/m^2$ (lighting, computing etc.);
- Single coil for heating, cooling and heat exchange;
- High design operating temperature of cooling coil (14°C - 18°C) to increase scope for free cooling time;
- Individual room thermal and air control;
- Ventilation capacity designed to meet air quality needs;
- Existing radiators but the heating system is only used in very cold weather.

Control Strategy

There are three different control modes; these are:

- Summer (260 hours/year): Cooling energy is produced mechanically using a chiller;
- Free cooling (1,180 hours/year): Outside air is used for cooling via the cooling coils, there is no need for mechanical cooling;
- Winter (650 hours/year): No cooling required.

Practical Experiences

- Free cooling could be used up to an outside temperature of 15°C , this is 83% of the total annual hours;
- Conditioning energy demand was measured to be 21 kWh/m². This is about half the average for an equivalent conventional building;
- This approach is adaptable for both new and existing buildings.

The Wärtsilä Diesel Building Vaasa, Finland

Project Data

Location:	Vaasa, Finland
Altitude	6m
Year of Construction	1950
Year of Renovation	1996
Number of Working Spaces	60
Heated Floor Area	1020m²
Unheated Floor Area	3672m²
Heated Volume	3672m³
Heating Degree Days	(17/12°C) 4730Kd
Cooling Capacity (Beams)	32.7kW
Cooling Capacity (A/C)	31.6kW

Basic Design Features

Part of the building was renovated with low energy chilled beam cooling in place of conventional cooling. The main design features were:

- Chilled beams with inlet temperature of between 14°C and 18°C;
- High thermal insulation combined with triple glazing;
- Radiator heating;
- Cooling and heat exchanger integrated into a single unit;
- Individual room temperature and air control.

Control Strategy

Operation is divided into three modes; these are:

- Summer: cooling energy is produced mechanically using a chiller;
- Free cooling: outside air is used to chill the water (outside air temperature at 14°C or below);
- Winter: no cooling is required.

Mechanical cooling and free cooling are used in parallel so that the chiller will be used below the summer set-point (14°C) when necessary. In the free cooling mode, water flow rate will be at its maximum.

Practical Experiences

- In free cooling mode the coefficient of performance (COP) is 29 compared to a conventional system performance of 7 – 21;
- The total cooling capacity of 64.3 kW is 29% lower than would be needed of a conventional approach;
- Average free cooling was 60% based on a 14°C outdoor air temperature threshold. Further savings were made by setting the cooling water setpoint to 17°C before mechanical cooling started (previously it was set at 16°C). No detrimental climate effects were observed;
- The annual cooling consumption was estimated at 62.2 kWh/m² of which 29.6kWh/m² can be produced by free cooling;
- Cooling energy is required throughout the whole year because of high indoor gains. 60% of the maximum cooling power is needed when the outside temperature is 0°C and even at an outside temperature of -26°C, 20% of the cooling capacity is needed;
- Monitored indoor air temperature varied predominantly between 22°C and 24°C during working hours in Spring and 21°C - 23°C in Autumn. The temperature only exceeded 25°C rarely. Average air velocity was < 0.2m/s and no draught problems were experienced.

4.7 Displacement Ventilation

The Néstle – France Head Office

Project Data

Location:	Paris, France
Altitude	130m
Year of Renovation	1994
Number of Working Spaces	142
Heated Floor Area	6936m²
Cooled Floor Area	3856m²
Cooling Degree Days	(18°C) 144Kd
Heating Degree Days	(20/12°C) 2600Kd

Basic Design Features

This is a building renovation in which a chilled ceiling approach is combined with a displacement ventilation system. The main features include:

- Chilled ceiling using plastic capillary tubes integrated into metallic panels;
- Cold water supply and temperatures are 15.5°C and 18.5°C respectively;
- Same system used for heating and cooling;
- High thermal insulation (0.5W/m²K);
- East, south and west facing windows fitted with automatic solar shading of factor 0.2;
- Displacement ventilation system in which outside air is pre-cooled by an air handling unit before supplying air to offices using low outlet grilles and low velocity. Extract air is taken at high level.

Control Strategy

The main components of the control strategy incorporate:

- Room temperature control: The water flow in each panel loop is controlled by an on-off slow-action valve operated by an ambient air thermostat fitted in the office desks;
- Fresh air control: The temperature of the air supplied to the offices is controlled by a sensor fitted to the air-handling unit. Pre-cooling with reheat for dehumidification of the fresh air is required to prevent the risk of condensation on the surface of the chilled ceiling panels;
- Anti-condensation control: A water sensor, fitted on the ceilings of the of the offices shuts off the cold water supply if room dew point temperature approaches the panel surface temperature.

Practical Experiences

Operational experience demonstrated the following:

- Cooling for the summer cooling period (4 months) was 37kWh/m²;
- Good comfort levels were experienced;
- Design temperature and climate conditions were satisfied.

The Hamburg Regional Bank, Hamburg, Germany

Project Data

Location: .... Hamburg, Germany
Altitude 10m
Year of Construction 1974
Year of Refurbishment 1994/96
Heated Floor Area .... 12000 m^2
Number of Floors 8
Cooling Degree Days .... (18°C) 215Kd
Cooling Capacity .... 1300kW (80W/m^2)

Basic Design Features

This building follows the principles of the previous two case studies in combining a chilled ceiling design with displacement ventilation. The basic design features include:

- Displacement ventilation at $6m^3/h.m^2$ of floor area;
- Single pass airflow with heat recovery;
- Static heating in perimeter zone to offset transmission loss;
- Good acoustic performance;
- All floors connected to a central atrium.

Control Strategy

The main controls strategy include:

- Room conditions: Summer 26°C, 50% RH, Winter 22°C, 50%RH, windows not openable;
- Ventilation: central processing of heating, cooling, humidifying and dehumidifying combined with 10 individual room circuits and 35 zone control circuits;
- Cooling water regulation: the minimum inlet temperature is dew point +1.5K. Flow is controlled by a counter flow heat exchanger and a straight through valve;
- Dew point monitoring.

Practical Experiences

Considerable benefits were achieved including:

- Substantial energy benefit including very much reduced fan/pump energy;
- User acceptability and comfort;
- Good cooling performance.

4.8 Ground Coupled Reversible Heat Pump

The Advanced House in Laval, Canada

Project Data

Location: .... Laval, Quebec
Altitude 17m
Year of Construction 1993
Heated Floor Area .... 132m^2
Number of Floors 2
Total Volume .... 412m^3
Cooling Degree Days .... (18°C) 250Kd
Heating Degree Days .... (18°C) 4540Kd
Energy Use 16000kWh/a

Basic Design Features

This building incorporates a range of innovative features aimed at providing energy and cost efficient year round comfort. Design features include:

- Rainwater storage and groundwater wells with reversible heat pump for cooling and heating;
- Heat recovery ventilation system;
- Fenestration to optimise solar gain (including polyester film and selective coatings according to orientation, to maximise solar penetration and minimise winter heat loss);
- Solar (hot water) collectors;
- Very high thermal insulation (walls 0.175W/m^{2}K, roof 0.095 W/m^{2}K).

Control Strategy

A phased cooling strategy is applied as below:

- When the room air temperature exceeds its set point value, rainwater storage is first pumped round a closed loop system through a heat exchanger which cools the ventilation air;
- If the indoor air temperature exceeds 25°C and rainwater is still below 20°C the rainwater tanks operate with groundwater pumping to continue providing cooling water through the heat exchanger;
- If ground and well water sources are unable to provide sufficient cooling and the inside temperature reaches 27°C the free cooling mode stops and cooling is achieved by operating the heat pump in reverse mode;
- The heat pump (using the well and rainwater tanks as thermal sources) is also used to provide most of the heating. When no longer adequate, electrical backup is used.

Practical Experiences

Operational experience indicated that:

- The system functioned correctly and was capable of providing useful cooling and heating;
- Occupants did not like a set-point of 27°C for heat pump cooling and changed it to 23°C;
- Capital costs were relatively high but this was attributed to the house being a demonstration project incorporating many features and the latest technology. The most cost effective process was the coupling of the groundwater wells to the heat pump;
- Heating and cooling energy consumption was considerably reduced (less than 1/3rd) when compared with conventional property.

4.9 Ground Cooling

The 'Schwerzenbacherof' Office and Industrial Building, Schwerzenbach, Switzerland

Project Data

Location:	Schwerzenbach, Switzerland
Altitude	440m
Year of Construction	1989/90
Number of Working Spaces	190
Heated Floor Area	8050m^2
Number of Floors	5 +2 basements
Heated Volume	27060m^3
Cooling Degree Days	(18°C) 198Kd
Heating Degree Days	(20/12°C) 3616Kd
Heating Capacity	240kW

Basic Design Features

To follow Swiss requirements that active cooling be used only in exceptional cases, it has become necessary to develop alternative technologies. This large complex therefore incorporates a range of features including:

- Airtight construction;
- Good thermal insulation (walls 0.3W/m^{2}K, windows 1.3W/m^{2}K);
- Automatic external solar shading, separately (and occupant) controllable for each façade. This is combined with fixed horizontal shading to give basic default shading;
- Light interior colours to improve daylighting;

- Direct interaction between indoor air and the thermal mass of the building, combined with night cooling;
- Ground coupling of the ventilation system (for cooling and heating) through an extensive parallel pipe network (fitted with bypass) buried 6m beneath the building and below the groundwater table. A total of 1000m of pipes are used constructed of high-density polyethylene of diameter 230mm, each having a length of 23m;
- Heat recovery (fitted with bypass).

Control Strategy

Separate strategies are used for Summer cooling and Winter preheat as outlined below:

- The ground-coupled system is activated in Summer when the outdoor air temperature exceeds 22°C and in Winter when the temperature falls to below 7°C;
- Ground coupling provides about 1/3rd of total cooling, the rest being provided by night cooling of the thermal mass. Thus ground cooling is only used as a supplement (mainly during the daytime) when night cooling is insufficient;
- In Winter, the ground system provides pre-heat for the incoming ventilation air. This also helps to cool the ground space for the Summer and prevent freezing of the rotary heat exchanger.

Practical Experiences

- The measured heating demand is 150kW at -8°C. Without ground coupling, the calculated need would be 240kW. The ground coupling itself can meet a peak demand of 60kW;
- The measured heating energy consumption was 144 MJ/m²a which is well below the Swiss Standard, at the time, of 240 MJ/m²a;
- The measured electrical current to operate the ventilation system was 23MJ/m²a which, again, was well below a conventional requirement of 90MJ/m²a.
- The maximum cooling rate was 54kW at an outdoor supply temperature of 32°C;
- Comfort cooling was achieved at all times;
- Lighting energy was slightly higher than expected at 160 MJ/m²a, it was still within the range of conventional buildings;
- All fittings must be made watertight. To account for expansion and shrinkage in the plastic piping, caused by seasonal temperature variations, special seals have to be used.

4.10 Aquifer Cooling and Heating

The SAS Frösundavik Office Building, Stockholm, Sweden

Project Data

Location:	Stockholm, Sweden
Altitude	30m
Year of Construction	1985/88
Number of Office Rooms	1450
Heated Floor Area	64000m²
Number of Floors	4/5
Heated Volume	217600m³
Cooling Degree Days	(18°C) 42Kd
Heating Degree Days	(20/12°C) 5480Kd
Heating Capacity	3700kW
Cooling Capacity	3300kW

Basic Design Features

The cooling and heating approach is based on pumping through a closed system, aquifer water into a heat exchanger. For heating, the output is extended by using a heat pump. The main features are:

- 'Cold' Wells at 2°C to 12°C for cooling ventilation air and use in cooling convectors;
- 'Warm' wells at 8°C to 15°C for heating ventilation air;
- Single pass ventilation (i.e. no recirculation) at 1900000m³/h;
- Supplemental heating by background heat gains and, when necessary, electrical heating (radiators).

Control Strategy

The following control strategy is applied:

- During the Summer, cooling is maintained by cooling convectors at high level. These are water cooled and maintained at a temperature of 14°C. This is served entirely by the aquifer system. Water is extracted from the 'cold' well and recharged (via the

building heat exchanger) into the 'warm' well (for Winter use). The aquifer system also cools the ventilation air to 18°C;
- In Winter the aquifer provides preheat to the ventilation air. Final heating of the ventilation air and the heating of domestic hot water is undertaken by three electrically driven heat pumps having a combined thermal power of 1,100kW.

Practical Experiences

- The aquifer satisfies a Summer cooling load of 300MWh/month and, in Winter, 180MWh/month. Total capacity is 2900MWh/a;
- Maximum heat energy production is 400MWh/month. Electrical standby is 400kW;
- Annual operating costs are substantially below that of equivalent conventional buildings (purchased energy reduction reduced by 65%);
- In a year the system replaced 2750 MWh of district heating and 260MWh of electricity consumption.

The Groene Hart Hospital, Gouda, The Netherlands

Project Data

Location: .... Gouda, The Netherlands
Altitude 2m
Year of Construction 1992
Number of Beds 450
Heated Floor Area 5200m²
Heating Degree Days .... (20/15°C) 3000Kd
Heating Load 900MJ/m²a
Cooling Load . 35MJ/m²a (23MJ/m²a from aquifer)

Basic Design Features

This is a retrofit and extension building which required upgrading for heating and cooling. Design and conceptual features include:

- Seasonal storage for heating and cooling;
- Separate heating and cooling wells;
- Same system for heating and cooling;
- Simple integration within existing system;
- For cooling, water is circulated via a heat exchanger from the 'cold' well to the 'hot' well. For heating, the flow path is reversed.

Control Strategy

- The aquifer system is used in conjunction with refrigerative chillers for Summer cooling. When cooling is needed, groundwater is pumped from the cold well. Supply temperature for air cooling is maintained at 10°C. If this cannot be satisfied from the groundwater system then conventional cooling is applied;
- In Winter, heat is taken from the hot well to preheat the ventilation air. The cooled water is returned to the 'cold' air;
- Short term cooling is stored (e.g. at the end of the Summer but when cooling is still needed) by pumping cold water into the aquifer at night for use the following day.

Practical Experiences

- In one year of monitoring about 210 MWh of cooling was 'stored' by the groundwater system;
- In the first Summer of operation about 350 MWh of cooling was taken from the aquifer;
- The overall COP for cooling was approximately 13.5;
- For cooling and heating, the COP was 8.6;
- Good performance and comfort conditions were maintained.

4.11 Sea Water Cooling

The Purdy's Wharf, Halifax, Canada

Project Data

Location:	Halifax, Canada
Altitude	Sea Level
Year of Construction	1983-89
Conditioned Floor Area	65000m^2
Number of Floors	4/18/22
Conditioned Volume	167000m^3
Cooling Degree Days	(18°C) 59Kd
Heating Degree Days	(20/12°C) 4254Kd
Annual Energy Use	13120mwh
Installed Cooling Capacity	4.9MW

Basic Design Features

The Purdy's Wharf project has developed a scheme of providing cooling to buildings by using cold seawater from the harbour. The main details are:

- High thermal insulation (walls 0.34W/m^2K, windows 2.44W/m^2K);
- An open loop system water extraction from 18m depth through two titanium heat exchangers in series;
- Daylighting;
- Coated glazing (solar energy transmittance 8% and reflectance 25%);
- Zoned heating and cooling in which inner zone always needs cooling while outer zone needs Winter heating;
- CO_2 controlled ventilation for good indoor air quality;
- Building slightly pressurised to reduce draught and to prevent the ingress of unconditioned air.

Control Strategy

- The ocean water is driven through the two heat exchangers;
- Both heat exchangers exchange heat from independent closed loop water circuits;
- Chilled water from the first exchanger goes directly to air handling units to reduce the temperature of ventilation air;
- The resultant heated water is returned to the heat exchanger for a further cycle of cooling;
- Chilled water from the second exchanger is used to cool condensers of mechanical compression chillers used by occupants for cooling specific rooms or the building as a whole when sea water cooling is insufficient on its own.

Practical Experiences

- To be effective, the cooling water must be below 10°C. At a depth of 18m, this condition is satisfied for 10.5 months of the year. During this time the COP is 40;
- It is only after the Summer (in September and October) that cooling water cannot be used. In this period chillers of 2.1MW in one tower and 2.8MW in the taller tower meets the additional cooling need;
- Some additional chilling is also needed in August, even although seawater temperature is 5°C-7°C.