Low Energy Cooling

Case Study Buildings

Edited by
Mark Zimmermann
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Annex 28 Low Energy Cooling August 1998

IEA Energy Conservation in Buildings and Community Systems Programme

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International Energy Agency
Energy Conservation in Buildings and Community Systems Programme
Annex 28 – Low Energy Cooling

Case Studies of Low Energy Cooling Technologies

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Energy Conservation in Buildings and Community Systems
Annex 28 – Low Energy Cooling

Case Studies of Low Energy Cooling Technologies

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August 1998

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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, the development of alternative energy sources and energy research development and demonstration (RD&D). This is achieved in part through a programme of collaborative RD&D consisting of forty-two Implementing Agreements, containing a total of over eighty separate energy RD&D projects. This publication forms one element of this programme.

Energy Conservation in Buildings and Community Systems Programme

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. Seventeen countries have elected to participate in this area and have designated contracting parties to the Implementing Agreement covering collaborative research in this area. The designation by governments of a number of private organisations, as well as universities and government laboratories as contracting parties, has provided a broader range of expertise to tackle the projects in the different technology areas than would have been the case if participation was restricted to governments. The importance of associating industry with government sponsored energy research and development is recognised in the IEA, and every effort is made to encourage this trend.

Annex 28 - Low Energy Cooling

The aim of Annex 28 is to investigate the feasiblilty and provide design tools/guidance on the application of alternative cooling strategies to buildings. Outputs from the Annex include a review of the technologies, early design guidance, 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 the technologies in a country or countries participating in the Annex and should not be taken as representative of the situation on a world wide basis.

Annex 28 Reports

This document is one of a series produced by Annex 28 to assist with the design of low energy cooling systems. The other documents are:

- *Review of Low Energy Cooling Technologies*
- *Selection Guidance for Low Energy Cooling Technologies*
- *Early Design Guidance for Low Energy Cooling Technologies*
- *Detailed Design Tools for Low Energy Cooling Technologies*

Introduction

Cooling is a significant user of energy in buildings, and its impact as a contributor to greenhouse gas emissions is enhanced by the fact that these systems are usually electrically driven. Increasing use of information technology has led to an increasing demand for cooling in the commercial buildings sector, with consequent problems for the utilities.

In response to these issues, the IEA's Future Building Forum workshop on Innovative Cooling (held in the United Kingdom in 1992) identified a number of technologies with the potential to reduce energy consumption in the field of alternative cooling strategies and systems, leading to the establishment of Annex 28. The emphasis for the project was on passive and hybrid cooling technologies and strategies. These require close integration of the dynamics of the building structure with the HVAC systems, and this is precisely the area in which the Energy Conservation in Buildings and Community Systems Executive Committee has established expertise.

Objectives

Passive and hybrid cooling systems will only be taken up in practice if such systems can be shown to meet certain criteria:

- The life cycle costs (including energy, maintenance etc.) of such systems are less than 'conventional' systems,
- The level of thermal comfort provided is acceptable to the occupants in the context of their task,
- The systems are sufficiently robust to changes in building occupancy and use,
- The design concepts for such systems are well defined, and that appropriate levels of guidance are available at all stages of the design process, from sketch plan to detailed,
- The necessary design tools are available in a form which designers can use in practice; and
- The cooling system is shown to integrate with the other systems (e.g. heating and ventilation), as well as with the building and control strategy.

The objective of the Annex was to work towards fulfilling these requirements.

Means

The project was subdivided into three subtasks relating to the three phases of researching and documenting the various cooling strategies:

Subtask 1: Description of Cooling Strategies

The aim of this subtask was to establish the current state of the technologies in the participating countries. The findings are detailed in the report:

Review of Low Energy Cooling Technologies

The report also contains national data for climate, building standards, heat gains, comfort criteria, energy and water costs for each of the participating countries.

Subtask 2: Development of Design Tools

Different levels of tools are required throughout the design process. To reflect these requirements, three different levels of tools have been developed by the Annex:

1. *Selection Guidance for Low Energy Cooling Technologies*

   This tool provides guidance on the initial selection of suitable low energy technologies. Paper and software (Visual Basic) versions of the tool have been produced.

2. *Early Design Guidance for Low Energy Cooling Technologies*

   A collection of simplified tools based on design charts/tables and practical guidance to assist with early design development of a technology.

3. *Detailed Design Tools for Low Energy Cooling Technologies*

   A collection of tools for use as part of or in conjunction with simulation software. Copies of source codes and executable files (where appropriate) are provided with the report on an enclosed diskette.

Subtask 3: Case Studies

The third element of the work was to illustrate the various cooling technologies through demonstrated case studies. Eighteen case studies have been documented in the Annex report:

Case Studies of Low Energy Cooling Technologies (this document)

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

Scope

A number of different technologies have been considered by the Annex. The Table below gives an overview of which of the Annex reports have information on which of the technologies.

Technology	Review	Selection Guidance	Early Design Guidance	Detailed Design Tools	Case Study No.
Night cooling (natural ventilation)	●	●	●	●	1, 2
Night cooling (mechanical ventilation)	●	●	●	●	3
Slab cooling (air)	●	●		●	
Slab cooling (water)	●	●	●	●	4, 5, 6
Evaporative cooling (direct and indirect)	●	●	●	●	6, 7, 8
Desiccant cooling	●	●		●	9
Chilled ceilings/beams	●	●			10, 11, 12
Displacement ventilation	●	●		●	12, 13
Ground cooling (water)	●	●	●	●	14
Ground cooling (air)	●	●	●	●	15
Aquifer	●	●		●	16,17
Sea/river/lake water cooling		●			18

Table 1: Overview table of Low Energy Cooling Technologies included in Annex 28 reports

The Case Studies

The case study buildings are located in countries with different climate conditions. The map shows the location of the eighteen different case study buildings, ranging from hot and humid to dry and cool. The temperature and relative humidity of the outside air gives different prerequisites for the studied technologies. The suitability of a technical alternative is thus often dependent on the location of the building.

Evaluating case studies presents a unique possibility to exchange and gain experience from similar technologies tested under scientific conditions in different countries. Different conditions influence the choice of alternatives and the feasibility differs. The case studies offer guidance based on experience, but do not give any guarantee for the suitability of a technology.

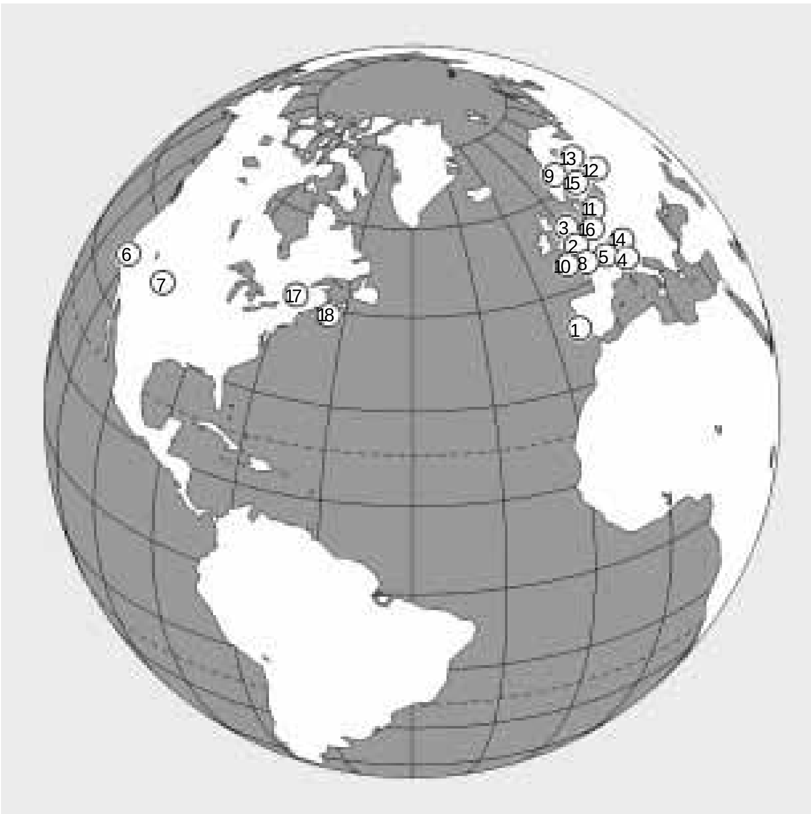


Table 2:
Survey of case studies and demonstrated technologies

No	*Name* and Location	Night cooling (natural)	Night cooling (mechanical)	Slab cooling (water)	Evaporative cooling	Desiccant cooling	Chilled ceilings/beams	Displacement ventilation	Ground cooling (air)	Aquifer	Ground cooling (water)	Sea/river/lake water cooling
1	*Vila Nova de Gaia* Porto, Portugal	●										
2	*The Open University 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, USA			●	●							
7	*The One Utah Center Building* Salt Lake City, USA				●							
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 Frösundavik* Stockholm, Sweden									●		
16	*The Groene Hart Hospital* Gouda, The Netherlands									●		
17	*The Advanced House* Laval, Canada										●	
18	*The Purdy´s Wharf* Halifax, Canada											●

Energy

Most of the case studies show that energy can be conserved by using these technologies instead of "conventional installations", usually meaning mechanical refrigeration. The studied technologies can either be used solely or as a first step in combination with other technical solutions, e.g. with mechanical cooling.

Most of the case studies use the building, or the ground under the building, as an energy store thus reducing both energy use and the size of the installed power. For detailed data about energy savings and achieved results, please refer to the detailed case study reports.

Costs

One of the objectives of the project was that the life cycle costs of a passive or hybrid cooling system as studied in this Annex should be lower than the equivalent costs of a ‘conventional’ system (normally meaning a mechanical system). Environmental considerations might in some cases justify a cost in the same order.

When comparing costs, local and national conditions, such as material costs, wages, exchange rates, make it difficult to transfer the result from one country to another or from one time to another. Bearing these uncertainties in mind, the cost comparisons presented in the case study reports are to be regarded as relative and could as such give a certain guidance. The following table showing exchange cross rates for the currencies of the countries participating in the Annex is also only to be used as a rough tool that was valid only on the day it was presented.

Country	Curr	FIM	FRF	DEM	NLG	PTE	SEK	CHF	£	CAD	USD	ECU
Finland	FIM	10	11.0	3.28	3.70	336	14.4	2.73	1.14	2.68	1.85	1.66
France	FRF	9.14	10	2.98	3.36	305	13.1	2.49	1.03	2.45	1.68	1.51
Germany	DEM	3.05	3.35	1	1.13	102	4.38	0.83	0.35	0.82	0.56	0.51
Netherlands	NLG	2.71	2.98	0.89	1	90.9	3.89	0.74	0.31	0.73	0.50	0.45
Portugal	PTE	2.98	3.28	0.98	1.10	100	4.28	0.81	0.34	0.80	0.55	0.50
Sweden	SEK	6.98	7.65	2.28	2.57	234	10	1.90	0.79	1.87	1.29	1.16
Switzerland	CHF	3.66	4.03	1.20	1.35	123	5.26	1	0.41	0.99	0.68	0.61
UK	£	8.90	9.73	2.90	3.27	297	12.7	2.42	1	2.38	1.64	1.47
Canada	CAD	3.72	4.09	1.22	1.37	125	5.34	1.02	0.42	1	0.69	0.62
USA	USD	5.41	5.94	1.77	2.00	181	7.77	1.48	0.61	1.45	1	0.90
ECU	ECU	6.01	6.60	1.97	2.22	202	8.63	1.64	0.68	1.62	1.11	1

Table 3: Exchange rates (August 1998)

Highlights from the Case Studies

Night Cooling / Natural Ventilation

1. Vila Nova de Gaia, Single-Family Residence in Portugal
This building is tighter and better insulated than required by the Portuguese regulations. No mechanical system is installed. To keep the building cool in summer, all windows are kept closed during day time. When outdoor conditions are suitable, selected windows are opened to provide natural ventilation and to utilize night cooling or cross ventilation.

2. The Open University Design Studio, Office Building in UK
When this building was refurbished, no mechanical cooling was installed. Instead the aim was to reduce internal gains and enhance natural night cooling to prevent summertime overheating. The original single glaze windows were exchanged to new better ones providing improved solar protection, better ventilation and greater user control. The heat storage capacity of the building was increased by removing ceiling tiles to expose the concrete soffit. Occupant surveys confirmed that staff found the conditions had improved especially in hot weather.

Night Cooling / Mechanical Ventilation

3. The IONICA Building, Office Building in UK
The building is provided with a selection of cooling options - wind towers extracting air from the atrium, hollow core slabs to enhance thermal storage capacity, natural and mechanical night cooling, indirect evaporative cooling and heat pump cooling. To utilize these options in an efficient way a fine tuned control system was required.

Slab Cooling (Water)

Slab cooling utilizes the building structure as energy store to smoothen out sudden temperature changes in the room and often to improve the efficiency of night cooling.

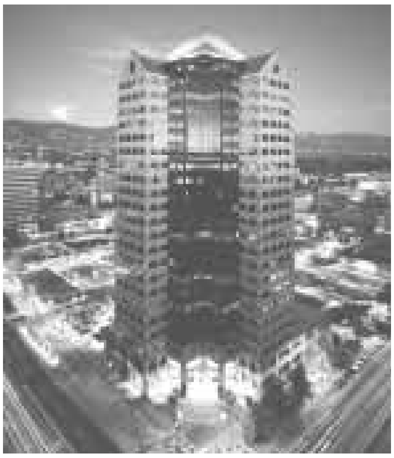
4. The DOW Building, Office Building in Switzerland
Concrete slab stores the heat gain from day to night when it is removed via air coolers connected to the water loops in the slab. Mechanical ventilation provides displacement ventilation through supply air inlets integrated in the suspended lamp support frames in the rooms. The cool air descends to the floor with low turbulence. Utilizing free cooling during two thirds of the time, the building is very energy effective compared to a fully mechanically cooled building.

5. The Sarinaport, Office Building in Switzerland
The heavy concrete floor slabs of the building are used both for heating and cooling. Due to the low temperature difference between the slab and the room, the system is self-regulating. As soon as the room becomes too hot, heat is rejected to the slab, whereas if it is too cool, heat is withdrawn. The air to the rooms is supplied through plastic ducts imbedded in the concrete slab and connected to displacement ventilation air inlets under the windows. The capital cost is lower and the annual operating costs are less than half of those for a conventional system providing the same comfort.

Evaporative Cooling

Evaporative cooling can be used either ‘direct’ in the supply air or "indirect". In the two US case studies cooling towers are used to cool water supplied to cooling coils in the supply air. In the French case study this is achieved by humidifying the return air that is then cooling the supply air via a heat exchanger. Often both applications, direct and indirect, are combined. In dry and semi-dry climates evaporative cooling is efficient and cost effective and can be used as sole source for cooling or as a first pre-cooling step.

6. The ACT2 Stanford Ranch House, Single-Family Residence in the USA
This building has an innovative combination of evaporative cooling, energy storage and slab cooling. The water passing the loop in the ground below the floor slab is effectively cooled at night in a cooling tower and provides thus the building with radiant cooling. At peak periods the cool loop water is run through a supply air fan coil unit.



7. The One Utah City, Office Building in the USA
The Building has an interesting combination of evaporative and mechanical cooling. The supply air is chilled in up to three steps in the air handling unit, (1) indirectly by a cooling coil connected to a cooling tower, (2) by a chilled water coil connected to a water chiller, and (3) directly. Steps 1 and 3 are always used at outside temperatures above 12 °C, step 2 only if needed to bring down the temperature before step 3 to 12 °C. Step 3 was also found to be an excellent air washer that removes pollen and dust from the supply air.

8. Gaz de France Research Centre, Office Building in France
This office building near Paris uses an indirect evaporative cooling system that was chosen after extensive testing. In summer the plant is run at night to provide night cooling. During a very warm summer with very hot outdoor air (August 1995) the internal temperature raised above the comfort zone. The occupants should therefore be informed about the risk for overheating with this type of low-grade air-conditioning system. Experience gained from reported deficiencies will be used when planning new plants.

Desiccant Cooling

9. InfraCity Commercial Centre, Office Building in Sweden
Desiccant cooling proved to be an interesting alternative when renovating a thirty year old office building only equipped with ventilation and no air-conditioning. The duct systems could still be used unchanged, only the roof mounted air handling unit had to replaced. Both installation and annual costs were found to be lower than for a conventional system. The users are very satisfied and the same type of system has also been chosen for other buildings within the same area. It is important to use a low cost source of energy for regenerating the drier; in InfraCity district heating water is used and bought at low summer price.

Ventilated Chilled Beams

With this system the temperature in each room is controlled individually by chilled water supplied to convector coils at ceiling level.

10. The Granlund Office Building, Office Building in Finland
The office rooms of this building have high heat loads necessitating cooling. This is achieved with ceiling mounted cooling beams used as room units. By using free cooling the energy use is reduced by 38 % compared to mechanical cooling.

11. The Wärtsilä Diesel Building, Office Building in Finland
This renovated office building with high internal loads was provided with chilled beam room units combining cooling and air distribution. Mechanical and free cooling are used in parallel. Existing radiators are used for heating.

Chilled Ceiling and Displacement Ventilation

In both these cases the systems were installed as part of a renovation of the buildings. The users are reported to be satisfied not only with the thermal climate but also expressed satisfaction with the silent system. As the main part of the cooling load is carried by water, the air flows can be reduced to cover only the hygienic air flow necessary for the air quality in the room. The system requires a ceiling height that permits the installation of the false ceiling (and in the French case study also a raised floor for the supply air distribution).

12. The Nestlé France, Office Building in France
This is a historic old building that was renovated and equipped with a chilled ceiling that, by changing the water loops, is used for heating in winter. The supply air to the rooms is distributed via ducts in a false floor to supply air grilles under the windows thus keeping the floor area free from terminal devices.

13. The Hamburg Regional Bank, Office Building in Germany
An old high-pressure air system no longer met the requirements and had to be replaced. Several alternatives were evaluated. The chosen system was found to result both in large energy savings and to reduced installation costs when compared to a conventional air-conditioning system.

Ground Coupled Reversible Heat Pump

14. The Advanced House in Laval, Single Family Residence in Canada
As should be the case with an advanced house, this building comprises several innovative solutions. The cooling system utilizes two rain water storage tanks, two ground water wells under the slab and a reversible heat pump, operating in this order at raising indoor temperature to cool the supply air to the house.

Ground Cooling (Air)

15. The Schwerzenbacherhof, Office and Industrial Building in Switzerland
The supply air is cooled in summer and preheated in winter as it passes through an extensive duct system in the ground under the bottom slab below the ground water level. The system has proved to function well both in summer and winter operation. It has provided the occupants with a thermal climate within the comfort zone. For this type of system it is important for good performance that the bottom slab is well insulated to keep it isolated from the ground coupled system.

Aquifer

Both these plants have worked very well and have proved that aquifers constitute a both reliable and cost-saving alternative provided that the local geotechnical conditions are suitable. The advantage with this solution is that it provides an annual energy store where the cold well water picks up the excess heat from the building in summer and stores it for use in the winter and vice versa. In both cases it was found that the plants were equipped with control plants ensuring that the aquifer storing capacity is used in an efficient manner both in winter and summer.

16. SAS Frösundavik, Office Building in Sweden
The plant has had a 100 % availability, it has reduced the annual operating costs considerably and has saved 65 % of the energy needed with a conventional plant. The room cooling is achieved by using cooling panels connected via a heat exchanger to the cold well loop. The ventilation air is cooled in summer and preheated in winter by aquifer water pumped through a second heat exchanger also connected to the heat pump evaporators. The heat pumps are connected to the final heaters of the air handling units and to the tap hot water heater.

17. Groene Hart, Hospital in The Netherlands
The plant has shown considerable savings on both natural gas and electricity. During extremely warm periods or at the end of the summer season when the cold well temperature is relatively high, a cold buffer can be formed in the aquifer at night to be used the next day.

Sea Water Cooling

18. The Purdy´s Wharf, Commercial Centre in Canada
These buildings located at the waterfront of Halifax is using free cooling from the cold sea water during ten months of the year. The salt sea water is run in an open loop through a titanium heat exchanger cooling the closed fresh water loop used for cooling the building. During fall when the sea water temperature raises above 10 °C the sea water is used to cool the condensers of two water chillers. The annual cost savings due to reduced electricity load are high giving a simple payback of about two years for the plant.

Participation

The participating countries in this project were Canada, Germany, Finland, France, Netherlands, Portugal, Sweden, Switzerland, United Kingdom and the United States of America. The funding bodies for each country are given below.

Canada

Buildings Group /
Heat Management Technologies
CANMET – Energy Technology Branch, NRCan

Germany

Bundesministerium für Bildung Technologie und Forschung

Finland

Technology Development Centre

France

Agence de l'environnement et de la maitrise de l'énergie (ADEME)

Centre scientifique et technique du bâtiment (CSTB)

Ecole des mines de Paris

Gaz de France

COSTIC

Netherlands

Novem BV

Portugal

Center for Energy Conservation

Department of Mechanical Engineering, University of Porto

Sweden

Swedish Council for Building Research

Switzerland

Swiss Federal Office of Energy

United Kingdom

British Gas

EA Technology

Gardiner & Theobald

Haden Young

MEPC Investments

Oscar Faber

Ove Arup

Department of the Environment, Transport and the Regions

United States of America

U.S. Department of Energy

National Experts

22 national experts have substantially contributed to the Low Energy Cooling project:

Canada

Kathleen Fraser
Fraser & Associates
Calgary

Sophie Hosatte
CANMET
Quebec

Germany

Uwe Franzke
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Single-Family Residence
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Portugal

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Energy design: E. Maldonado
Engineer: E. Maldonado
Modelling: H. Gonçalves INETI
Reporters: E. Maldonado &
J. L. Alexandre

Date: August 1998

Night Cooling
Natural Ventilation

- Night cooling by natural ventilation
- High thermal inertia
- Low heating needs
- No air-conditioning

Background

Most of the energy consumed in Portugal is imported. Moreover, there is growing pressure on the electrical grid due to increased use of air-conditioning in summer. In 1990, the government introduced new legislation to improve the thermal quality of building envelopes, to decrease the energy consumption and to achieve longer periods when it is possible to obtain comfort in the buildings without auxiliary energy needs, both in summer and in winter. In 1998, new legislation to achieve energy conservation in HVAC systems has also been introduced. Together, these two regulations contribute to improving the rational use of energy in the building sector.

Introduction

This building is an example of how to obtain comfortable indoor conditions in a moderate climate during the whole summer without mechanical cooling. It combines high inertia with good insulation of the envelope and effective shading of all glazed areas to reduce cooling loads. It also uses night-cooling obtained by horizontal and vertical natural ventilation.

It was built to requirements much above those demanded by present regulations, both with thicker insulation layers and with very effective shading techniques, and southern solar exposure has been maximised to increase useful solar gains in winter and to minimise solar gains in summer. But the same type of solutions implicit in the regulations have been used, to show an easy path towards tighter requirements in future versions of equivalent regulations.

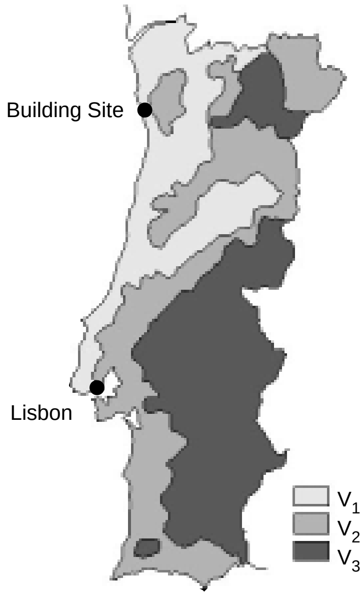

Figure 1: Location of the demonstration building in Portugal. Summer climatic zones are also shown, from moderate (V_1) along the north coast, to hot (V_3) in the interior south.

Figure 2: Location of the building in its near neighbourhood at the top of a hill

Building Description

Project Data

Location	Vila Nova de Gaia Portugal
Altitude (elevation)	200 m
Years of construction	1991/1992
Heated floor area	316 m^2
Unheated floor area	96 m^2
Number of floors	4
Total volume	920 m^3
Cooling degree days (20)	118 Kd
Heat. deg. days (20/12)	1979 Kd
Heating load	12.3 kW
Cooling load	7.7 kW

The building has four floors:
- basement (storage and garage),
- ground floor (kitchen, pantry, dining-room, living-room, guest bedroom and a small WC),
- first floor (master bedroom, two offices and two WC's) and
- upper floor (one room and attic space).

The most important areas are on the south façade, with corridors, bathrooms and storage areas to the north, providing thermal buffering in winter. Internal doors may completely separate north and south zones, if desired.

Figure 3: South façade and section of the building

Design Concept

General Energy Concept

The climate in Porto is moderate both in winter and in summer. The average ambient air temperature in the cooler months is 8 °C and in the hottest months in the summer it is around 20 °C. Thus, it is possible, with a correct building design, and in the absence of strong internal gains, to achieve indoor conditions suitable for comfort most of the time. The main design principles are as follows:

- an appropriate level of insulation in the envelope for winter protection,
- efficient solar protection for all glazed areas in summer,
- high thermal inertia, to minimize temperature fluctuations, avoiding overheating except for a few hours on very warm days or when there are more visitors,
- natural ventilation with cooler outdoor air at night to remove the heat accumulated during the day and lower the mean internal air temperature.

Demonstrated Energy Technology

The building has a central heating system but no mechanical cooling. It has a gas furnace in series with a heat recovery unit in the fireplace. This unit is mounted in a bypass loop controlled by a temperature sensor, i. e., water flows in the heat recovery loop only if the sensor detects combustion in the fireplace. The hot water circulates through a network of radiators, one in each room. The radiators have no thermostatic control (Figure 7).

Occasionally, electric radiators are used when the occupants only wish to heat a small part of the house when the rest is unoccupied.

The building has small windows in the north and east façades. Together with the larger south-facing windows, they provide the means to establish natural cross-ventilation throughout the building. Natural ventilation can also be established vertically, through operable openings in the basement and in the attic, taking advantage of the staircase.

High thermal inertia coupled to night ventilation with cool air and limits to internal and solar gains ensure a comfortable indoor environment in summer.

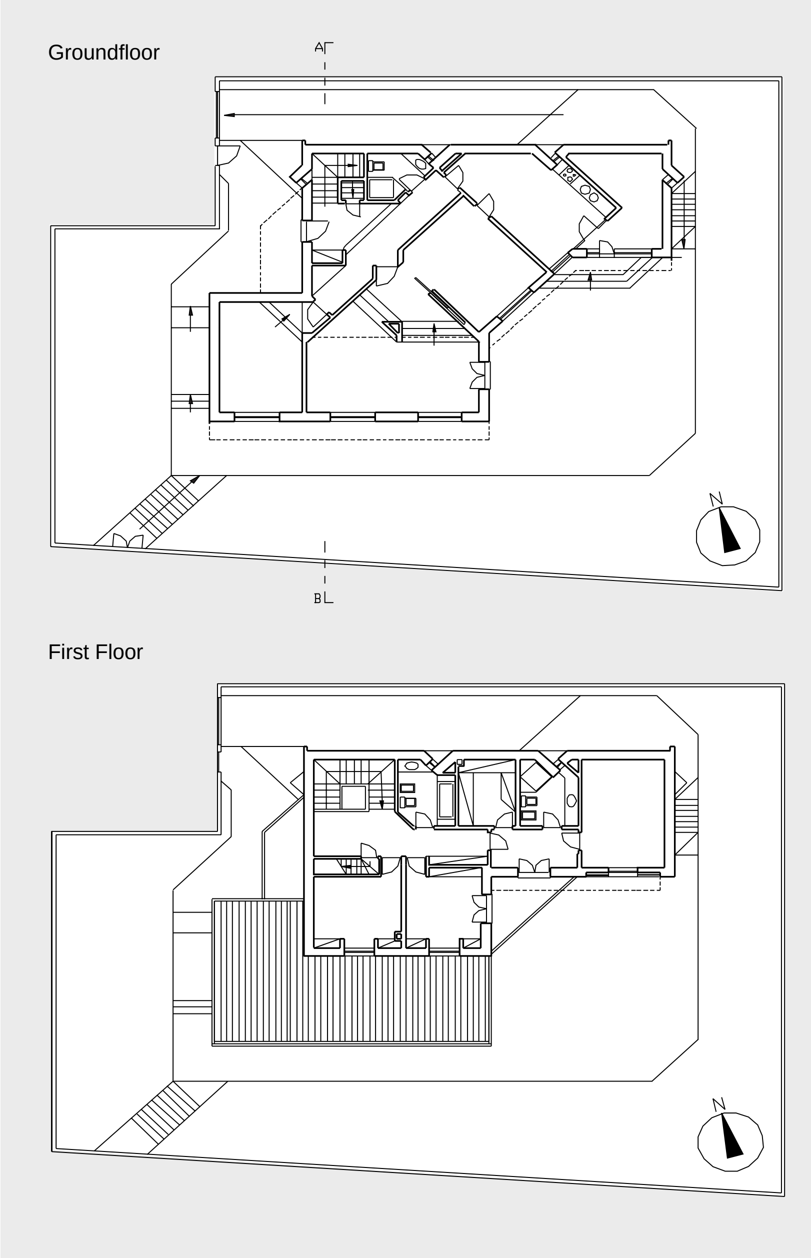

Figure 4: Groundfloor and first floor of the building

Design Details

Building Envelope

All the walls are made of two layers of hollow bricks, 11 and 15 cm thick, separated by an air-gap. Also a 3 cm layer of extruded polystyrene is glued to the outer surface of the inner brick layer.

External Walls	0.65
Floor	0.5
Windows	3.9
Roof (attic)	0.5
Roof (rooms)	0.7

Table 1: U-values of the envelope in W/m^2K

Solar Protection

The building has effective solar protection devices to reduce the solar gains during the summer season:

- South-facing windows of the living-room, dining-room and guest-room, downstairs, have both internal and external solar protection: there are wooden folding shutters indoors and a well sized structural overhang on the outside (see Figures 6 and 8).
- South-facing windows of the kitchen only have an external overhang.
- Upstairs, the windows of the two offices and of the master bedroom have an external roller shutter or an awning device (see Figure 5) and internal wood panels (see Figure 6).
- No windows face either east or west, and north-facing windows are small and need no shading.

Heating System

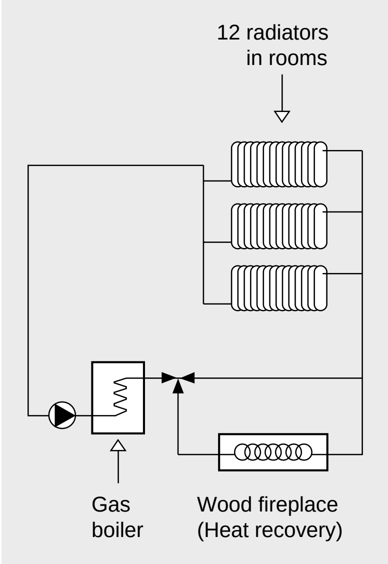

Figure 7: Schematic of heating system

Figure 5: Details of outside awing roller shades

Figures 6: Details of internal wood panels

Natural Ventilation

In summer, most of the time, all windows are kept closed: during the day, because it is hotter outside and for safety when the house is not occupied; during the night to eliminate noise that would make sleeping difficult.

When conditions are suitable, i.e., outdoor temperatures are lower than indoors, though not too low (generally, above 18 °C), and indoor temperatures are above 24-25 °C, natural ventilation is effected by opening up suitable windows, both downstairs and upstairs. Sometimes, natural ventilation only takes place upstairs, as it is the warmer floor due to stratification.

The ground-floor plan has a relatively complex shape, with multiple paths for ventilation. The top floor has a more linear plan, but several possible modes are available for natural ventilation. The master bedroom presents the most difficulty, as it only has a south facing window and a nearby door to the rest of the house, with little interaction with most of the room. Cross ventilation, is however, also possible using the north window of the contiguous bathroom (see Figures 3, 4 and 9).

The internal doors are kept open most of the time, allowing the free flow of air. However, the envelope is reasonably airtight (about 0.3 air changes per hour at 50 Pa in a pressurization test with a blower-door) and air movement is low unless windows are open. No mechanical ventilation system has been installed.

All shading devices and window openings are controlled manually by the occupants.

Figure 8: Structural overhang for shading the south-facing windows

Performance Data

Internal Gains

The building is occupied by a family of two. It is generally empty during the day and occupied after 6 p.m. until 8 to 9 a.m. in the next morning during weekdays, and 24 hours a day during most weekends.

Cooling Performance

The building was monitored during the summer of 1993 over a two-week period. The climate was typical for the site, with a few very hot days before and at the beginning of the monitoring period followed by average days with peaks around 25 °C. Despite the early hot period, the building's high inertia and careful load avoidance control by the occupants prevented serious overheating indoors: the indoor temperature upstairs never went above 27.5 °C. Then, it slowly cooled down to around 25 °C with daily indoor amplitudes of about 2 K.

As surface temperatures indoors are lower than air temperatures, comfort is always possible, and the black bulb-temperature upstairs, where it is warmer, always stayed between 24 °C and 26 °C. The temperature in the basement, which is in direct contact with the soil because it is buried on all sides but one, is basically constant (0.2 K variation over the two week period) and slightly below the average outdoor air temperature, as can be predicted by theory.

The ground floor is generally 1 to 2 K cooler than the upper floor, showing a slight stratification and confirming a low air circulation rate between both floors.

Impact of Ventilation for Natural Cooling

A closer look at the graphs shown in Figure 10 can clearly demonstrate the effectiveness of night-cooling cross-ventilation in this building. Figure 12 shows detailed temperatures for July 30 to 31. When windows are opened and natural ventilation starts in both floors at around 7:30 p.m., indoor temperatures suddenly drop to a value closer to outdoors and remains there while the windows are open. Then, after closing the windows, at about 9:30 p.m. downstairs and at 2 a.m. upstairs, the temperature rises again but to a value lower (about 1 K) than if natural ventilation had not taken place.

Heating Performance

The building was also monitored during the winter 96/97. Most of the time, there is no heating indoors and the temperature fluctuates around 15-17 °C in the main areas of the building, where the occupants spend most of their time. When temperatures become colder, in late evening and during weekends, heating is turned on and the temperature indoors rises to 18 °C or above (Figur 11).

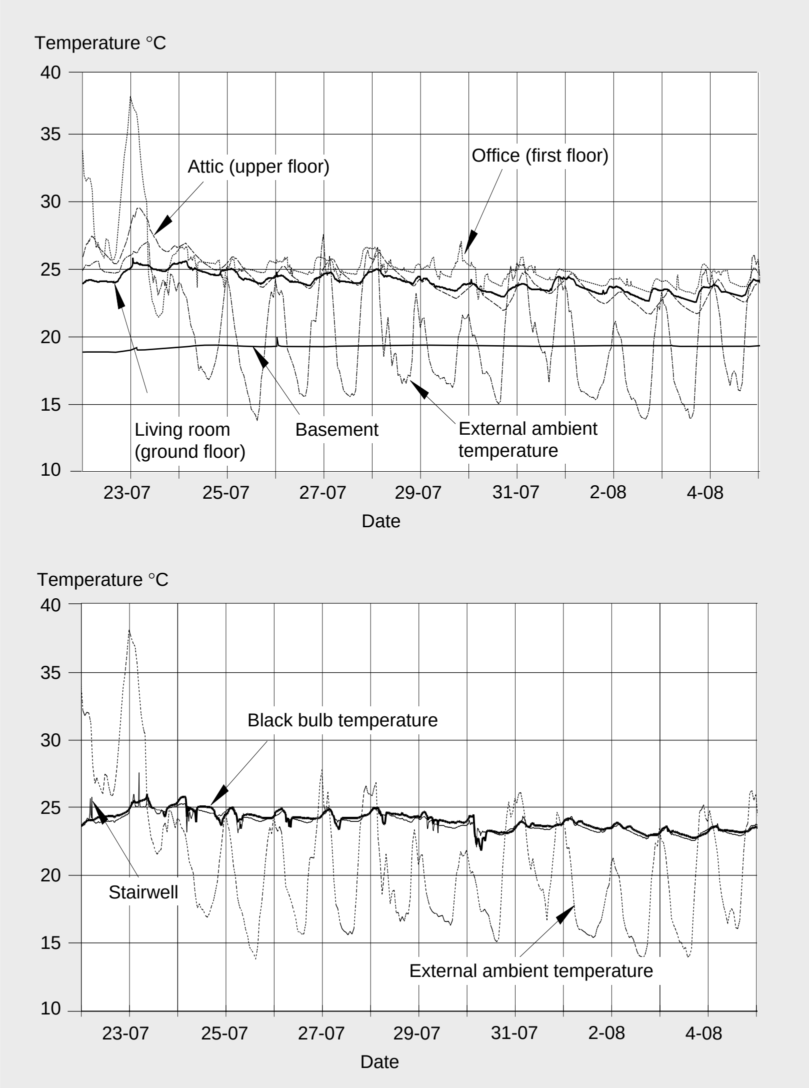

Figure 10: Indoor temperature of the different spaces in summer

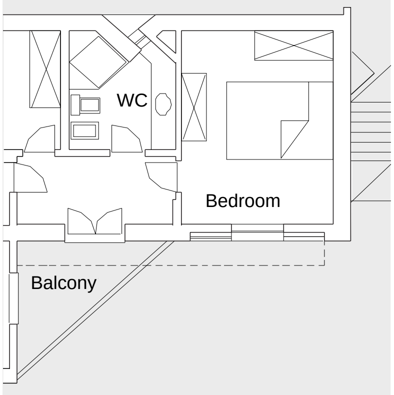

Figure 9: Space with natural ventilation upstairs (master bedroom)

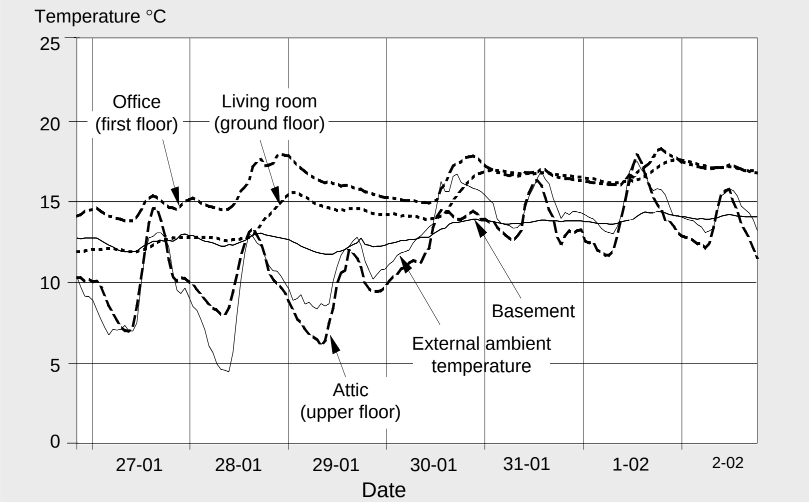

Figure 11: Indoor temperature of the different spaces in winter

Costs for Construction and Operation

As for most passive systems, construction costs for this building were no different to comparable construction techniques of similar quality: about 100,000 PTE (US$ 560 or 505 ECU) per m². Normal costs for buildings can be found in a range of ±20 % around that figure.

Heating costs are low and there are no cooling costs.

Heating Consumption and Costs

Winter 96/97

Gas (propane):	315 kg 50,400 PTE (US$ 300 or 260 ECU)
Electricity:	450 kWh 5,400 PTE (US$ 30 or 25 ECU)
Wood (fireplace):	2,000 kg 25,000 PTE (US$ 150 or 130 ECU)
Specific heating consumption:	~ 160 MJ/m²a

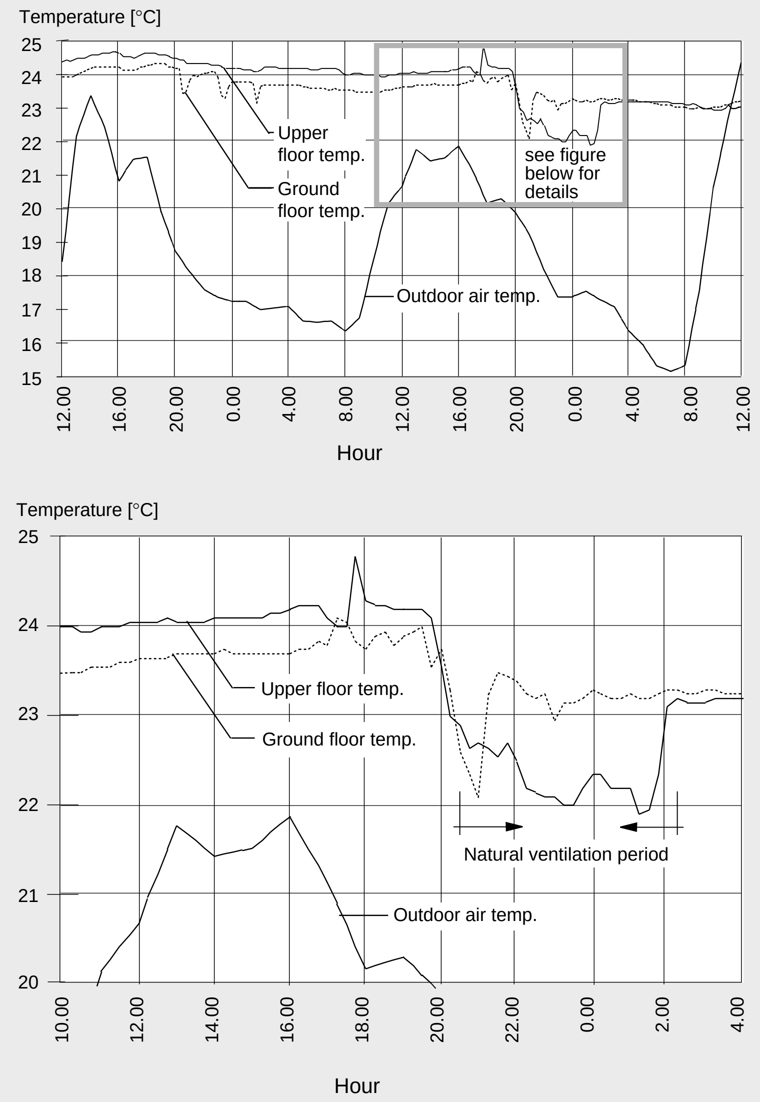

Figure12: Detail of cooling performance under natural ventilation during July 30 and July 31 with two different magnifications

Summary

This building is a typical example of how to obtain comfortable indoor environments in summer without the help of any mechanical cooling. A few hours a day of natural ventilation at night can pre-cool the building structure enough so that daytime solar gains, provided that they are well controlled, are insufficient to overheat the building.

This technique can be successfully applied to most residential buildings in most of Europe [3], save for those in the warmest southern and central regions, and also for many nonresidential buildings, provided that internal gains are kept low. Mechanical ventilation can perform similar tasks in more complex buildings where natural ventilation may have difficulty penetrating every area. With well designed buildings and ventilation systems, this type of system will provide cooling with low energy consumption.

In commercial buildings, night ventilation can be combined with other low-energy cooling techniques, e.g., slab-cooling with water or buried pipes, with similarly good results [4].

Practical Experience

The building has been occupied now for five years and the occupants are extremely happy with the thermal performance of the building. Conditions are not yet optimum due to the somewhat cool temperatures in winter. Thus, a retrofit is planned for the near future to add more insulation to the envelope.

The same design team has been applying these same design principles to several other buildings, both residential and non-residential, with equally positive results.

These examples have been used as arguments for tightning of the requirements of Portuguese Building Regulations, as well as for acting at CEN level for European Standardization. The underlying design principles are firmly accepted as the most adequate for Portuguese buildings, and regulations will be revised accordingly.

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Acknowledgements

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Figure 13: View of the North and West façades of the residence

The
Open University Design Studio
Milton Keynes, UK

Night Cooling
Natural Ventilation

Architect: ECD Partnership
Energy design concept: WBA
Lighting Engineer: SVM
Reporter: Denice Jaunzens

Date: August 1998

- Reduction of summertime overheating due to electronic drawing equipment
- Refurbishment of office building to reduce internal gains and to enhance natural cooling
- Glazing upgraded from single to triple
- Internal blinds and curtains replaced with midpane blinds
- User operated control gear attached to windows
- Ceiling mass exposed
- Higher efficiency lighting system and improved controls installed

Background

This case study is an example of passive refurbishment, where the need for mechanical cooling was avoided through a program of measures to:

- reduce internal gains, and
- enhance the potential of natural night cooling.

The aim of the refurbishment was to prevent summertime overheating.

Introduction

Energy-relevant provisions contained in the UK Building Regulations:

- Minimum requirements for insulation including allowances for glazing
- Approved methods of minimizing infiltration
- Requirements for provision of heating system controls
- Requirements for provision of hot water storage system controls
- Minimum requirements for insulation of vessels, pipes and ducts
- Minimum requirements for efficacy of lamps and provision of lighting controls

Figure 1: Map of UK showing location of Milton Keynes near Cambridge

Building Description

Project Data

Location	Milton Keynes, UK
Altitude	50 m
Year of construction	1970
Year of refurbishment	1993
Degree days (20/12)	2,478 Kd
Conditioned floor area	400 m^2
Conditioned space	1,080 m^3

Building Layout

The University's campus is on the outskirts of Milton Keynes. The Open Design Studio was built in 1970. It is a typical three storey office building with a concrete frame, brick cladding and a flat roof. The windows were a continuous ribbon of single glazing in metal frames. A lightweight fourth storey, with a mansard roof, was added subsequently. The lower three floors have an internal depth of 13 m, a length of 40 m and a ceiling height of 2.7 m. The top floor has an average height of 3.1 m. The focus of this study is predominantly on the open plan first floor design studio in Block B.

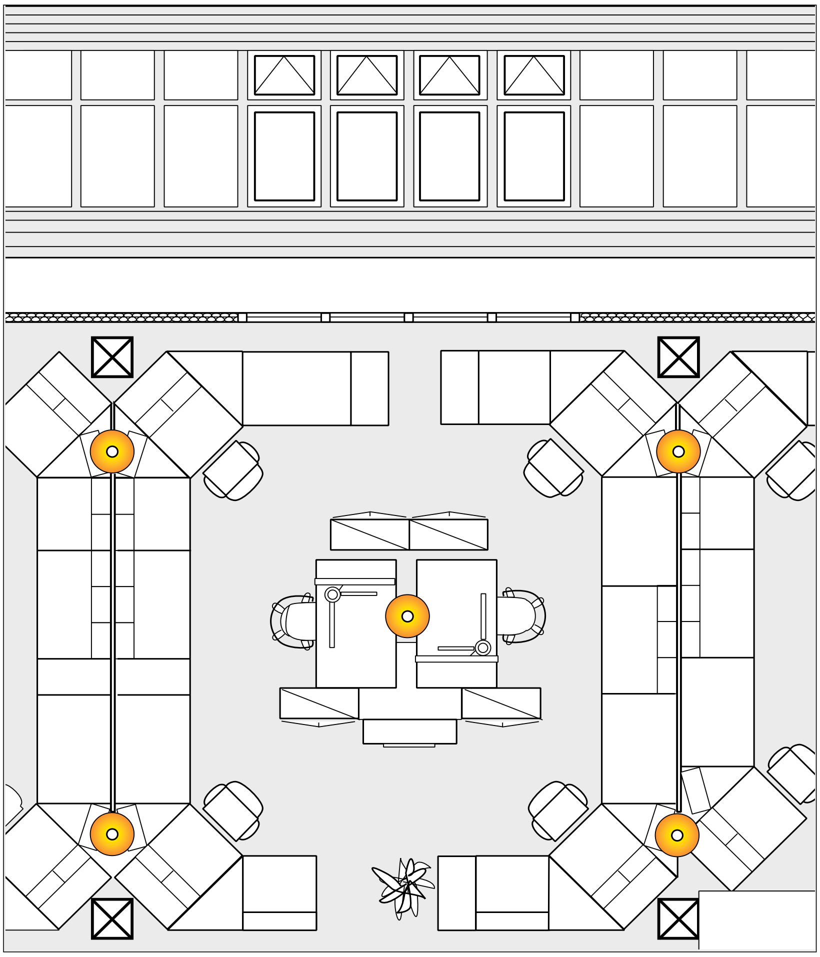

Figure 2: Open floor plan of the design studio (below) and view of window layout of east façade (above)

Design Concept

General Energy Concept

Building Envelope
External walls are cavity brickwork with blown fibre fill, black artificial slate covered mansards with 50 mm polystyrene insulation, and a flat metal-deck roof with 19 mm insulating board, 25 mm polystyrene insulation, and three-layer felt with a green mineral finish.

Internal partitions are either brickwork or plaster board on stud. Floor slabs are concrete with carpet overlay.

Solar and Overheating Protection
The original studio design had 60 % ribbon single glazing on the main facades with aluminium frames. Solar control was by internal curtains and occasional Venetian blinds. This coupled with increasing internal gains due to the introduction of automated drawing equipment had made the space prone to overheating in the summertime.

The initial proposed solution was to provide comfort cooling using fan coils or a variable refrigerant flow system. However the client preferred to examine the possibility of achieving comfortable conditions through passive means. Following building simulation exercises and site monitoring of summertime conditions it was concluded that acceptable conditions could be achieved on the first floor by:

- fitting new windows for better ventilation to facilitate natural night cooling, improve solar control, and to provide greater user control,
- removing ceiling tiles to expose the thermal mass of the concrete soffit, thereby increasing effective heat storage capacity,
- providing more energy efficient and better controlled lighting.

The success of this strategy, which was implemented in November and December 1993, is discussed in this case study. Comparisons are made with the performance of the second and third floors of Block B which have not been refurbished. The second floor is mostly cellular with some existing exposed ceiling mass. The third floor is a combination of cellular and open plan space but is contained within the lightweight mansard roof and thus requires the use of a fan coil cooling.

Demonstrated Energy Technology

The concept of night cooling involves allowing the internal mass of a building to build up a store of coolth overnight which can then be released the following day to reduce peak internal temperatures within the office space.

Night cooling can be driven by natural forces such as wind pressures due to night breezes and thermal buoyancy (stack effect), or by mechanical forces.

Control of night cooling can range from a simple manual regime carried out by the users to a more sophisticated automated control of window openings and fan operation.

The success or suitability of a naturally driven night cooling system is dependent upon:

- ensuring that users understand and operate any control system correctly,
- ensuring that sufficient exposed mass is present to act as thermal storage,
- minimizing the internal gains within the space to maximize the opportunities for natural night cooling to achieve comfortable conditions.

			Gas/Oil	Electr.	Total
Type 1	Naturally ventilated cellular office	typical	200	48	248
		good practice	95	36	131
Type 2	Naturally ventilated open plan office	typical	200	85	285
		good practice	95	61	156
Type 3	Deeper plan air conditioned office	typical	222	202	424
		good practice	100	132	232
Type 4	Prestige air conditioned space	typical	273	361	634
		good practice	132	261	393

Table 1: Specific energy consumption of UK office buildings (kWh/m^2 heated floor area and year)
The first floor Design Studio is considered to be Type 2 office space, the second floor is Type 1 office space and the third floor Type 3 office space.

Design Details

The refurbishment scheme involved several measures

Windows

- Replacing the original single glazed aluminium ribbon glazing (having fixed panes and centre-pivot windows) with a triple glazed aluminium-clad timber system having centre pivot windows and high level inward-opening bottom-hung hopper windows (see Figure 3).
- Reducing heat gain from the sun and glare by replacing three in every seven windows with solid insulating panels.
- Replacing internal curtains and blinds with captive Venetian blinds within the window system, located in the space between the outer single-glazed leaf and the inner double-glazed sealed unit.
- Replacing the simple window catches (which had to be shut at night) for the centre pivot windows with an espagnolette locking system with two levels of secure night ventilation.
- Including winding handle mechanism for the hopper windows which was readily accessible to and operable by the users, enabling the hopper windows to be left open for the purposes of night ventilation.

Thermal Mass

- Removing acoustic tiles on battens from the ceiling and replacing them with sprayed acoustic plaster to help expose the thermal mass of the concrete slab to the room.

Lighting

- Replacing ceiling mounted fluorescent lights with freestanding compact fluorescent uplighters with electronic ballasts and individual choice of on/off and high/low level.
- Including controls which allow all lights to be switched off from the exit doors, but only the corridor lights to be switched on again from this position.
- Retaining fluorescent task lights as required.

Office Equipment

Minimizing internal gains by grouping the shared laser printers in an adjacent room with mechanical extract. The photocopier was put in a separate room.

In addition several measures were introduced to improve the general atmosphere of the studio:

- Window and blind controls were made accessible to all room occupants.
- The desk layout was improved to create groups of workstations divided by low screens.
- Plants were introduced and walls were painted a neutral colour to improve the feeling of coolness and relaxation in the space.

Control Strategy

Natural night cooling is achieved by staff ensuring that they open the high level hopper windows overnight. The hoppers can be opened using a winding handle mechanism which is common for each group of four windows. This allows cool air to flow over the exposed surface of the ceiling which then acts as a store of coolth to be dissipated the following day.

The system relies on staff using their own judgement to determine whether windows should be left open. There is no interlock between window opening and operation of the radiator heating system. Security staff are able to close the windows in case of adverse weather conditions overnight.

Figure 3: Internal views of office layout showing centre pivot windows below, bottom-hung hopper windows in the upper part

Performance Data

Overall Performance

A detailed analysis of the energy saved due to the introduction of natural night cooling is not possible. The differences between the fabric and layout of the comfort cooled third floor to the naturally night cooled first floor do not allow a direct comparison. However certain observations can be made.

The lighting and annual electricity consumption of the first floor is 87 kWh/m^2. This can be compared with Type 2 (see Table 1) ratings of 85 kWh/m^2 for a typical office and 61 kWh/m^2 for a good practice office. The total monitored night time/weekend residual electrical load of 1.5 kW could be reduced.

The lighting and small power annual electricity consumption on the second floor is 36 kWh/m^2 which can be compared with Type 1 (see Table 1) ratings of 48 kWh/m^2 for a typical office and 36 kWh/m^2 for a good practice office.

There were occasions on the third floor on which the comfort cooling and heating systems were operating simultaneously. This could have been avoided by switching the cooling system off completely outside of the summer months and dissipating excess heat through the openable windows.

Cooling Performance

Design predictions forecast that the whole package of refurbishment measures would reduce peak temperatures by 4 K. This would be in addition to any reductions made by removing the heat generating equipment. Night cooling was predicted to account for approximately 1 K of this. Temperatures were predicted to only rise above 27 ^{o}C on a few occasions in a typical year.

In order to test these forecasts monitoring of internal air and globe temperatures was carried out on all three floors over a three month period between July and October 1995. External air temperatures and east and west facade air temperatures were also taken. The latter showed the effects of solar absorption by the brickwork during the day increasing the ventilation air temperature, whereas at night the external (ambient) and façade air temperatures were in accord.

Temperature of the Thermal Mass
Temperature sensors connected to the ceiling thermal mass in the design studio and to a cellular office on the second floor show the reduction in the first floor slab temperature below that of the second floor (Figure 4). It is also possible to see a lag develop between the globe and ceiling mass temperatures in the design studio over a period of cooler weather as the storage of coolth takes place (Figure 6). The floor 1 mass temperature peaked at 26 °C when the external temperature was at 30 °C.

Through spot measurements using hand held equipment it was also possible to detect ceiling 'hot spots' where the cross ventilation was restricted. Also above the uplighters a rise of 1-2 K was noted.

Reductions in Peak Temperature
The results (Figure 4, Table 2) show that the first floor design studio temperatures are always below those on the second floor. This can be by conditions both close to, and away from, the open windows.
Temperature stratification is apparent. This is most marked at night when occupants are not present to stir up the air with their movement, and when cool night air is entering the building through the open windows and sinking to the floor.

Floor	1	2	3	Ext.
Weekday (max)	27	29	25	28
Weekend (max)	26	28	30	28
Night (min)	22	24	25	15

Table 2: Globe temperatures [°C] for period of eight hot days

Window Effectiveness
Temperature recordings from the second floor cellular offices show the benefits to be achieved by optimizing the user control of the available window openings and blinds.

The effectiveness of the hopper windows is also illustrated on the second floor where measurements showed at the start of the day a 2 K lower ceiling mass temperature in a west facing office with hopper window than in either a west facing office without an open window, or an east facing office which has lower daytime solar gains.

Comfort Cooling - Third Floor
Monitoring revealed a common problem with the use of stand alone systems, that of simultaneous heating and cooling. The comfort cooling should be switched off completely outside of the warmer summer months.

Lighting
Typically, the uplighters were switched on first thing in the morning when they were needed and not switched off or adjusted subsequently.

A timed switch-off or switch to low power mode may help occupants to reassess their need for artificial light. The current timed-off at 9 pm could take place earlier.

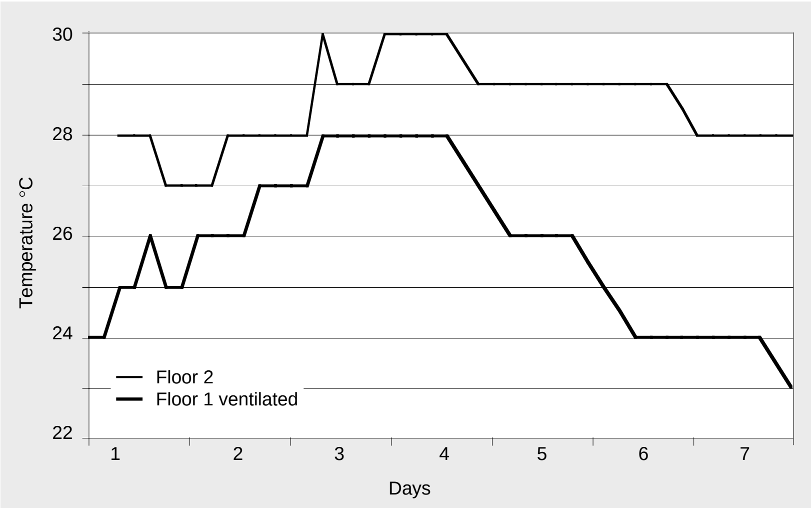

Figure 4: Ceiling temperatures of 1st and 2nd floor ceiling slabs

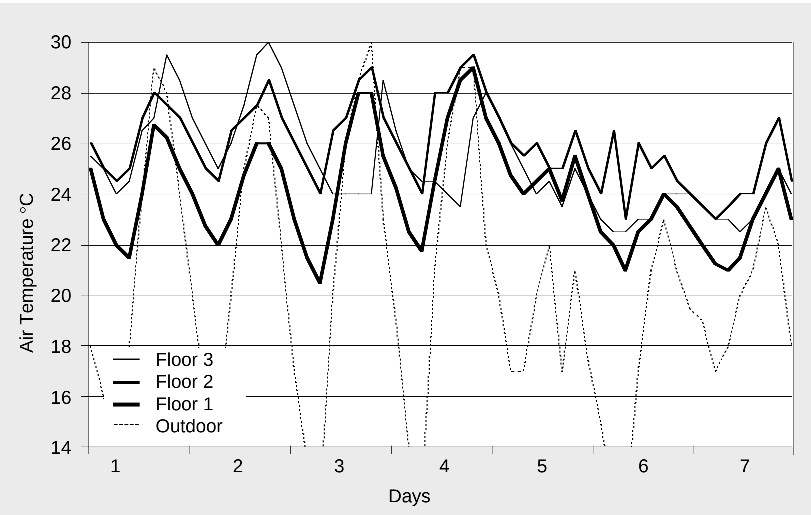

Figure 5: Comparison of room air temperatures of floor levels 1, 2 and 3

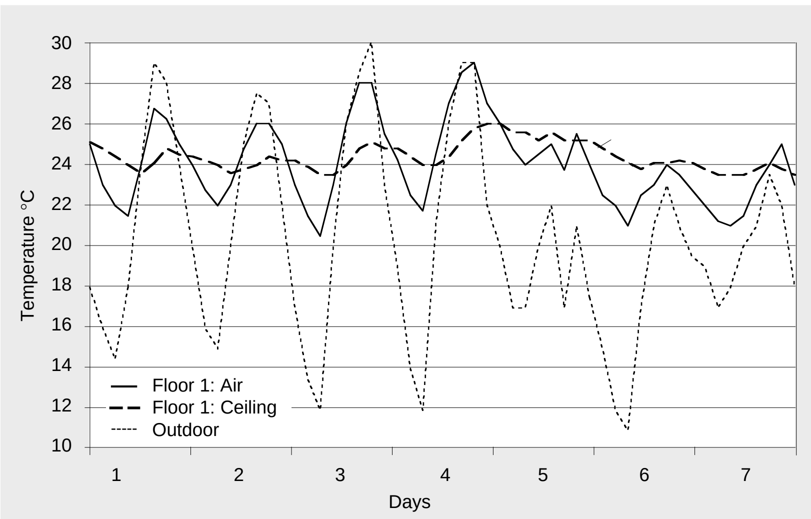

Figure 6: Room air temperature and ceiling temperature of 1st floor

It is often the case that the lights are on when nearby high level window blinds are closed. This lights-on / blinds-down mode of operation is a common problem.

Small Power

An examination of small power loads showed a 1.5 kW residual load overnight and at weekends. This was mostly attributable to the drawing and photographic equipment, with some corridor lights and a refrigerator consuming the remainder.

Ideally time switches could be introduced on major items of equipment.

User Experiences

Three occupant surveys were carried out over the summer of 1995 on the first, second and third floors of the building. This was to contrast the experience of those staff occupying naturally ventilated spaces with those occupying the comfort cooled space on the third floor. The second floor has been considered to provide some indication of the first floor conditions before the design studio was refurbished.

The summer of 1995 was unusually hot and therefore proved to be a worthy test of the effectiveness of the night cooling strategy. The results of the second and third floor questionnaires have been used to set the results from the first floor into context. A pilot questionnaire had also suggested differences in opinion between those seated close to a window and those seated in the centre of the space. This issue was further explored.

Control

As should be expected design studio staff seated closer to the windows felt that they had more control over temperature than their colleagues in the centre of the space, especially in October which was the coolest month. Control over ventilation follows a similar pattern. Control over lighting is seen to be at its most apparent in August, tailing off towards the end of the summer.

Temperature

The frequency of feeling too hot reduces as the external temperature drops, and is not related to position in the space. By contrast on the third floor where comfort cooling is available the situation is reversed and staff feel too hot more often in the cooler weather.

Occupants of all three floors generally felt too cold with greater frequency as the external temperature decreased between August and October. The subjects feel cooler in the studio in each case, especially those in the aisle seats, with the morning being the most often cited problem time.

Ventilation

Changeability is slightly more of an issue on the first floor than on the others due to the comments of those people occupying aisle seats. Draughts occur most often on the first floor in the aisle seats and to the least extent to those seated away from the window on the second floor.

Stuffiness in very hot weather is a problem less often on the first floor than on the second floor but the third floor offers the best environment in this context. The situation is reversed during the cooler period of the summer.

Daylight Control

Daylight reflections in the computer screens are more of a problem for those seated away from the windows than those seated by them. However subjects by the windows suffer more from discomfort due to the sun than those in the centre of the space.

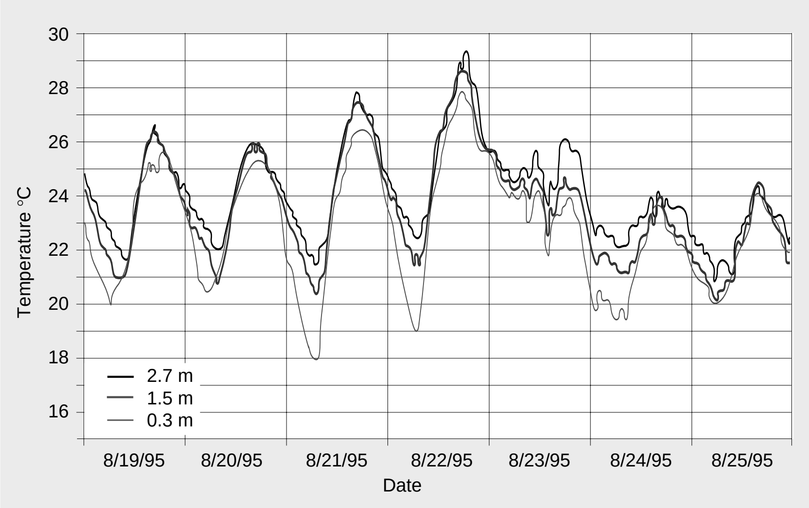

Figure 7: Temperature stratification within the 1st floor open plan office at different levels above floor

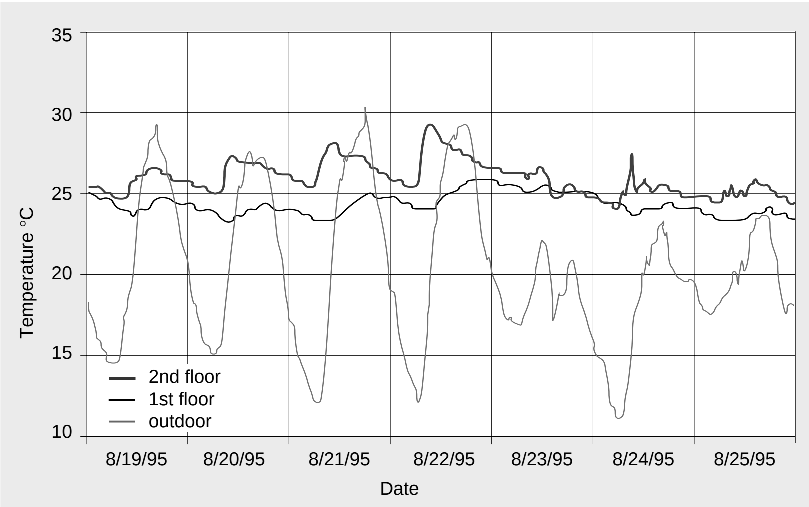

Figure 8: Ceiling thermal mass temperatures at 1st floor open plan office and 2nd floor cellular offices (no hopper windows)

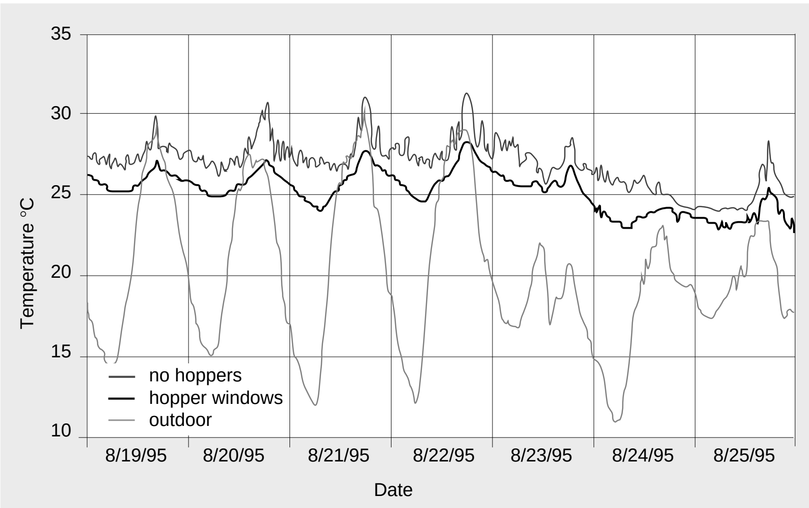

Figure 9: 2nd floor west cellular office temperatures: hopper windows versus no hoppers

Construction and Operating Costs

The originally proposed strategy for dealing with the problem of overheating was to install room fan coil units connected to either a chilled water or a direct expansion system. The Open University were keen to avoid mechanical cooling and to minimize energy costs. Computer modelling techniques were therefore used to predict the likely success of a naturally ventilated solution subject to refurbishment of the space.

The costs of refurbishing in the manner described here were comparable with the installation of comfort cooling. However there are no major operating or maintenance costs associated with the operation of a natural night cooling system. Staff are generally content with the conditions in the design studio even on a hot day because of the general effect of the refurbishment which is pleasant and well planned. On the comfort cooled third floor as much as 200 kWh can be consumed in a day.

Conclusions

The survey confirmed that staff found the conditions in the refurbished first floor studio to be more satisfactory than those on the unrefurbished second floor. This in spite of the fact that it has a greater level of heat gain due to the use of computers and also that the studio is open plan, which can sometimes cause dissatisfaction. The improvement is especially noticeable in hot weather, and is due to the sense of control which occupants have as well as to the actual conditions they experience.

Occupants of window workstations feel that they have reasonable control over temperatures and in 'normal' summer weather their rating of it equals that of the comfort cooled third floor.

The comfort cooling on the third floor appears to give the occupants a particularly powerful sense of control over temperature in very hot weather i.e. August. However this feeling diminishes as the need for cooling reduces. This strong sense of control spills over into other areas of satisfaction. There may also be a contrast effect with third floor occupants comparing themselves with those on the first floor.

The studio occupants in the centre of the space feel that their environment is inferior to that of their colleagues due to their lack of control and what is perceived to be poorer quality lighting.

But in general staff were pleased with the overall environment created in the design studio, in particular the lighting, general layout and 'airy feel'. Working conditions were found to be more satisfactory in the morning than in the afternoon.

Productivity was deemed to be affected most severely in the hottest month, especially for those people seated away from the window in the design studio. The effect of temperature was even greater on the second floor. However on the third floor the effect of temperature on productivity was seen to be very little throughout the summer.

Practical Experience

External pollution and security may be an issue in urban locations. Dirty desks are a potential problem for those seated near the windows in the design studio.

The relatively small module of the new window system (860 mm) allowed it to be installed from inside the building. It was originally intended that the windows should be in pairs but the furniture plan did not permit this as it would have caused either contrast or reflected glare on the VDU screens in the corner positions.

Draughts are caused in the middle of the design studio when the upper windows are open. Further refinement of this design may be required. Staff who are not near a window need more control over their environment.

Controls may be left in default states which are not optimal, for example 'blinds down - lights on'. It may be possible to reset controls on a daily basis either manually or automatically.

User education is equally important in passive buildings. This could include the training of occupants and security staff and cleaning staff.

Summary

This case study confirms the suitability of the refurbishment approach adopted by the Open University.

A combination of effective techniques to reduce internal heat gains coupled with the selection of an appropriate window system allowing effective night cooling has produced a comfortable and well liked working environment.

This has been achieved at a comparable cost to installing a mechanical comfort cooling system, but has the benefit of reduced maintenance and operating costs.

The *IONICA* Office Building Cambridge, UK

Night Cooling / Mechanical Ventilation

Owner: St John's College
User: Ionica
Architect: RH Partnership
Structural Engineer:
Hannah Reed Associates
Services Engineer: Rybka Battle
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Date: August 1998

- Natural and mechanical night ventilation
- Evaporative cooling
- Solar shading & daylighting
- Wind towers
- 24hr working office
- Environmental friendly design
- Individual user control

Background

In 1993, IONICA decided to build a new headquarters building with a modern, high-tech image to help establish its identity in the telecommunications marketplace. It is significant that in seeking to establish such an image *IONICA* explicitly specified an energy-consious design to demonstrate the environmental friendly image of the young company.

Design Brief

The brief called for 4,000 m^2 floor area building between *IONICA* (building user) and St. John's College, Cambridge (building owner). The building had to be ready within 18 months. The brief also included the development of an energy efficient office of high environmental quality and comfort with the ability for individual users to control their work spaces. The building was not to be a sealed air-conditioned office but was to incorporate opening windows and open plan areas, a necessity to help maintain the continuity and motivation of the existing work teams and to encourage communication between them.

Building Design

The architect proposed a building on three floors with three zones on each floor; north east, north west and south. Externally, the building creates a formal mansory elevation on the north road side and a more delicate arrangement of stepped roofs, curtain walling, balconies and sunshade on the south side. The roof line is punctuated by six wind towers which provide the natural ventilation exhaust path.

Internally, the building is designed around a 54 m long glazed roof with opening vents over a central atrium. The southern office zones are open plan and are intended to be predominantly naturally ventilated. They are provided with a mechanical ventilation systems which is being used only during extreme conditions in winter and summer to ensure environmental comfort. The open floor plans are terraced beneath the glazed roof which provides glare free daylighting to the office area. The northern zones are designed to allow the addition of partitions to create meeting rooms if required. These areas are primarily mechanically ventilated although the facility to manually open windows has been provided.

Environmental Design Aims

- Maximum use of daylight whilst ensuring minimal increase of heat gain in summer and loss in winter.
- Maximum use of the building mass to store or reject heat, to provide a means of cooling or heating.
- Use of free cooling and natural resources.
- Achieves comfortable internal space temperatures during the summer.
- Maintain good air quality throughout the year.
- Maximize occupant ability to control personal environment.
- Use simple and proven technologies in an innovative way.

Figure 2: Location of demonstration building

Project Data

Location	Cambridge, UK
Altitude	near sea level
Year of construction	1993/1994
Cool. degree days (18°C)	104 Kd
Conditioned floor area	4,000 m^2

Heating/air treatment systems
- Four air handling units, each including
  - thermal heat recovery wheel
  - evaporative cooler
  - heat pump
- Electrical perimeter units

Costs in ECU/m^2
- Building total 1,435.-
- Space heating/air treat. 165.-

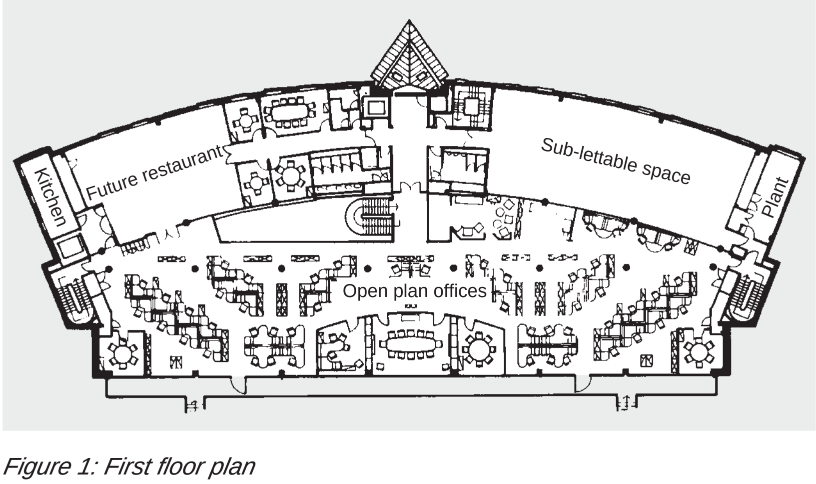


Figure 1: First floor plan

Design Concept

General Energy Concept

Solar and Overheating Protection

Figure 3: Solar shading on the southern façade

The building façades play a vital role in moderating the external climate. The façade has the following functions:

- External shading reduces glare and solar gain during mid-season and summer (south only).
- Internal blinds allow occupant control over daylight levels and solar penetration especially during periods of low angle sun.
- Opening windows with automatic openings provide night time ventilation (south only).
- Allows the ingress of a high degree of daylight reducing artificial light requirements.
- Winter heat loss minimized by a well insulated construction with low-emitting glazing.
- Provides good views.

Demonstrated Energy Technology

Natural Ventilation

Natural ventilation in the southern zones is carried out using two manually openable windows at low and mid level combined with operation of a high level window above. This is under the control of the Building Management System at night and under occupant control via a switch during the daytime. The air from the windows passes through the office space and into the three storey atrium. This allows natural cross ventilation to take place during most of the year. The roof of the atrium contains six wind towers which are designed to exhaust air from the atrium irrespective of wind direction. The wind towers are protected from the rain by a canopy and are expected to provide controllable natural ventilation under 95 % of all weather conditions. When the wind blows from a particular direction the two wind towers at either end of the building close in order to prevent reverse air flow back into the atrium. The provision of the wind towers is a particularly important design feature. Other buildings which use conventional rooflights under automatic control to facilitate natural ventilation have been found only to operate for approximately 65 % of the required time due to closure as a consequence of high wind and/or rain.

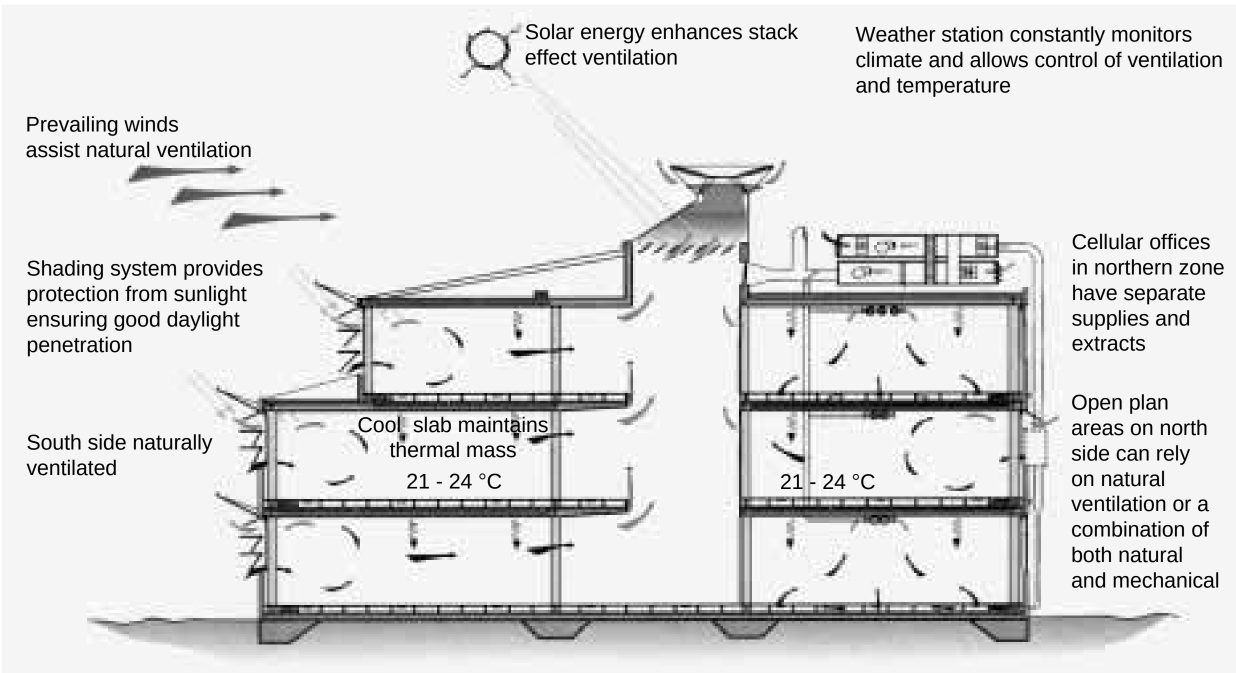


Figure 4: Cross section through the building showing the ventilation strategy (Courtesy of Battle McCarthy)

A shading system at the top of the atrium provides the offices protection from direct sunlight and an even distribution of daylight. During the summer, heat trapped in this area enhances the stack effect through the wind towers.

In winter the passive solar gain heats the air which is mechanically extracted at high level from the atrium. This is used to preheat the incoming fresh air via a thermal wheel operating between the supply and exhaust ducts.

Mechanical Ventilation

Four air handling units (AHU's) mounted on the roof each serve an office zone (AHU's 1,2 4 and 5 - AHU 3 serves the toilet areas). Each plant incorporates a thermal wheel for high and low temperature recovery, an evaporative cooler and an electrically driven heat pump for winter heat production and additional cooling if required in the summer. Heating is provided by an electric pre-heat coil and an electric reheater.

Electrical perimeter heating units are used to counter window/fabric heat loss.

100 % fresh air is distributed via ductwork to the hollow core slabs. The air passes through the slabs via the pressurized underfloor plenum into the occupied space via displacement ventilation grilles. The approach offers the following advantages:

- Guaranteed minimum level of ventilation day and night.
- Access to the centre of the hollow core slabs, giving improved thermal storage properties.
- Greater degree of controllability over the use of the thermal store.
- Ability to precool the structure mechanically by night, using off-peak electricity or by day using indirect evaporative cooling.
- Lower ventilation requirements and better comfort by using air and radiant temperature control.
- Controlled winter ventilation.
- No requirement for a false ceiling allows increased floor to ceiling height.

Air extract is via the mechanical extract system in the northern zones which removes air at high level from each floor. The southern zones have the option of using this method or of extracting air passively via the atrium and wind towers.

Cooling Elements

The southern zones of the building have the option of using passive or active cooling elements or a combination of both. Passive cooling during the day or at night provides the least expensive option if the weather conditions and requirements of the occupants allow (see control strategy). However, the building is partially occupied 24 hours per day and this limits the areas of the building that can be passively cooled via the windows and atrium extract. Mechanical ventilation can also be operated to provide 'free' air cooling under appropriate conditions via the hollow core slab. This moderates the temperature of the slab, providing a radiant cooling effect to the occupied space and providing cooling to the incoming air when this is above the slab temperature.

When necessary, the 'free' air cooling can be assisted by active cooling via the evaporative cooler (daytime cooling) and the electrically driven heat pump (primarily intended to be used for cooling at night during periods of low electricity tariffs). Monitoring has shown that when the supply air is passed through the hollow core slabs the supply air temperature is tempered to within approximately 0.5 K of the slab temperature. Thus, although the cooling of the slab may be taking place, there is unlikely to be any sensation of draught on the occupants. It is worth noting that the flexibility of the design allows the building manager to select which cooling system to apply, taking into account the effect on occupant comfort and running costs.

AHU		Air Flow m^3/s	Absorbed Power kW
1	Supply	3.57	5.5
	Extract	3.35	6.0
2	Supply	3.75	5.1
	Extract	3.75	5.1
4	Supply	3.57	5.5
	Extract	3.35	6.0
5	Supply	1.68	2.5
	Extract	1.68	2.3

Table 1: AHU design details

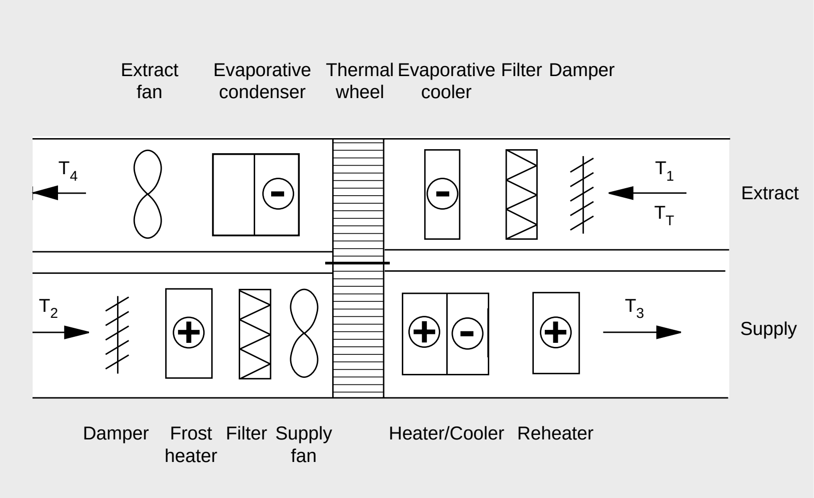


Figure 5: Schematic of air handling unit (AHU)

Performance Data

Overall Performance

Monitoring of the building has taken place over the first six months of 1996.

Internal Temperature
The effect of the hot weather during June resulted in high space temperatures (over 27 °C) in the office areas. The south western and south eastern zones were noticeably warmer than the northern zones, particularly on the ground and first floors. The heat pump cooling was manually initiated during the hottest periods.

The internal temperatures during the other periods were generally satisfactory, being maintained between approximately 20 °C and 24 °C.

Cooling Performance

The number of hours that the internal temperature exceeded specified limits was calculated for the period between the hours of 09.00 and 18.00 from Monday to Friday for the period from 17 January to 20 June 1996 (i.e. a total of 3454 hours). The results show a total of approximately 5 hours over 27.5 °C for the monitored period corresponding to external temperatures greater than 30 °C (the design allowed for a total of 29 hours above 27.5 °C).

The design minimum temperature was 19 °C with a proviso that it might be exceeded for up to two occasions per year. The general office areas went below 19 °C for less than two hours during the monitored winter period, with one exception on the second floor NW zone, which may have been affected by an open window.

Slab Temperature
Slab temperature variations for the second quarter monitoring period are indicated in the table below. The maximum values for the monitored period occurred on 7 June 1996 coinciding with the hottest period. The minimum values were recorded in April 1996 following a period of low external temperatures.

	NE2	SW1	SW2
Maximum slab temperature [°C]	25.1	24.7	25.1
Minimum slab temperature [°C]	19.9	20.9	20.9

Table 2: Slab temperature variation

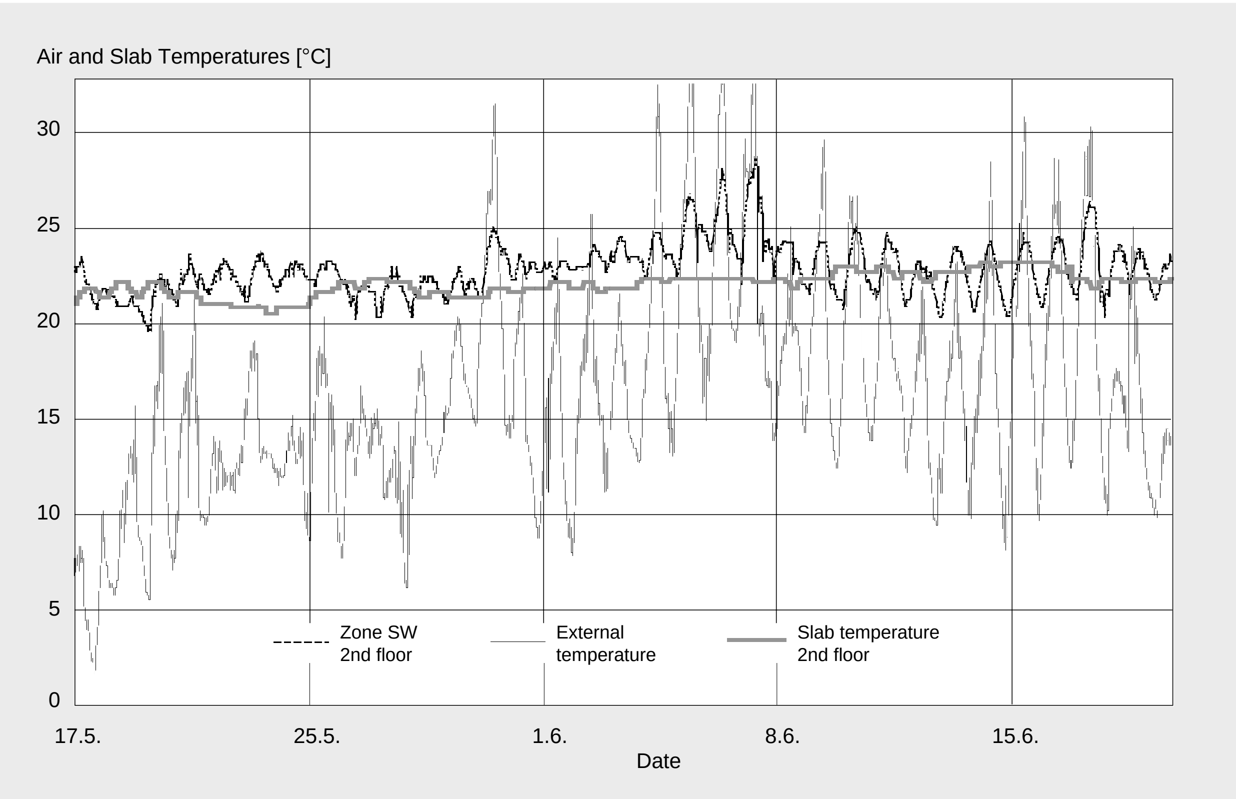


Figure 6: Slab temperature compared with internal temperature

The performance of the plant components were assessed using spot measurements as follows:

AHU		Supply Inlet temp. T_2 (°C)	Outlet temp. T_3 (°C)	Extract Inlet temp. T_1 (°C)	Outlet temp. T_4 (°C)	η $\frac{T_3-T_2}{T_1-T_2}$
1	Actual	6.9	16.9	22.4	11.7	65 %
	Design	6	14.7	19	10.4	67 %
2	Actual	7.0	14.4	19.5	11.5	59 %
	Design	6	14.5	19	12.4	65 %
4	Actual	6.0	9.2	13.8	8.5	41 %
	Design	6	14.7	19	10.4	67 %
5	Actual	6.7	13.3	20.2	9.8	49 %
	Design	6	15	19	10.1	69 %

Table 3: Thermal wheel in heating mode (External temperature = 6 °C)

AHU		Supply Inlet temp. T_2 (°C)	Outlet temp. T_3 (°C)	Extract Inlet temp. T_1 (°C)	Outlet temp. T_4 (°C)	η $\frac{T_2-T_3}{T_2-T_1}$
1	Actual	no meaningful data				
	Design	29.0	24.5	22.0	26.7	67 %
2	Actual	no meaningful data				
	Design	29.0	24.5	22.0	26.7	67 %
4	Actual	no meaningful data				
	Design	29.0	24.5	22.0	26.7	67 %
5	Actual	22.2	19.8	18.2	21.4	55 %
	Design	29.0	24.2	22.0	26.7	67 %

Table 4: Thermal wheel in cooling mode

AHU		Air to cooler dry bulb temp. °C	Air off cooler dry bulb temp. °C	Wet bulb temp. (assumed at 40 % RH)	Effi-ciency
1	Actual	22.4	16.8	9.5	43 %
	Design (summer)	28	21.5	13.8	46 %
2	Actual	20.8	16.0	10.1	45 %
	Design (summer)	28	21.5	13.8	46 %
4	Actual	no meaningful data	-	-	
	Design (summer)	28	21.5	13.8	46 %
5	Actual	20.2	14.6	8.0	46 %
	Design (summer)	28	21.5	13.8	46 %

Efficiency: $\varepsilon_c = 100 \cdot \frac{(T_1-T_4)}{(T_1-T_T)}$ where, T_1 = entering air, dry bulb temperature; T_4 = leaving air, dry bulb temperature; T_T = entering air, wet bulb temperature

Table 5: Performance of evaporative cooler

Control Strategy

The ventilation system operates in many modes dependent upon the internal and external temperatures. These modes are summarised in Table 6. The occupants have the provision to control the blinds, windows and perimeter heating thermostats.

Energy Consumption

The building is all electric with the exception of gas used for catering. The electrical power consumption for the first six months is high for a building of this type. A breakdown of electrical loads is being undertaken but it is apparent that the building has a particularly high IT load.

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 temp. < 20 °C	Night	AHU runs with thermal wheel only (to re-distribute heat in the slab)
Minimum zone temp. > 19 °C at night and < 24 °C the previous day	Night	All plant off
Minimum zone temp. > 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 6: Control modes of ventilation system

Construction and Operating Costs

The costs associated with the novel aspects of this building were:

- 15 £/m² for drilling into, cleaning and sealing the hollow cores in the slab for air transfer,
- 18 £/m² for six wind towers,
- 5 £/m² to seal the raised floors to create airtight service plenums,
- 20 £/m² for large double glazed bespoke aluminium framed, glazed area above the central atrium,
- 78 £/m² for double glazed windows in aluminium and wood on southern façade with external sunshield plus individual windows on northern façade.

The painted soffit rather than suspended ceiling reduced the cost by 15 £/m². Further cost savings are achieved since terminal units and their associated controls are not required.

The plant maintenance costs are expected to be similar to those of a conventional air conditioned building. However, the running costs associated with the main plant are expected to be less, primarily due to much reduced power consumption for cooling and the use of natural ventilation in the southern zones except during periods of extremes of climate.

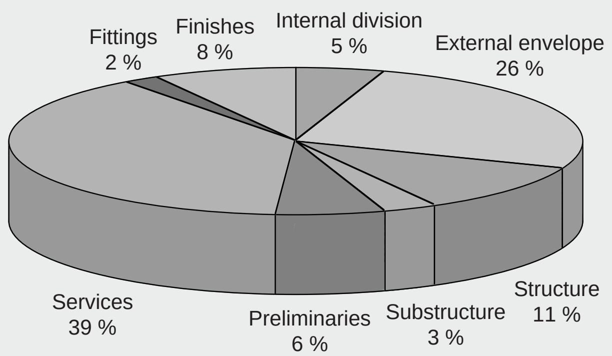


Figure 7: Cost breakdown of IONICA building

Summary

The provision of a selection of cooling options has led to a flexible solution to maintaining comfort conditions at the lowest cost.

The systems are complex but fine tuning of the control system and the facility to override it e.g. to provide heat pump cooling or to prevent draughts due to natural ventilation allows the required conditions to be met.

Practical Experience

- Draughts sometimes occur due to high air velocities created by the wind towers.
- The building is occupied late into the evening. This conflicts with passive night cooling requirements.
- Incorporation of slab temperature monitoring to indicate/preempt slab overheating/overcooling would improve internal temperature control.
- Atrium lights on during passive night cooling encourages the ingress of insects through the rooflights. The use of the windtowers only would minimize the problem.
- The occupants allow the building to overheat when operating under natural ventilation before the windows are opened.

References

[1] Cambridge Calling, The Architects' Journal, December 1, 1994, pp29 - 38

[2] Fletcher J, Martin AJ: Night Cooling Control Strategies, TA14/96, BSRIA, 1996, ISBN 0 86022 449 X

[3] Framed in Steel 27 - Ionica, St John's Innovation Park, Cambridge, British Steel,

[4] Evans, B: Technical and Practice: Low Energy Design for a High Tech Office, Architects' Journal, December 17, 1993. pp29-32

[5] Jackaway A & Greene D: Shedding Light on Ionica, Architects' Journal, March 28, 1996. pp51-53.

Figure 7: Natural light penetrates the space and uplighters are photo-electrically controlled

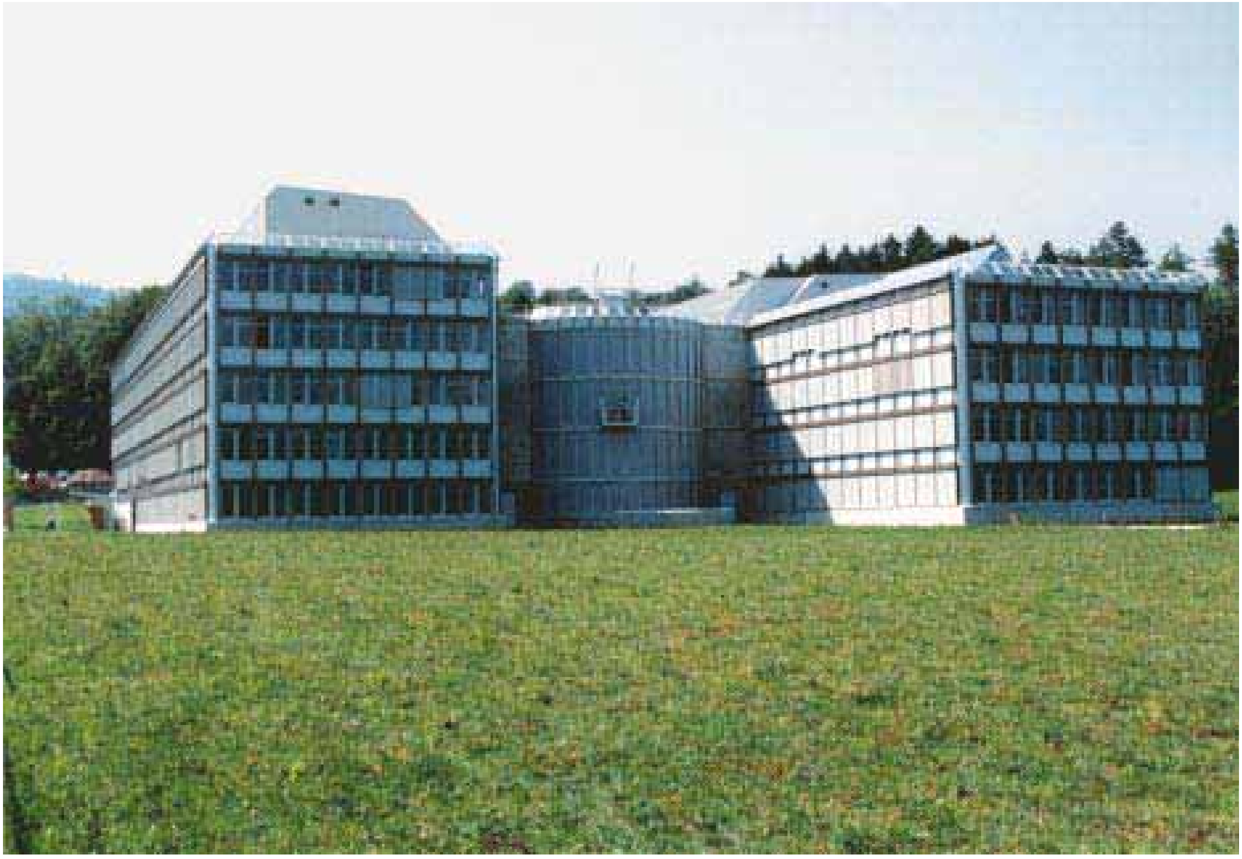
The *DOW Building* Headquarters *DOW Europe* Horgen/Switzerland

Slab Cooling (Water)

Owner: DOW Europe SA
Architect: Bruno Gerosa
Energy design concept:
Robert Meierhans
Engineer: Meierhans & Partner AG
Reporters: Mark Zimmermann
Robert Meierhans

Date: August 1998

- Active mass coupling
- Load shift to cooler night hours
- Low system costs
- Low energy consumption
- Low operating and maintenance costs



Background

Recent energy legislation permitting active cooling only in exceptional cases has encouraged efforts to develop passive HVAC systems capable of achieving an acceptable level of indoor comfort.

Introduction

In 1975, the new headquarters of DOW EUROPE SA were completed in Horgen/Switzerland on the south-west bank of Lake Zurich. The office building corresponded to the then current state of the art. The building originally had a completely sealed suspended façade, gold-tinted insulation glass and a powerful air-conditioning system (interior zones: high-pressure dual-duct system; façade zones: high-pressure quadruple loop induction system). The building did not entirely satisfy employees' expectations with regards to comfort.

In 1988, it became necessary to double the available office space, and an architectural competition was organised. This was won by the Zurich architect Bruno Gerosa. In selecting the HVAC engineer, a new procedure was adopted. The invited architects were requested to present examples of unconventional solutions in buildings designed by themselves. The owner's primary emphasis was on innovative potential irrespective of building type. The engineer was required to show that he could keep the new building at a physiologically reasonable level of comfort without the need for conventional air conditioning. The owners wished to take preventative measures in view of anticipated new energy legislation. The new energy legislation is intended to avoid new office buildings being mechanically cooled purely and simply on the grounds that the architecture does not lend itself to efficient energy utilisation. Thus air conditioning will only be permitted on fulfilment of certain design conditions:

- Thermal insulation conforming to regulations
- Adaptable shading devices, transmission factor ≤ 15 %
- Mass coupling (insulation outside, mass inside, no suspended ceilings that would thermally isolate the room from effective heat storage)

To keep energy consumption for heating, ventilation and air conditioning to a minimum, mass coupling, solar protection and adequate insulation are provided.

Experience to date has shown that appropriate systems can markedly lower energy consumption without reducing comfort. It was also shown that energy efficient measures do not necessarily entail higher investment costs but may, on the contrary, lead to worthwhile cost reductions.

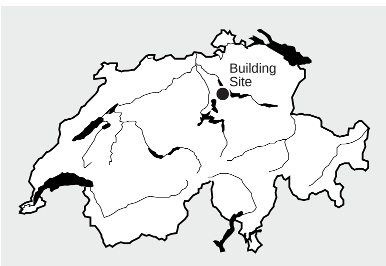


Figure 1: Location of the demonstration building in Horgen near Zurich/ Switzerland

Building Layout

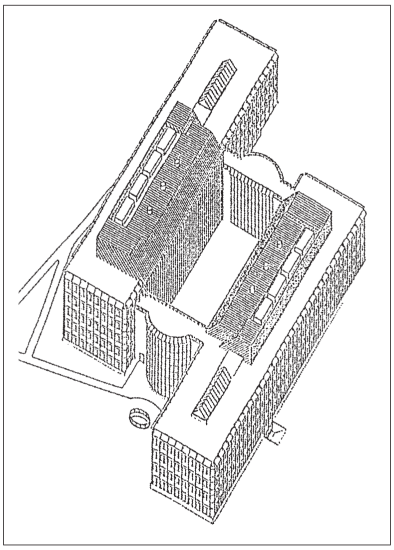


Figure 2: Bird's eye view of the DOW building with two office wings facing onto an open courtyard

Building Description

Project Data

Location	Horgen/Zurich
Altitude	437 m
Year of construction	1990/1991
Number of working spaces	300
Heat. degr. days (20/12)	3616 Kd
Cooling degree days (18)	198 Kd
Heated floor area	14,400 m^2
Slab cooling area	7,500 m^2
Installed capacity	
• Heating	510 kW
• Cooling	400 kW
• Ventilation	120 kW
• Ventilation rate	3 m^3/m^2h
Heating consumption	213 MJ/m^2a
Cooling consumption	17 MJ/m^2a
Costs in US$	
• Heating	792,000
• Ventilation	1,670,000
• Cooling	1,080,000
• Slab Cooling	235,000

Design Concept

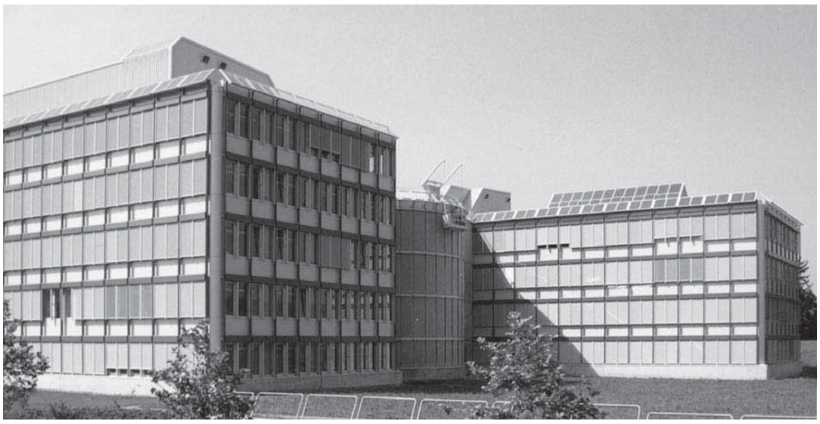


Figure 3: View of the DOW building from the east

General Energy Concept

Building Envelope

The building envelope, which is of aluminium and glass, is airtight and well insulated. The U-values are about 0.3 W/m^{2}K for the walls and 1.7 W/m^{2}K for the glazing. Thermal bridges have been avoided as far as possible.

Solar and Overheating Protection

The entire building is equipped with automatically controlled external shading devices that can be operated separately for each façade and/or directly by the occupants.The design of the façades with tall windows and using bright interior colours ensures excellent daylighting. To minimise internal loads, artificial lighting has been kept to a minimum.

At each workplace, about half the artificial illumination is provided indirectly and the rest directly. The lamps are mounted on a frame at a distance of approximately 35 cm from the ceiling, and may be displaced horizontally.

Optional Window Ventilation

As the building is situated on a quiet site and looks out onto the countryside, it was decided to provide for window ventilation. The mechanical ventilation system is designed for the base load such that during hot summers and cold winters, the windows may be kept closed if desired.

Mechanical Ventilation

The lamp support frame serves as a post-heater. For this, the supply air is passed through hollow bars in the frame and enters the room through vertical, laminar-flow, inlets above each workplace. The flow path within the frame is about 7 m in length. The temperature increase depends on room temperature, itself being dependent on heat load, and is self-regulating. The particular shape and surface properties of the hollow bars ensure a temperature level about 1-1.5 K below room temperature. This gives a gentle downward flow of air without risk of draughts.

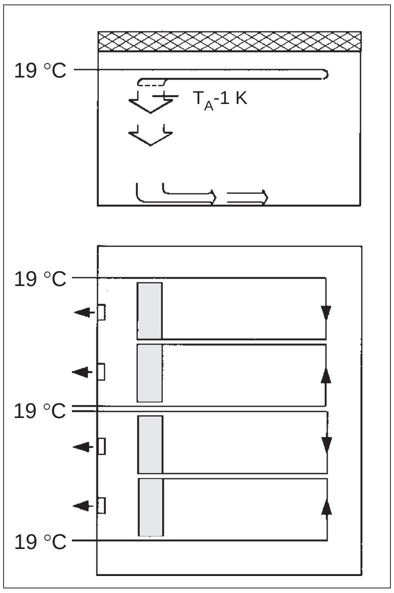


Figure 4: Displacement ventilation with air inlets in the suspended lamp support frame. The cool air is heated to just under room temperature before entering the room and descends to the floor with low turbulence.

Demonstrated Energy Technology

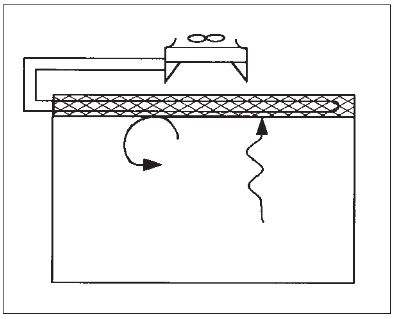


Figure 5: Concrete slab cooling allows the thermal load to be shifted from the day to the night. The thermal gains are stored in the slab during the day and removed during the night via air coolers during the night.

Room cooling is achieved on a similar basis to floor heating systems using cooling pipes. Numerical simulations have shown that the effective room temperature does not rise above 26 °C for heating loads up to 80 W/m^2 (52 W/m^2 internal plus 28 W/m^2 external load). The results from a simple, two-dimensional heat balance model showed that efficient cooling of the concrete slabs may be achieved with cool night air, Figure 5, at all times of the year with the exception of seven single days. In spring and autumn, the warmer areas of the building are cooled simply by circulating water around the building. This also serves to compensate lower temperatures in rooms with lower thermal load on the shaded side of the building.

Design Details

Slab Construction

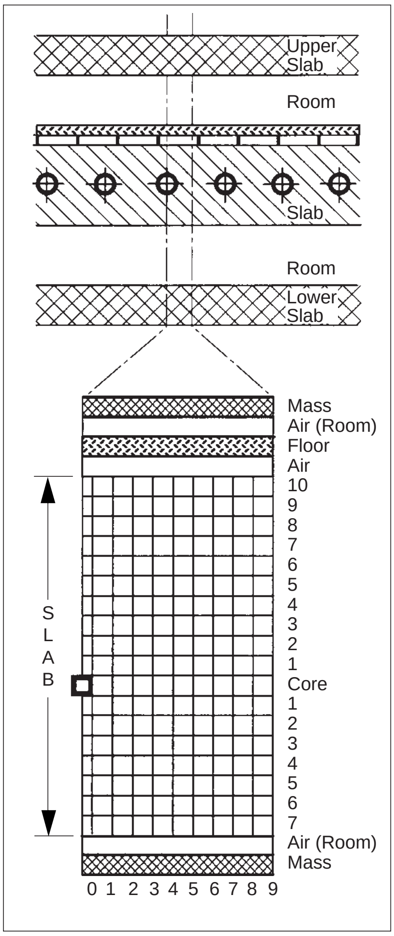


Figure 6: Schematic section trough concrete core (top) and illustration of the finite element model (bottom)

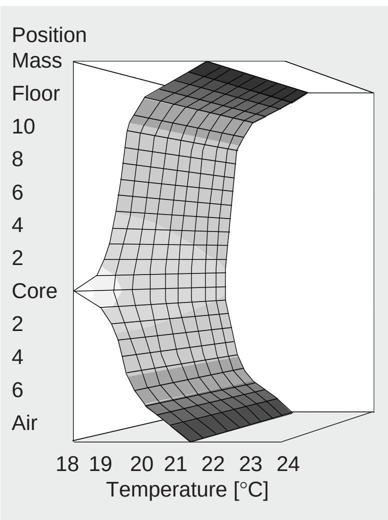


Figure 7: Two-dimensional calculation of average core temperature

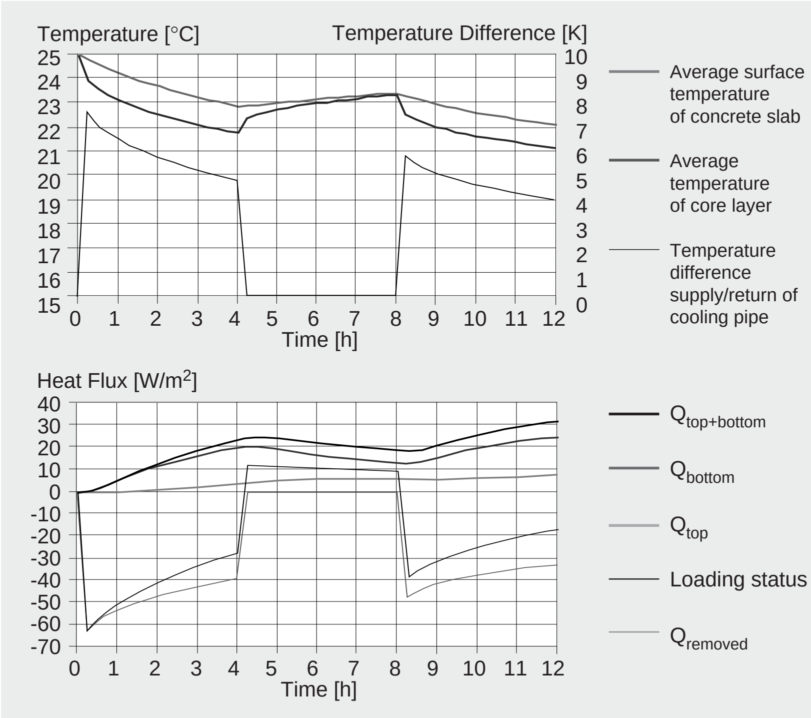


Figure 8: Dynamic temperature variation and cooling capacity assuming an initial slab temperature of 25 °C and cooling interrupted for 4 hours

A two-dimensional heat balance model with 210 nodes was used to determine the suitable floor construction and the optimal position of the pipes. The floor was divided for calculation purposes into discrete elements of length equal to the distance traversed by the water in one second. A three-dimensional representation was achieved by coupling the elements in series. The purpose of this calculation was to determine the average temperature of the core in the plane of the pipes. This temperature is required for further calculations with the DOE program.

Intermittent operation of night cooling causes part of the heat to be returned to the room during the night, this being either removed by the ventilation system or rejected through the façade. For continuous operation of compression cooling (e.g. at high night-time air temperatures) or with powerful ground coupling (for example with boreholes), the power used for night cooling operation is approximately 15-20 % of peak cooling capacity.

Construction Procedure

The plastic piping (PE 12/16 mm) was mounted over a length of approximately 80 m on the upper reinforcement (2 m x 5 m). Each pipe end was led through a plastic connecting box. This was fixed to the shuttering with its opening facing downwards. Each pipe was fitted with an air pressure valve

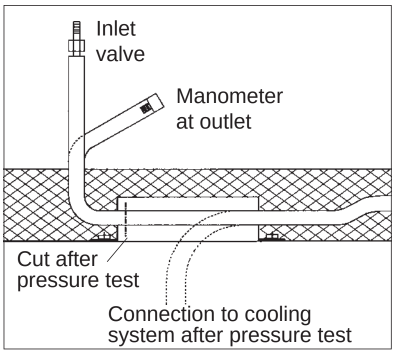


Figure 9: Premounted connection box for pipes

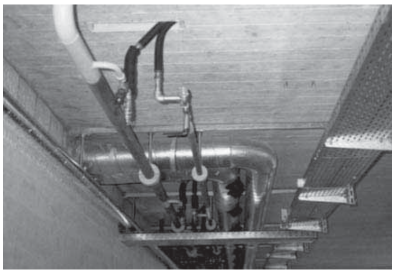


Figure 10: View of the premounted connection box

and a manometer. After the pipes were fitted above the lower reinforcement using distance pieces, all pipes were pressurised to 6 bar. The pressure, which served to stiffen the pipes, was checked at intervals until the concrete had set. After removing the shuttering, the pipes were visible in the plastic boxes from below. The pipe ends were trimmed and bent downwards before connection to the system. All 765 pipes were successfully brought into operation.

It is essential to co-ordinate the piping with the remaining installation at the design stage and to clearly mark the positions of the chases for installation of further piping should this prove necessary.

Dimensioning of Base-Load Ventilation

One-person offices were three panels wide (a panel designating that part of the façade between two supports) and two-person offices four panels wide, the strip lighting being designed to correspond with the distance of 1 m between the façade supports.

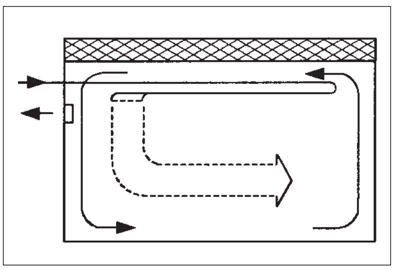


Figure 11: The slightly lower temperature of the ceiling and the supply air cause a vortex to develop.

One-person offices have two lighting strips (two air inlets) and two-person offices three lighting strips (three air inlets). The cross section of the ducts limits the flow rate per strip to 20 - 30 m^3/h. For one-person offices, a maximum of 60 m^3/h (16.7 l/s), and for two-person offices 90 m^3/h (25 l/s) can be supplied. The final value chosen was 40 m^3/h (11 l/s) per person.

Air is conditioned in a central plant all the year round and distributed at 19 °C to the strip lighting. Depending on the particular value of room temperature and the radiation intensity of thermal loads, the air leaves the inlets at approximately 1 to 1.5 K below room temperature.

As the cooling water enters the piping system from the corridor side, the temperature of the ceiling adjacent to the corridor is lowest. From here, air descends, setting a room vortex in motion. As the air inlets are also at the corridor side, the fresh air is carried along on top of the vortex, and delivered uncontaminated to the workplace. By this means very good ventilation efficiency is achieved.

Figure 12: The fresh air flows above the vortex falling from the ceiling

Figure 13: Air coolers on the roof

Control Strategy

The control strategy is extremely simple. Supply air is kept at 19 °C all the year round, i.e. either heated with air heaters or recuperation heat, or cooled. The flow rate is reduced to 50 % at night. With a supply air temperature of 19 °C, any condensation on cold internal surfaces can be avoided.

The cooling water flow temperature is likewise set at 19 °C. Cooling water circulation is started around midnight and continued until the temperature difference on the water side in the cooler is less than 1 K. Circulation is then interrupted. After one hour, the procedure is repeated, and this is continued until the temperature of the water returning from the concrete slab falls below a set value. In this way, cooling water circulation is adjusted to suit the very slow rate of heat discharge from the concrete slab. Results show that the performance of the intermittent system is very satisfactory measured in terms of energy expended to energy supplied.

Performance Data

Overall Performance

In performing the measurements, two objectives were followed:

- to analyse comfort levels in selected rooms; and
- to determine the proportion of free cooling in relation to total cooling requirements.

Comfort

The level of comfort and ceiling performance were investigated during normal office hours in summer, 1992. Due to difficulties experienced with intermittent absence of office employees on vacation and their irregular time-keeping, only a rough assessment of comfort could be made. Nevertheless, during one extremely warm period (13th to 23rd August, 1992), the limiting values stipulated by energy legislation were complied with, without the assistance of mechanical cooling. Admittedly, a rise in temperature of the mass storage was noticed, resulting in higher room temperatures during the week. Luckily, internal loads during the assessment period were moderate.

Originally, conditions for taking measurements had been far from ideal, so that in summer, 1993, the owner provided three empty rooms at the south-east side of the building for this purpose. Electric heaters were installed to simulate thermal loads. Figure 14 shows the temperature profile for three different cooling strategies. In one room having a high internal load of 52.5 W/m^2, the ceiling cooling and mechanical ventilation systems were switched off. Ventilation and cooling were effected solely by opening the windows for a period of 10 min/h (curve 2). The temperature in the other two identically equipped rooms with loads of 52.5 W/m^2 and, more realistically, 17.5 W/m^2 are shown by the mid-

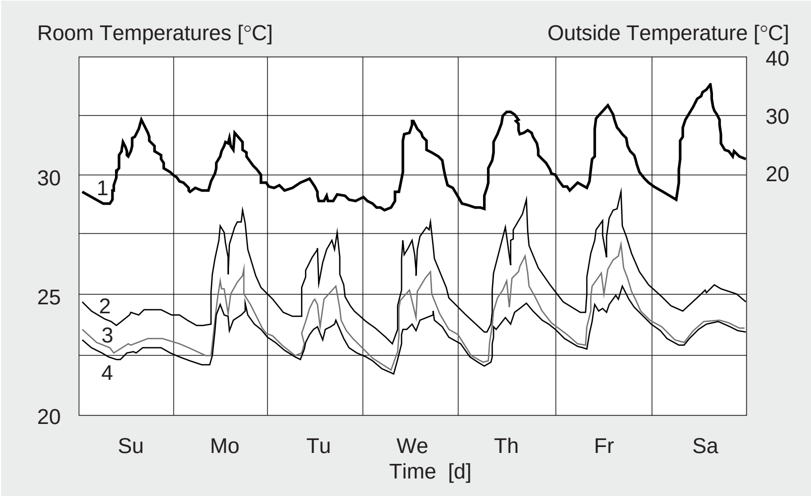


Figure 14: Room temperature profiles with two operating modes and two constant internal loads (people + office machines) in summer 1993

1. *Outside air temperature (measured in ventilated space between façade and shading device)*
2. *Window ventilation only*
3. *Concrete core cooling + mechanical ventilation, sum of internal load Q_i = 52.5 W/m^2*
4. *Concrete core cooling + mechanical ventilation, sum of internal load Q_i = 17.5 W/m^2*

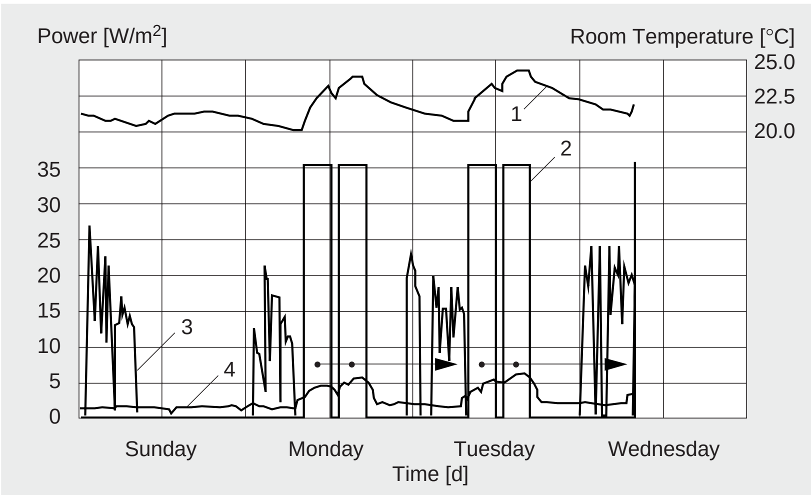


Figure 15: Internal loads stored during day time in concrete slab and removed during night hours

1. *Operative room temperature*
2. *Sum of internal load*
3. *Power of concrete core cooling during night hours*
4. *Cooling power of mechanical ventilation*

dle (3) and bottom (4) curves. Analysis of the curves shows that omission of overnight cooling and mechanical ventilation results in almost the same rise in temperature as an increase in thermal load by a factor of three (17.5 to 52.5 W/m^2).

During the tests the sun blinds were automatically lowered over the complete façade to exclude solar radiation.

The results clearly show that reasonable comfort can be achieved without difficulty using a simple core cooled concrete system. The system's self-regulating features even enable it to deal effectively with faulty operation. For example, if the sun blinds are opened in summer, leading to a noticeable rise in temperature, no additional energy is consumed, and the user receives a prompt and effective warning.

Cooling Performance

Figure 15 shows the cooling effect of the ventilation system and of the cooled concrete ceiling during the night. The mechanical ventilation system accounts for only a relatively small fraction of this (maximum about 5 W/m^2). Due to the constant temperature of the supply air of 19 °C and the continuous flow rate (50 % during the night), performance is dictated only by room temperature.

Cooling of the concrete core usually extends over a period of about seven hours at an average load of approximately 15 W/m^2. About 40 % of the internal load leaves the room by heat transfer to neighbouring rooms and via the façade at night.

Energy Efficiency

The second part of the project investigated cooling efficiency for three operation modes:

- Mechanical cooling of ceiling and supply air during very hot weather,
- Free cooling of ceiling, and mechanical air supply,
- Free cooling of ceiling and supply air.

During operation of the mechanical cooling system, electrical energy is required for motors, circulation pumps and heat exchanger fans. With free cooling, it is necessary to power only circulation pumps and heat exchanger fans. Table 1 gives details of energy effectiveness for the cooling system. The energy effectiveness (cooling energy per kWh electricity consumption) of free cooling (5.8 and 6.1) is more than twice as high as that of mechanical cooling (2.7).

Two thirds (67 %) of total cooling demand of the DOW building are covered by free cooling.

	Mech. Cooling Ceiling + Supply Air	Free Cooling Ceiling	Free Cooling Ceiling + Supply Air
Refrigeration [MJ/m^{2}a]	16.2 ±0.2	23 ±1.7	9.7 ±0.7
Electricity [MJ/m^{2}a]	5.9[1)]	4.0	1.6
Energy Effectiveness	2.7 ±0.15	5.8 ±0.45	6.1 ±0.45

1) Cooling machine: 3.9 MJ/m^{2}a; pumps, fans: 2.0 MJ/m^{2}a

Table 1: Measured energy consumption in MJ per m^2 and year and energy effectiveness – also called Coefficient Of Performance COP – (cooling in kWh per kWh electric power consumption)

Summary

Free Cooling During Day

The amount of energy extracted from a building by means of free cooling during the night depends on the average night temperature. Figure16 shows this interrelationship. Cooling is most effective at average outdoor night temperatures between 15 °C and 18 °C. At higher outdoor temperatures, cooling potential declines, disappearing completely at about 20 °C. At lower outdoor temperatures, cooling demand is lower. Thus below 13 °C, there is usually no significant cooling demand. Exceptions are nights with a sudden drop in temperature (see far left of the diagram). When such low temperatures occur at night, it is normally cool during the day and frequently very cloudy. The building has low external thermal loads and the heat can leave the building by transmission, infiltration and through open windows.

The maximum free cooling capacity at night (100 Wh/m^2) has approximately the same magnitude as the internal thermal load during the day. In the case of buildings with higher internal loads and/or superinsulation, the necessary cooling capacity increases, so that the optimum is shifted toward lower average outdoor temperatures.

Future Perspectives

It is apparent that the cooling system, which in itself is very efficient, can readily be adapted to provide ‘mild’ wall heating in winter. All subsequent buildings did without a separate heating system (see report [2], Art Museum Bregenz).

References

[1] R. Meierhans: Untersuchungen an einem Bürogebäude mit passiver Nachtkühlung der Betondecke, NEFF-Projekt 464

[2] R. Meierhans, M. Zimmermann: Slab Cooling and earth coupling, IEA Future Buildings Forum Innovative Cooling Systems Workshop Report, 1992

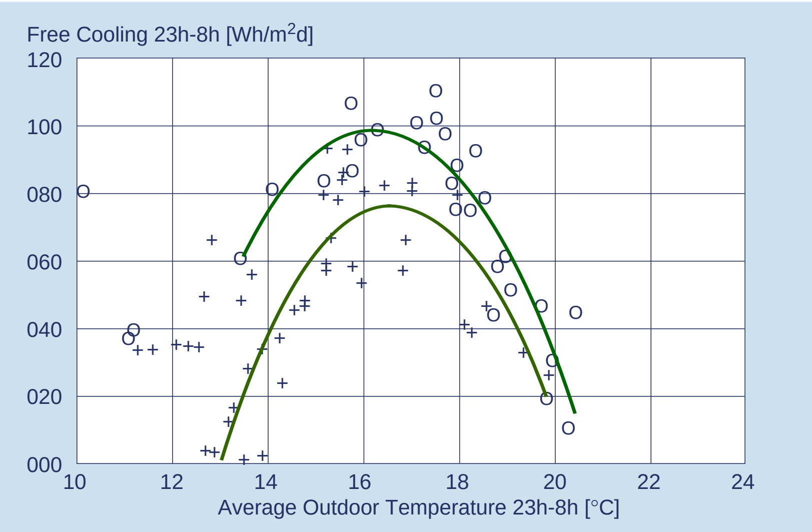


Figure 16: Free cooling energy as a function of the average night outdoor temperature (average internal load about 100 Wh/m^2 and day)
+ Evening core temperature < 22.5 °C
o Evening core temperature > 22.5 °C

Practical Experience

Experience following two years’ optimization, measurement and evaluation has shown the importance of optimum commissioning of multi-faceted, intercoupled systems, and not least how expensive this can be. The effort is undoubtedly justified, as it enables full realisation of existing energy-saving potential. To be realistic, however, if progressive energy concepts are to continue to be put into practice, an operative control and optimization period of one to two years should be provided for. The building executives at DOW acknowledge the advantages gained from the measurement project and may certainly be regarded as a good reference when realising future projects of this kind.

The technology of mass storage kept at a specific temperature gives excellent performance and may be used in numerous situations. The combination of satisfactory insulation and solar shading with large heating and cooling surfaces enables system temperatures to be kept close to room temperature. The relatively *high* cooling and *low* heating temperatures are ideally suited for ground coupling, and favour self-regulated systems. In future, buildings cooled by means of water at 21 °C and heated at about 23 °C are envisaged. The basement of an art gallery in Bregenz (in Austria) offers a practical example. This is immersed in groundwater and is fitted with piping coils, enabling the building to be heated and cooled all year round using water at 22 °C and without the use of mechanical cooling.

The *Sarinaport* Office Building Fribourg, Switzerland

Slab Cooling and Heating (Water)

Energy design concept and Engineering: Geilinger SA
Reporters: Mark Zimmermann
Charly Cornu

Date: August 1998

- 10 % lower capital investment
- Energy consumption halved
- Low operating costs
- High thermal comfort in summer and winter
- No draughts
- Optimum space utilisation

Background

Introduction

The main task of a building is to ensure optimum indoor climate for those working within it. Buildings of poor thermal design require powerful equipment to provide the required level of comfort. This results both in high capital investment and high operating costs.

With modern, highly insulated buildings and efficient solar protection, the influence of outdoor climate may largely be eliminated, permitting drastic simplification of the technical installations. The results are large savings in capital investment and operating costs that far outweigh the additional cost of improving the building envelope. In comparison to buildings with conventional air conditioning, building costs may be reduced by as much as 10 %!

The design is based on three mutually dependent principles:

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

Building Concept

The first consistent implementation of the design was at the *Schäublin* management headquarters in Delémont, Switzerland, by the firm of Geilinger SA (Figure 1). This was followed by a further building in Fribourg, the *Sarinaport* office building. The design, which is now known under the name of *BATISO®* (Bâtiment isotherme), has now also been successfully applied at several other sites in Switzerland and Germany.

The task of the technical installations of highly insulated buildings is primarily to control internal loads, and for this, the average power requirements are quite modest. Under these circumstances, heating and cooling of the building may be realised with flow temperatures departing little from the room temperature (± 3 K).

Both for heating and for cooling, the heavy concrete floor slabs are exploited. These have the ability to quickly store excess heat, and, when necessary, to provide heating energy to the room. Owing to the low temperature differences, this process is entirely self-regulating. As soon as the room becomes too hot, heat is rejected to the slab, whereas if it is too cool, heat is withdrawn.

The resultant buildings provide the user with a high level of comfort and very low operating costs, are simple to operate, and do not require extensive installations or control equipment.

Figure 1: The Schäublin SA administration building in Delémont was the first building to be based on the BATISO® principle

Project Data

Location	Fribourg, Switzerland
Altitude	677 m
Year of construction	1993/1994
Number of Working spaces	380
Heat. degr. days (20/12)	3616 Kd
Cooling degree days (18)	183 Kd
Heated floor area	9,500 m^2
Heated space	27,000 m^3
Inst. heating capacity	150 kW
Costs in US$	
• HVAC,control system	110.-/m^2

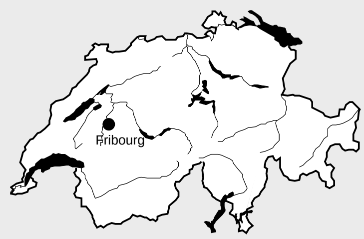


Figure 2: Location of Sarinaport demonstration building in Fribourg

Design Concept

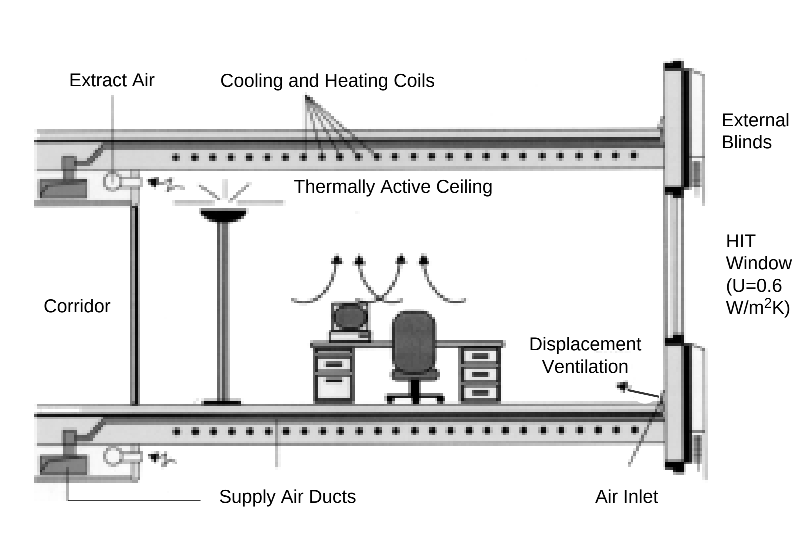


Figure 3: Schematic section through BATISO building

With displacement ventilation, neither summer nor winter operation is adversely effected when windows are opened by the occupants.

With this ventilation concept, very low air flow rates are sufficient to ensure a high standard of air quality in occupied zones. An air change rate of 0.8 per hour, or approximately 30 m^3 (8 l/s) of fresh air per person and hour, are sufficient to meet hygienic standards. Thanks to the reduced air flow rate, owners benefit both from lower capital investment in ventilation plant, and, due to the energy saved, from markedly reduced operating costs.

General Energy Concept

The energy concept represents an optimum combination of building envelope and technical installations.

Building Envelope
The central feature of the building is a painstakingly insulated envelope avoiding thermal bridges. The so-called "HIT" windows have high insulating and sound damping properties.

The surface temperature of the windows diverges only slightly from that of the room. This enables the room to be more efficiently utilised. Workplaces may be located in the immediate vicinity of windows without jeopardising comfort. Draughts normally resulting from cold window surfaces are completely eliminated.

When closed, the windows are absolutely airtight; they may however, be opened at any time.

External sun blinds prevent excessive heating of the building in summer. The sun blinds are automatically controlled to prevent office rooms that are not in use being overheated by strong sunshine. The control system can, however, be overridden by the occupants.

Displacement Ventilation
Displacement ventilation has the advantage of providing excellent indoor air quality at low energy consumption rates. In this system, air is introduced to the room at floor level at a temperature slightly under room temperature. Being cooler and more dense than that of the room, the supply air spreads out to form of a pool of fresh air along the floor. Rising convection currents (plumes) are formed around any heat sources present in the room, transporting air upwards from the pool towards the ceiling. In this way, occupied areas are supplied at distinct points with fresh, clean air. The hotter "spent" air together with contaminants is carried towards the ceiling where it is extracted through openings and rejected via the heat recuperation system.

Demonstrated Energy Technology

Thermoactive Ceiling
All buildings have considerable capacity for energy storage in the form of building mass (floors and ceilings). Changing the temperature of the stored heat requires time and involves large quantities of energy. When the building façade is designed to allow only small quantities of energy to pass, the technical installations need only to make small corrections to maintain the storage temperature at a constant value. This may be done by the aid of water-cooled pipe coils within the concrete floor slabs. In this way, heating may be supplied in winter and excess heat rejected in summer.

Design Details

Building Envelope
The windows are an important feature of highly insulated building envelopes. Winter and summer they must effectively prevent heat transmission (U-value $< 1 W/m^2K$). Parallel to that, low radiation transmission factor ($g < 40$ %) and good light transmissivity ($\tau > 60$ %) are desired.

Ventilation
For “displacement” ventilation with minimum air change rate, space requirements for air conditioning and distribution are modest. The flow area can be so dimensioned that the distribution ducts may largely be integrated within the concrete floors.

In passing through the concrete floors, the temperature of the supply air automatically adjusts itself to near that of the room. This avoids draughts and improves the level of comfort.

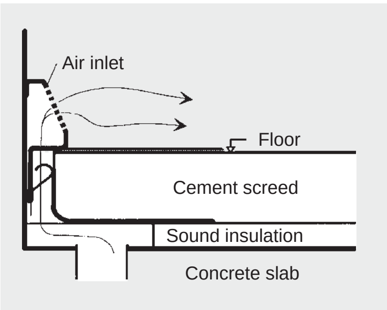


Figure 4: Special air inlets at floor level for displacement ventilation

A special skirting board was developed for the air inlets. This ensures that the room is uniformly ventilated. Through these, the supply air enters the room at low velocity and turbulence.

The sum total is a compact, low priced ventilation system with no additional space requirements. No expensive panelling or false ceilings are required.

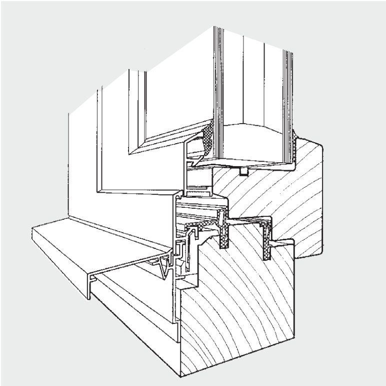


Figure 5: The façade is fitted with so-called High Insulation Technology (HIT) windows (U: 0.6 W/m^2K, g: approx. 35 %, τ: approx. 60 %). They also ensure an excellent sound absorption (40 to 49 dB(A)).

Cooling and Heating Ceilings
The entire installation for heating and cooling is integrated within a single circulation system. The low system temperatures are ideal for alternative heating and cooling systems. The entire cooling load is covered by an adiabatic cooling tower. For heating purposes, a small gas boiler is normally used, but a heat pump could also be considered.

For heating, a flow temperature of approximately 26 °C is sufficient to maintain a ceiling surface temperature of 22 °C. Solar collectors, absorbers or heat wells can supply these temperatures over much of the year without need for auxiliary heating. Furthermore, heat pumps with low output temperatures of up to 26 °C have a very high coefficient of performance. Collectors or absorbers integrated within the building façade represent a further method of saving primary energy.

For cooling, flow temperatures of about 20 °C are sufficient to ensure acceptable room temperatures. This can be achieved without mechanical cooling using adiabatic cooling (evaporative cooling). Electrical energy consumption may thereby be reduced and the use of environmentally harmful refrigerants avoided.

For the pipe coils, oxygen-tight piping of the type used for floor heating is adopted, this being located at the centre of the concrete floor slabs. The coils are arranged

Figure 6: Interior view of the offices. Minimum space requirements for technical installations permit generous and flexible utilisation of room space

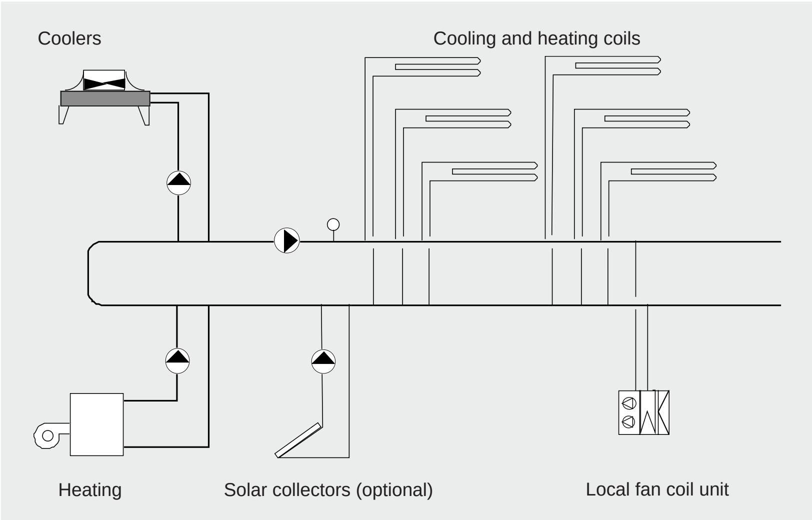


Figure 7: A single circulation system suffices both for cooling and for heating. The flow temperature varies between 20 and 26 °C depending on time of year.

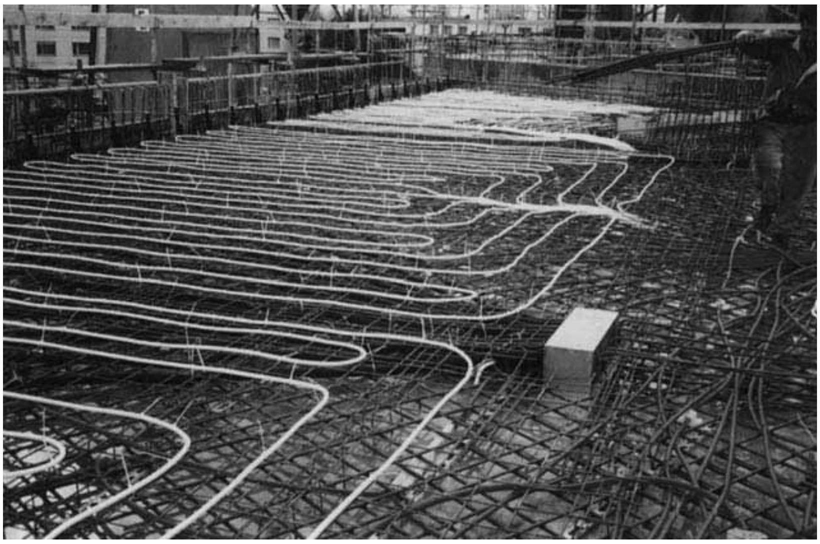


Figure 8: View of ceiling installations before filling. The cooling and heating coils may be identified by their white colour. The ventilation ducts (black) are also mounted in the ceiling. The remaining pipes contain the electrical connections.

about 15 to 30 cm apart depending on heat load and room volume. The flow temperature deviates only slightly from that of the room, varying according to the time of year between 20 °C and 26 °C.

The life cycle of the piping is at least as long as that of the building. The cast-in pipes are made of oxygen-tight aluminium, coated internally and externally with polyethylene. This completely prevents corrosion and silting. Thanks to the isothermal mode of operation of the thermoactive ceilings, material ageing as a result of thermal stress is greatly reduced.

Control Strategy

Owing to the high thermal inertia of the thermoactive ceilings, reaction to load changes is slow, and conventional control strategies are inapplicable. Since external heat loads are largely eliminated by the highly insulated building envelope, the thermoactive ceiling need only compensate the internal loads, and can thus be designed to be self-regulating. The temperature of the thermoactive ceiling is kept at 22 °C all year round. Should the room temperature fall to 21 °C, the ceiling acts as a “heating ceiling”. Conversely, should the room temperature rise to 22 °C, the thermoactive ceiling automatically functions as a cooling ceiling. Self-regulation is effective owing to the high quality insulation of the façade which prevents the occurrence of extreme heating or cooling loads. Excess heat from rooms with high internal loads accrues to the benefit of rooms with less heat generation. The excess heat from south-facing rooms can be transferred to rooms on the north side of the building. This ensures that the temperature of the entire building is kept at an isothermal level of 22 °C. The thermoactive ceiling with a temperature of 22 °C heats and cools all rooms in the building smoothly and efficiently.

Performance Data

Overall Performance

The specific heating energy consumption of the Sarinaport building is 80 MJ/m^2a, amounting to a mere 25 % of the permitted maximum for new Swiss buildings.

Electricity consumption for the system including auxiliary energy for heating and cooling amounts to 44 % of the permitted maximum.

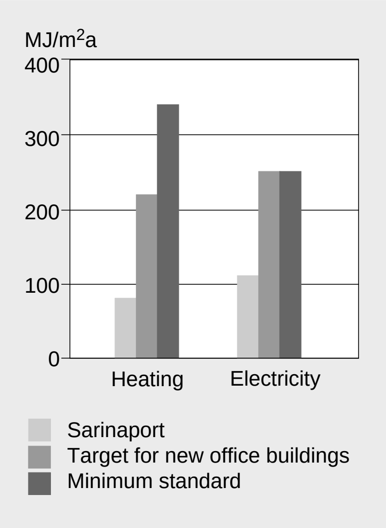


Figure 9: Energy consumption of the Sarinaport building in relation to Swiss targets and minimum standard for new office buildings

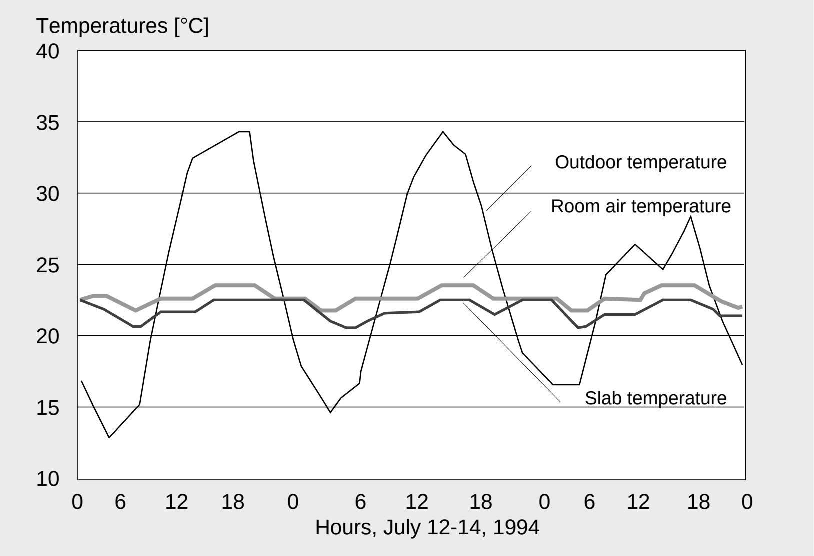


Figure 10: Temperatures during typical summer period. The room temperatures lie well within the comfort zone

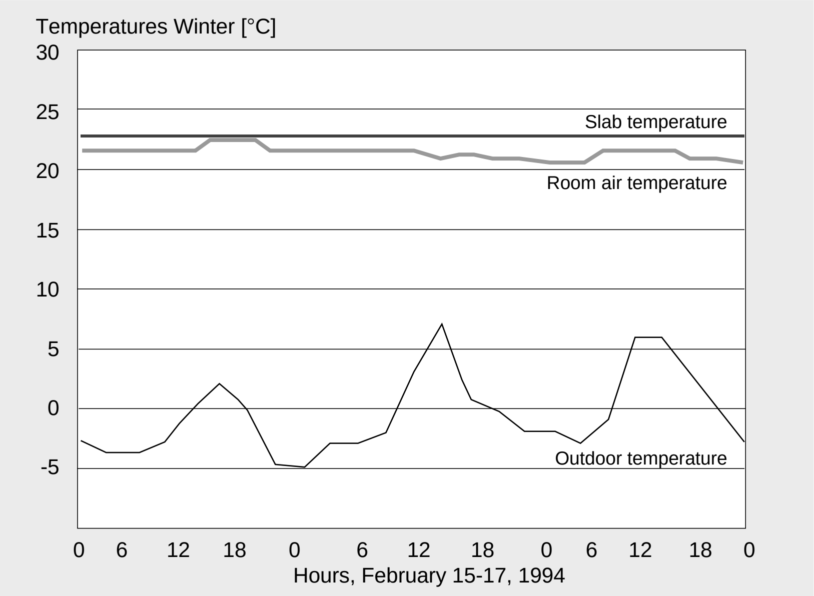


Figure 11: Temperatures during typical winter period. The room temperature is practically constant.

Cooling Performance

During a normal working day (8 h), cooling output is 15 to 20 W/m^2. The maximum capacity is 30 W/m^2, the daily cooling load amounting to approximately 120 to 150 Wh/m^2. For small areas (1 or 2 individual rooms in the building), a maximum load of 50 W/m^2 during 8 hours per day is also acceptable.

The maximum cooling capacity is of course dependent on the availability of cooling equipment. In cases where particularly high internal loads must be removed (>30 Wh/m^2, 10 h/day), additional cooling equipment may be employed.

Electricity Consumption

The electricity consumption of the *Sarinaport* building is comparable to other electricity efficient buildings. The Swiss target level of 90 MJ/m^{2}a is very low for such buildings. Many new office buildings do not fulfil this standard. The *Sarinaport* building uses about 9 % less electricity than the target value. Large consumers of electricity are office equipment, telephones and coffee machines. Only 48 MJ/m^{2}a, which are about equally used for lighting and mechanical equipment, are directly influenced by the building concept (Figure 12).

Two thirds of the Swiss target value, i.e. 23 MJ/m^{2}a, of electricity are used for heating, ventilation and cooling. Only a small part of it is used for the pumps. About twice as much is needed for ventilation purposes (Figure 13).

Construction and Operating Costs

Capital investment for heating, cooling and ventilating the two buildings amounts to 8 to 10 % of the total building cost. For conventional buildings having the same level of comfort as *Sarinaport*, capital investment accounts for 15 to 30 % of the total building cost. Possible savings with respect to total building cost amount to about 5 to 10 % (reduced size of building, simplified installations).

Efficient reduction of external influences on room climate and consistent exploitation of internal loads lead to specific building operating costs as shown in the diagram.

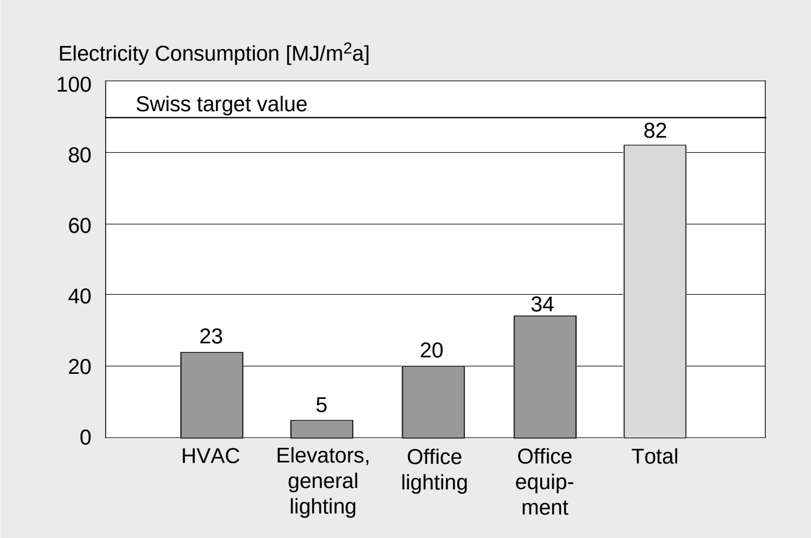


Figure 12: Annual electricity consumption of the Sarinaport office building

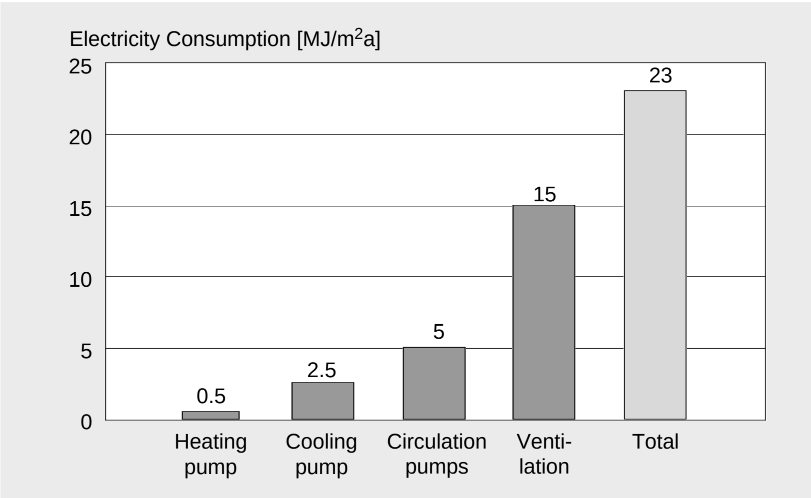


Figure 13: Detailed split of the electricity used annually by the mechanical equipment

Operating costs	BATISO®	Conventional
Heating (gas)	1.00 CHF/m^{2}a [1)]	2.40 CHF/m^{2}a [1)]
Electricity (incl. refrigeration)[2)]	4.60 CHF/m^{2}a [3)]	13.90 CHF/m^{2}a [3)]
Maintenance	1.00 CHF/m^{2}a	2.10 CHF/m^{2}a

1) Based on equivalent oil price of 0.05 CHF/kWh
2) According to SIA Recommendation 380/1[3]
3) Based on 0.20 CHF/kWh

Table 1: Operating cost for the Batiso® slab cooling and heating system compared to conventional systems (Figures of Schäublin SA administration building)

Summary

Figure 11: Overall view of the Sarinaport building from the south-east

Economic Benefits

- Heating and cooling is combined in a single element, i.e. in the thermoactive ceiling. Air flow rates are reduced to an absolute minimum. This results in savings in capital investment and operating costs.
- No obtrusive heating surfaces are required. No ventilation equipment is present at the ceilings of rooms in active use. The main distribution ducts are situated in access areas.
- The absence of heating surfaces permits optimum utilisation of room space. Since no equipment is mounted at the ceiling, total building volume can be reduced. Furthermore, since all installation work is done during shell erection, no particular coordination of interior decorating work is required. The cost-benefit ratio is thereby improved by about 10 %.

Ecological Benefits

- The discribed principle reduces energy consumption of buildings, thus reducing environmental load.
- The use of CFC and other refrigerants is avoided.

Physiological Benefits

- Draughts and noise are prevented.
- Thanks to the higher level of comfort, the productivity of those working in the building is improved.
- The building users appreciate the possibility to open the windows.
- *BATISO®* buildings can be erected in areas with high noise levels.

Interior Design

- Neither the appearance of rooms, nor their interior design, nor the activities within them, are compromised in any way by heating surfaces or ventilation equipment.
- Optimum exploitation of available space is achieved.

Areas of Application

- Management headquarters and other office buildings
- Industries
- Hotels
- Hospitals
- Flats

Practical Experience

Initially, owners and participating firms alike voiced considerable scepticism as to the viability of the new design. However, as those involved were invited to participate at an early stage in the planning process, the original scepticism very soon gave way to positive enthusiasm. To the occupants, the building came as a pleasant surprise. Despite the fact that there are no visible heating or ventilation installations, the rooms are neither too hot nor too cold. This positive, though subjective, impression is supported by the measurements, which clearly show that room and ceiling temperatures vary very little. Room temperature is maintained in winter at 22 °C + 0.5 K independently of outdoor temperature. In summer, the room temperature remains below 25 °C even when the outdoor temperature is as high as 32 °C.

Capacity

- Maximum cooling load 30 W/m^2 (for continuous operation)
- Limited individual control of room temperature (local cooling or control equipment may be installed)

Complementary Criteria

- External sun blinds obligatory for façades facing from south to west
- False ceilings for noise absorption not possible, but a vertical sound absorbing elements with large openings between may be used

References

[1] feedback, Geilinger Information Nr. 19 (in German)

[2] feedback, Geilinger Information Nr. 14 (in French)

[3] SIA Empfehlung 380/1: Energie im Hochbau

The *ACT^2 Stanford Ranch House* Rocklin, California, USA

Architect: Gordon Rogers
Energy design: Dick Bourne, Davis Energy Group
Engineer: Dick Bourne
Builder: McKim Builders
Reporter: Joe Huang

Date: August 1998

Slab Cooling and Evaporative Cooling

- Radiant cooling by night evaporatively cooled coils under the slab
- Direct evaporative pre-cooling of room air during the night.
- Indirect evaporative cooling of room air during the day.
- Additional direct evaporative cooling during the day if needed.

Background

In 1990 the *Pacific Gas and Electric Company (PG&E)* embarked on a multi-year research project called *Advanced Customer Technology (ACT^2)* to demonstrate that through the use of high-efficiency end-use technologies and an integrated design process, residential and commercial buildings can achieve as much as 75 % energy savings compared to standard construction.

In the residential component of *ACT^2*, PG&E contracted the design, construction, and monitoring of two single-family houses located in California's Central Valley, and the retrofits of two existing houses. In the two new houses, integrated packages of energy-efficient appliances, lighting, and building envelope eliminated or minimized the need for mechanical cooling in a climate with a 40 °C outdoor design temperature.

Introduction

The *Rocklin House* is a conventional-looking single-storey ranch house located in a standard housing development with hundreds of other houses by the same builder. However, despite its normal appearance, the house design incorporates 28 different energy-efficiency measures from an architectural redesign to improve solar and thermal control, an engineered wall system, an innovative cooling system, to energy-efficient lighting and appliances.

The *Rocklin House* was completed in April 1994, and monitored continuously through the summer of 1996. The house was sold in November, 1994 and is currently owner-occupied.

Energy-Efficient Strategies in the *Rocklin ACT^2 House*

- Redesign of building envelope to reduce wall and window areas and minimize east- and west-facing windows
- Engineered wall framing system
- Low flow showerheads and fixtures
- Light-coloured walls
- Efficient fans and motors
- Advanced windows (Low-emission facing southwest, argon-filled clear glass elsewhere)
- Insulated doors
- Water heater relocation
- Hydronic heating with condensing water heater
- Night underfloor evaporative cooling system
- Anti-convection valves
- High efficiency refrigerator clothes washer, & dishwasher
- Outdoor light motion sensor
- Parallel piping for hot water
- Built-in lighting improvements
- Water heater pressure temperature valve improvements
- Dryer heat recovery
- Portable lighting improvements
- Extra water heater tank insulation
- Slab edge insulation

Figure 2: Location of demonstration building in California

Building Description

Project Data

Location	Rocklin, California
Altitude	73 m
Year of construction	1994
Heating degr. days (18)	1,746 Kd
Cooling degr. days (18)	648 Kd
Conditioned floor area	153 m^2
Conditioned space	420 m^3
Passive cooling capacity	7 kW
Costs in US$	
• total	200,000
• efficiency measures	30,000

Figure 1: West elevation of Rocklin House

Design Concept

The ACT[2] Design/Build Team consisted of a local builder who provided the site and original house design, an architect, and an energy specialist. Starting from the original design, the energy specialist identified a number of Energy Efficiency Measures (EEMs) and worked with the architect to incorporate them into the house design. In selecting the EEMs, the energy analyst estimated the energy savings of a large number of candidate EEMs and calculated their Cost of Conserved Energy (CCE). Since many of the candidate EEMs were just emerging, approximate mature market costs, rather than current costs, were used to more realistically reflect each measure's competitiveness. To allow for uncertainties in the mature market costs, PG&E allowed the Team to consider EEMs up to 150 % of the cost of new energy supply. Following this methodology, the Team identified 28 EEMs that were implemented in the *Rocklin House* (see list on previous page).

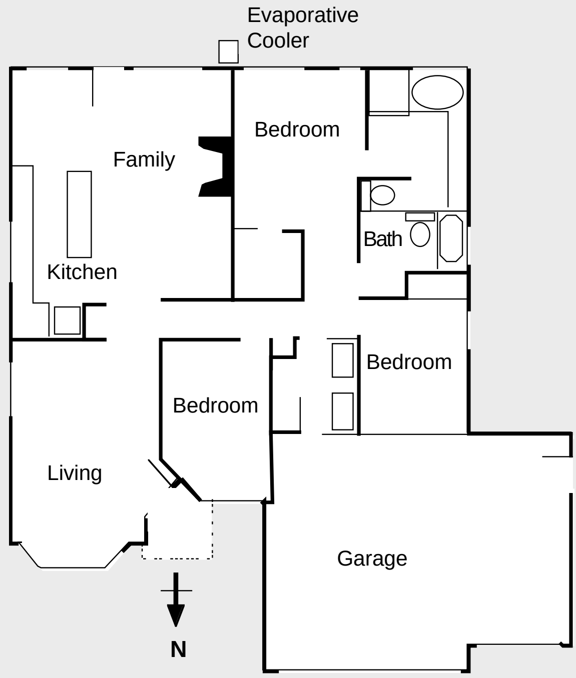


Figure 3: Plan of the ground-floor

General Energy Concept

The primary objective for the design of the *Rocklin House* was to maximize its energy efficiency, within economic constraints, by reducing the external thermal loads as much as possible, use that load reduction to reduce the size of the HVAC equipment, and install the most efficient equipment available to minimize the remaining energy use.

Demonstrated Energy Technology

The *Rocklin House* combines evaporative cooling with thermal storage and slab cooling to provide cooling to a comparatively well-built house in a climate where the peak daily temperatures often reach 40 °C. A direct evaporative cooler simultaneously provides cooled water to coils under the slab while pre-cooling the house at night. During the day, the cooled water is circulated through a fan coil unit to provide indirect evaporative cooling. If needed, the direct evaporative cooler can also be used.

Design Details

Building Layout

While the house could not be reoriented on the site, the redesign produced a building shape that minimized perimeter length and glazing area on the east and west facades. The reduced perimeter resulted in decreased exterior wall surface area, thereby reducing overall thermal gains and losses. The reduced window area, together with an improved window U-value of 2.10 W/m^{2}K, lowered the heat loss in the winter by half. To minimize unwanted summer heat gain, low-emission windows with a shading coefficient of 0.50 were used in place of double-pane windows. Furthermore, the glazing was concentrated on the south-facing wall, with overhangs to provide shading during the summer. The total window area is less than 14 % of the floor area, with only 3 % facing east or west. These strategies are estimated to reduce the space conditioning load by 18 %.

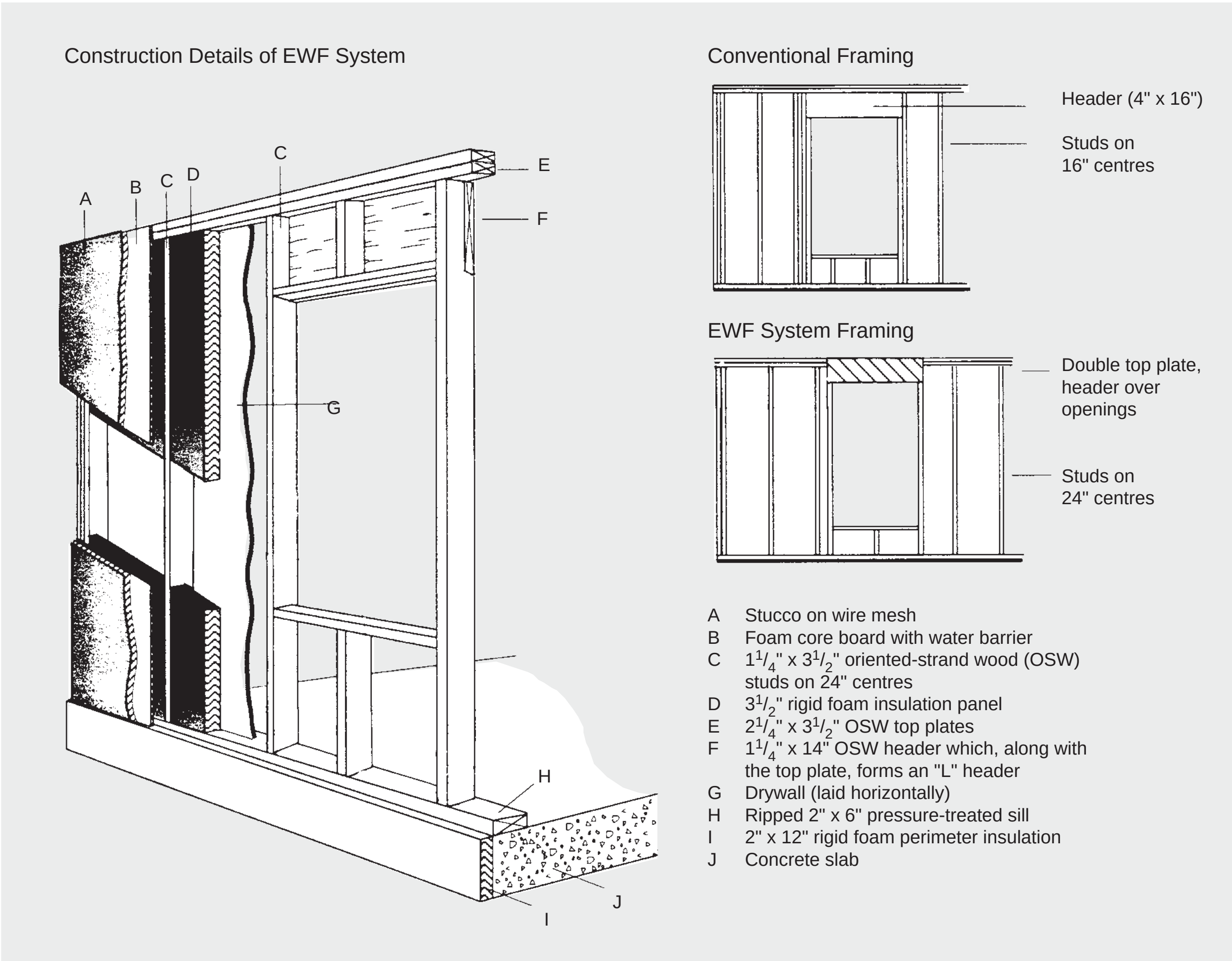


Figure 4: Engineered wall framing system (EWF)

Wall Framing

An innovative feature in the *Rocklin House* is the use of an Engineered Wall Framing (EWF) system in place of standard wood-frame construction. The EWF system wall reduces the wood content of the construction from 30 - 35 % to 9 - 10 % and increases its thermal resistance by 20 - 25 % compared to conventional wood framing.

Cooling System

The cooling system consists of a custom-designed direct evaporative cooler connected to 350 m of 5 cm diameter plastic tubing located below the floor slab.

This strategy takes advantage of the greatly increased efficiency of evaporative cooling during the off-peak hours. The direct evaporative cooler is operated at night, simultaneously pre-cooling the house and providing 15 °C chilled water to the plastic coils. Cooling the ground below the floor slab provides thermal storage at relatively low cost.

On average summer days, the radiant cooling provided by the floor slab is sufficient to maintain indoor comfort. However, during peak summer days when the thermostat calls for additional cooling, water from below the slab is pumped to a fan coil unit with a 0.76 m^3/s fan. This system was estimated to be 64 % more efficient than a conventional cooling system and reduce peak demand by 4.4 kW.

Control Strategy

The direct evaporative cooler is controlled by a time clock to operate every night during the cooling season. Because of its low energy usage, the Team did not feel there was a need for a more complex control system. However, for the night pre-cooling to work properly, the occupants need to open the windows to provide relief for the evaporatively cooled air and avoid excessive moisture build-up.

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 variable-speed fan accordingly.

Energy Strategy during the Heating Season

The heating load of the building is small enough that a single high-efficiency hot water heater can meet both space and domestic water heating demands. A condensing hot water heater was selected with a heating capacity of 29.3 kW and a recovery efficiency of 94 %. The supply air flow is 1,700 m^3/h (0.47 m^3/s).

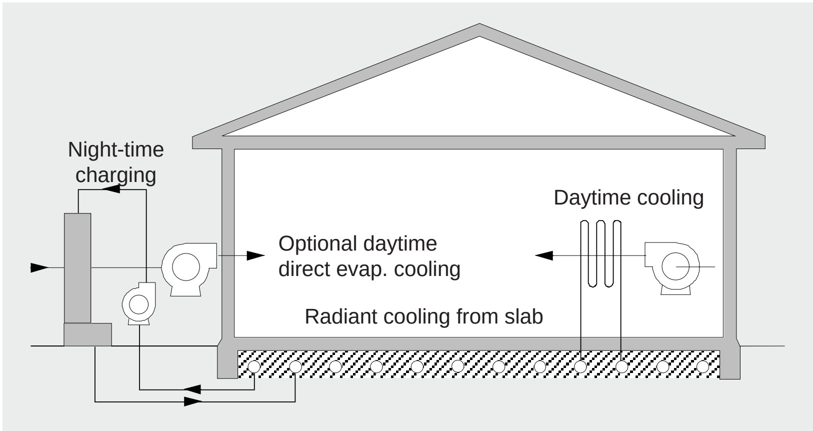


Figure 5: Schematic drawing of cooling system

Figure 6: Plastic tubing being installed

Figure 6: South elevation showing evaporative cooler

Performance Data

The *Rocklin House* was instrumented and monitored from its completion in April 1994 through 1996. From April to November 1994, data showed that indoor temperatures in the unoccupied house never exceeded 26 °C using only radiant cooling through the slab. After the house of occupied in November 1994, the *ACT²* project continued to monitor the house for through two more winters and summers.

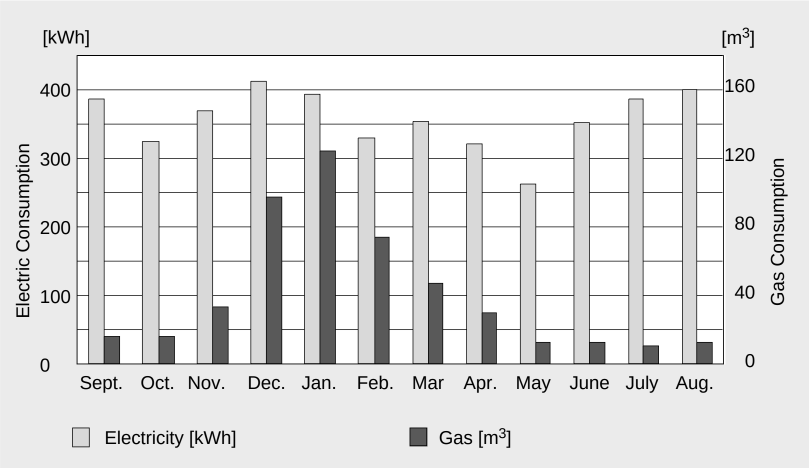


Figure 8: Measured monthly energy consumption (Sept. 1995 - Aug. 1996)

Overall Performance

For the 12 months from September 1995 through August 1996, the total energy consumption of the house was 4,293 kWh of electricity and 485 m³ of natural gas, which are both roughly half the usage of a typical house in the same area. The weather-normalized savings for all the Energy Efficiency Measures (EEMs) are estimated to be 50 % in electricity, 60 % in natural gas, and 54 % in source energy, compared to a typical new home.

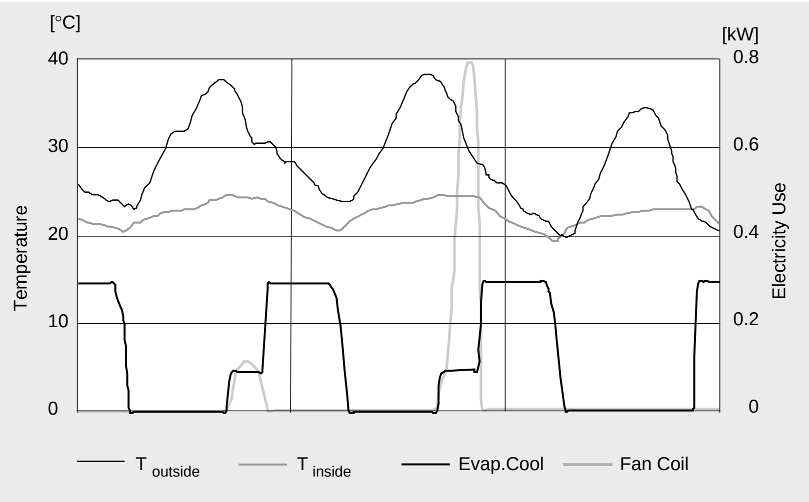


Figure 9: Hourly temperature and electricity use in late August 1995

Cooling Performance

The evaporative cooling system had some problems in the early part of the first year, but once that was traced to a malfunctioning temperature sensor and fixed, the system provided an excellent level of comfort and significant energy savings. With the thermostat set at 24.5 °C in August and September when the outdoor temperatures exceeded 40 °C for 3 days, 38 °C for 7 days, and 35 °C for 15 days, the system had a peak demand of only 0.81 kW while maintaining indoor temperatures at below 25 °C. For the two month period, the electricity consumption was 168 kWh for the evaporative cooler, and 39 kWh for the fan coil

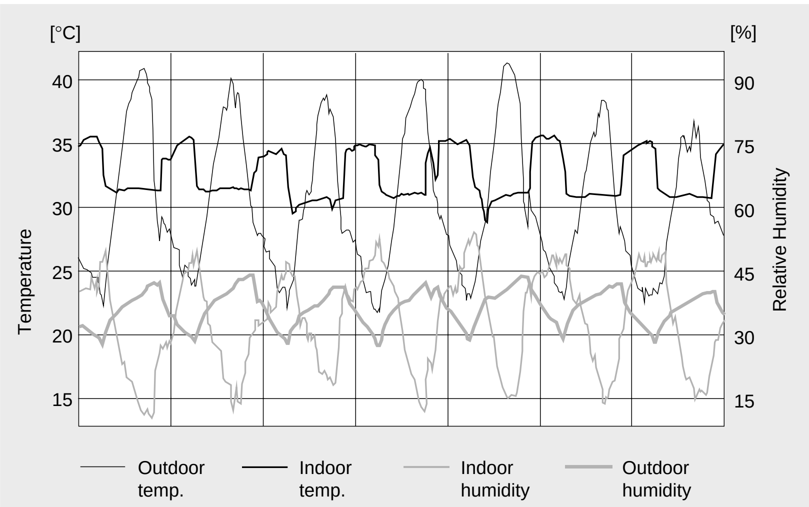


Figure 10: Hourly temperature and relative humidity in July 1996

unit. The total cooling electricity cost was $ 24.73.

It is estimated that 81 % of the cooling is delivered by the direct evaporative cooling unit, first by flushing and pre-cooling the house from 10 p.m. to 7 a.m. and then by passive cooling through the floor slab during the day. The low cooling energy use is evident in the electricity bills over a 12-month period, which show no noticeable increase for the summer months.

Heating Performance

The heating system performed up to the project's expectations. It was able to maintain indoor temperatures at 21 °C during the day and above 18 °C at night when the heating system was turned off. The average monthly heating usage over the seven month season was 34 kWh and 2.5 GJ at a cost of approximately $ 18.50. An unexpected advantage of the efficient system was the quietness of the variable speed fans, with the homeowner often unaware it was operating.

Construction and Operating Costs

In selecting the energy-efficiency measures, PG&E compared their investment costs to that for a power plant, i.e., utility discount rates and life-cycle costing were used. Since many of the candidate energy efficiency measures are just emerging, estimated mature market costs, rather than current market costs have been used to more realistically reflect each measure's competitiveness. To allow for uncertainties in the mature market costs, the designer was allowed to consider measures up to 150 % of the cost of new supply.

Following this criteria, the *ACT*^{2} design team identified 28 Energy-Efficiency Measures (EEMs) that were implemented in the *Rocklin House*. The total cost for these EEMs was US$ 30,000, which the research team estimated can be reduced to slightly over US$ 1,000 at mature market costs when the technologies are fully developed and available in the marketplace. Since PG&E assumed these incremental costs, as well as those for research and redesign, the house was sold at the same price as comparable houses in the housing development.

The engineering and design costs are difficult to estimate because of the research nature of the project, and the researchers having to work concurrently on several sites. The total PG&E expenditure for the *ACT*^{2} project covering two new and two existing single-family homes, three commercial, and one agricultural site, was US$ 15 million over 6 years, including administration, contracting, analysis, architectural and engineering design, construction and evaluation.

The cost of the installed cooling system was approximately US$ 2,790, US$ 500 for the polyethylene piping, US$ 1,750 for the evaporative cooler, and the rest for labour. The energy specialist who designed the system estimates that in a mature market the cost would be closer to US $1,500.

Summary

The *Rocklin House* demonstrated that an integrated package of Energy-Efficient Measures (EEMs) provide the opportunity for achieving whole building energy savings significantly greater than those achievable through individual measures, with measured energy savings of 85 % in cooling, 56 % in heating, and 54 % in total energy use. These savings are only slightly lower than those predicted during design (87 % cooling, 74 % heating, and 61 % total), indicating that the initial evaluation and design process was generally sound.

The *ACT²* Project relied on mature market economics and 30-year life cycle costing to justify the added expense of the Energy-Efficient Measures. In order for the mature market pricing of these EEMs to become reality, the housing industry must embrace energy efficiency and the integrated design process and be willing to absorb initially high costs until volume production is achieved. An alternative approach would be to identify or develop construction techniques and efficient technologies that can provide savings without increasing or perhaps even decreasing the total cost of the building.

The practical experience from the *Rocklin House* indicate that public acceptance of a low-energy cooling technology will be affected by many factors beyond technical performance or energy use to include convenience or even perceived future market value.

Practical Experience

The installed space conditioning system was used for two years after the house was purchased.

The owner was particularly impressed by the quietness of the heating system. Because the system used a proportional thermostat and variable speed fan, the owner heard the system running only during the brief start-up period each morning.

During the first month the owner used the cooling system, he reported the house got too humid from the night-time evaporative pre-cooling. This problem was quickly solved by shutting off the water supply to the evaporative cooler 30 minutes before shut off, allowing the fan to flush the moist air out of the house.

After two years of use, the owner was satisfied with the comfort provided by the slab and evaporative cooling system, but felt it required slightly too much effort in opening and closing windows every night. In addition, he expressed concern about the effect of the heating and cooling system on the resale value of the house. Therefore, the owner decided to ask PG&E to replace the system with a conventional gas furnace and air conditioning system, an option that was provided by the *ACT²* Project.

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[2] Pacific Gas and Electric Company 1990. Facts on ACT². Issues 1-6: October 1990, January 1991, March 1991, July 1991, September 1991, February 1992. PG&E Research and Development Dept., San Ramon CA, USA

[3] Eley Associates 1996, *ACT² Stanford Ranch Residential Site EEM Impact Analysis*, PG&E Research and Development Dept., San Ramon CA, USA

[4] Phillip Hasley, "Cooling by the Stars", in Home Energy, May/June 1996, Vol. 13, No. 3, p. 7

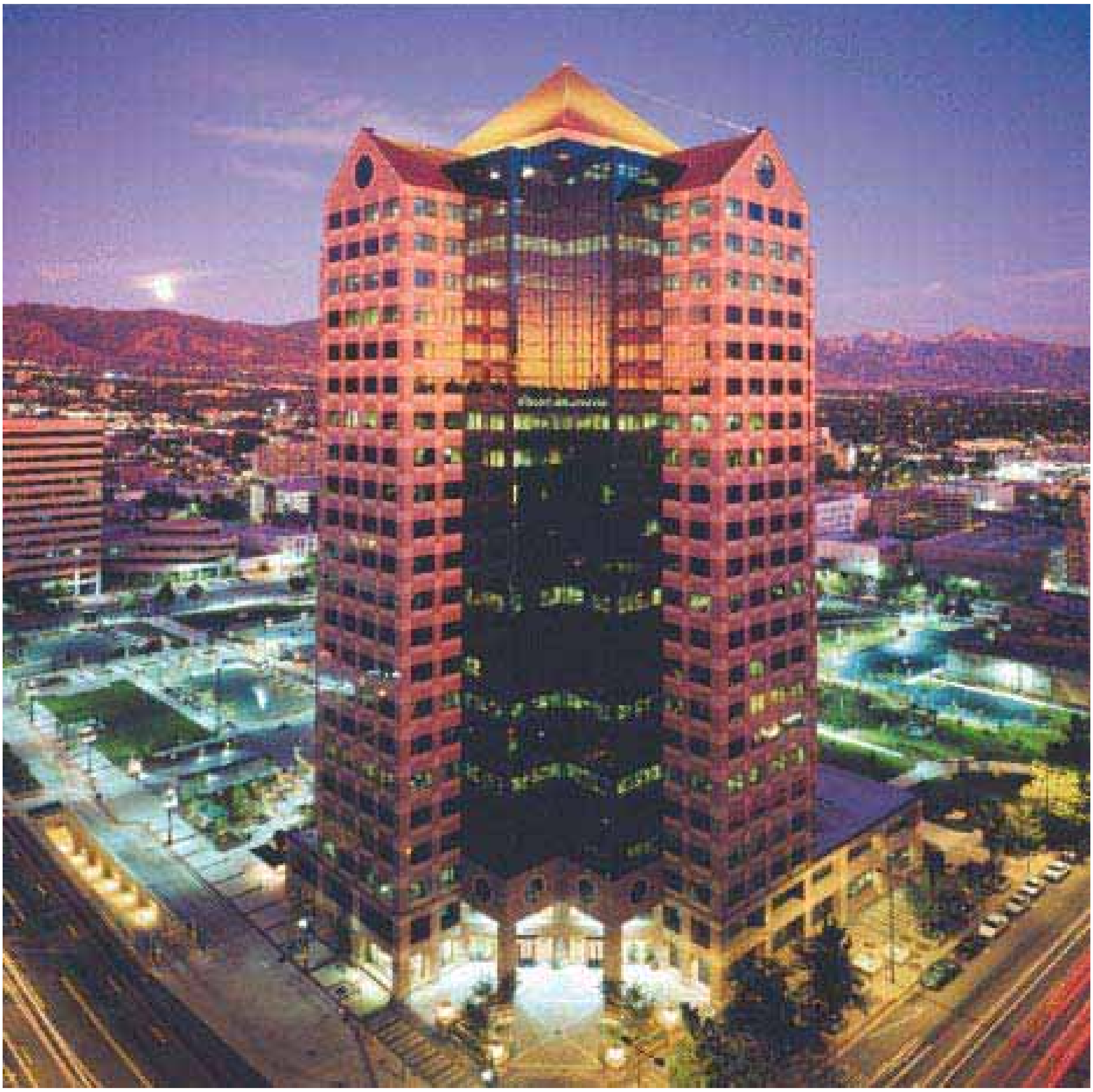
The *One Utah Center* Building Salt Lake City, USA

Evaporative Cooling System

Engineer: Tom Colvin,
Colvin Engineering
Reporter: Joe Huang

Date: August 1998

- 100 % outside air
- 3-stage indirect, chiller, and direct evaporative cooling system
- Identical supply air conditions as for conventional systems
- Improved indoor air quality
- Heat recovery in winter



Background

Architecturally, *One Utah Centre* is a fairly standard 24-storey, 38,925 m^2 office tower commercial office building with energy-use characteristics similar to those of other large office buildings in the region. In the design of the mechanical system, however, the engineer took advantage of the dry summer conditions in Utah to install an innovative cooling system that uses direct and indirect evaporative cooling to meet most of the cooling load, and a downsized chiller to meet the remaining load when the wet-bulb temperatures are too high. This design maintains indoor conditions identical to those from a conventional air-conditioning system, but provides improved indoor air quality through filtered 100 % outside air, and significant energy savings by reducing the full-load hours of the chiller to 30 % of that of a conventional system.

Introduction

Salt Lake City is located in a fertile valley between the Wasatch Mountains and the Great Salt Lake Desert. The summers are moderately short, hot, and very dry, with a 1% design dry-bulb temperature of 35 °C at only 15 % relative humidity. Even at the 1% design wet-bulb condition, the relative humidity is still only 35 %. These climate conditions are very well suited for the use of evaporative cooling, which can often cool the air to below 15 °C.

Despite these favourable conditions, the standard design practice in Salt Lake City, as elsewhere in the U.S., is to rely on mechanical cooling, with the cooling tower used only for heat rejection. The *One Utah Center* cooling system represents a different design solution that uses the cooling tower and a direct evaporative system as primary cooling devices, while the chiller is used to provide only the additional cooling when the wet-bulb temperatures are too high or the cooling loads too large to be met by the evaporative cooling system.

Building Description

Project Data

Location	Salt Lake City, Utah
Altitude	1,768 m
Year of construction	1991
Heating degr. days (18)	3,409 Kd
Cooling degr. days (18)	550 Kd
Number of floors	24
Conditioned floor area	38,925 m^2
Conditioned space	148,000 m^3
Inst. cooling capacity (2 chillers)	2,816 kW
Costs in US$ (1991)	
• evap. system	0.18 million
• total mech. system	5.3 million

Figure 1: Location of demonstration building in Utah

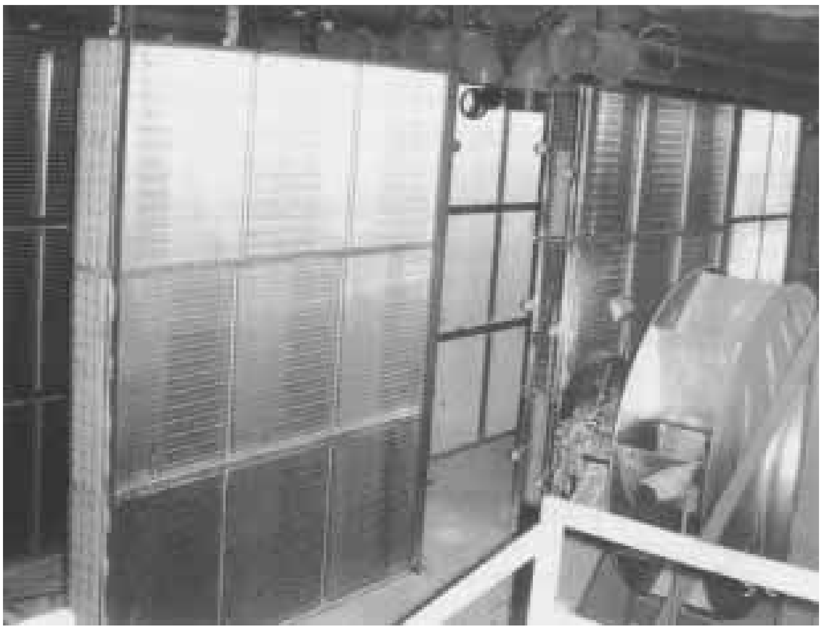


Figure 2: One of four plug fans and coil bank during installation

Design Concept

General Energy Concept

Indoor air quality and energy efficiency were the primary objectives during the design phase for the mechanical systems of the *One Utah Center*. Maximizing the use of evaporative cooling achieves both objectives, since the system can provide filtered 100 % outside air, while consuming much less electricity than a conventional refrigeration system.

Cooling Strategy

The basic cooling strategy is a three-staged system consisting of an indirect evaporative cooler, conventional chilled water coils, and finally a direct evaporative cooler. Putting the chilled water coils before the direct evaporative cooler allows the chiller to provide only sensible cooling without “fighting” against the humidity added by the direct evaporative cooler. In effect, the chiller becomes a supplemental sensible cooling device that is used only when the wet-bulb temperatures are too high or the cooling loads to large for the evaporative coolers to handle. On an annual basis, the evaporative coolers furnish over 80 % of the building’s cooling requirements without the use of mechanical refrigeration.

The indirect evaporative cooling coils are supplied by four two-speed cooling towers that are also used to cool the condenser water. However, compared to the cooling towers found in conventional air-conditioning systems, these cooling towers are twice as large, and designed for 3 - 5 K colder water temperatures.

The direct evaporative cooling system uses standard rigid cellulose media, with an added bypass damper to prevent overcooling the supply air on moderate warm days.

The two chiller, one at 880 kW and the other at 1,936 kW, are used on the few days when the outdoor wet-bulb temperature reaches 20 °C or more. Because of the presence of the evaporative cooling system, the chiller capacity of the building is only 60 % of that for a typically designed air-conditioning system.

The variable-air-volume air handling system consists of four plug fans supplying a maximum of 50 m^3/h (179,400 l/s) of air; two vane-axial relief fans in the basement, and two more at the top of the building.

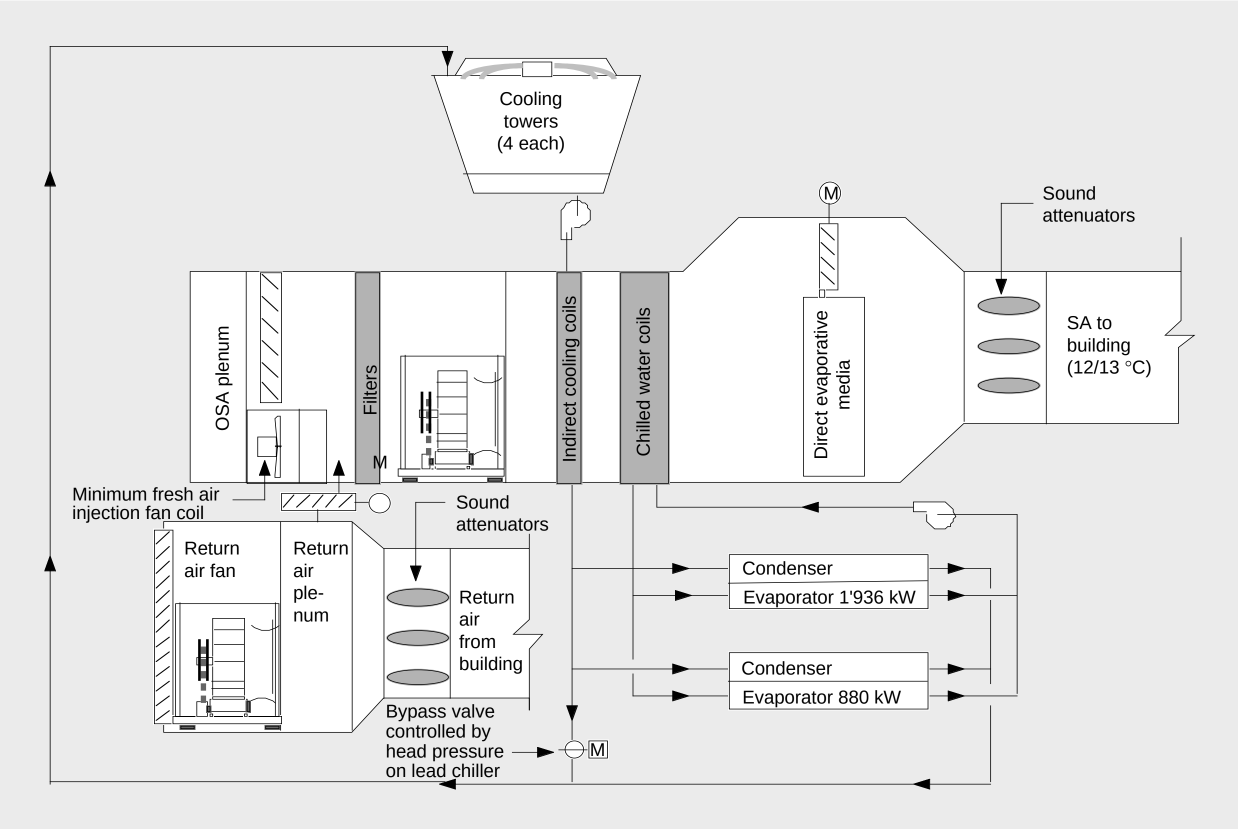


Figure 3: General system configuration

Design Details

Control Strategy

The air-handling system is operated to provide 100 % outside air to the building whenever the outside temperature is above 12 °C. The outdoor air is first indirect evaporatively cooled by coils from the cooling tower. If needed, mechanical cooling is utilized to bring the discharge wet-bulb temperature to 12 °C. Direct evaporative cooling is then used to adiabatically 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 two figures below show the psychrometric processes under design dry-bulb and wet-bulb temperatures. In the former condition, the air is hot but very dry, with evaporative cooling meeting 78 % and the chiller only 22 % of the cooling load. Under design wet-bulb conditions, however, evaporative cooling is less effective and 50 % of the cooling load is met by the chiller. The direct evaporative cooler is not turned on at all.

The indirect evaporative cooling stage circulates condenser water from oversized cooling towers through cleanable 6-row cooling coils to sensibly cool the 100 % outside air to within 4 K of the outdoor wet bulb temperature.

With leaving air from the condenser water coils at 21/12 °C on a design day, the air is then evaporatively cooled using a 305 mm deep rigid media and leaves the media at 13/12 °C without the need for chiller operation.

On the few days when the wet bulb temperature reaches 20 °C, the chiller is required to lower the temperature of the supply air a few degrees before it enters the direct evaporative media. Since the evaporative cooling system can meet the building's cooling loads most of the time, the chillers are not needed except during July and August for a few hours per day. This will substantially extend the life of the chillers and reduce annual chiller maintenance requirements.

The cooling tower sumps and the evaporative media sumps are all equipped with sidestream centrifugal solids separators to remove dirt from the sump water. This reduces the need for routine sump cleaning, maintains a high clarity in the water and continuously removes the food source for any microbial organisms.

Lastly, the building also has a thermal storage system that can be used during either the winter or summer to pre-heat or pre-cool the water and avoid using electricity during peak conditions. The thermal storage system consists of three 88 m^3 thermal storage tanks used for both heating and cooling. The two figures on the next page show the flow control of the thermal storage system in the summer during occupied and unoccupied hours.

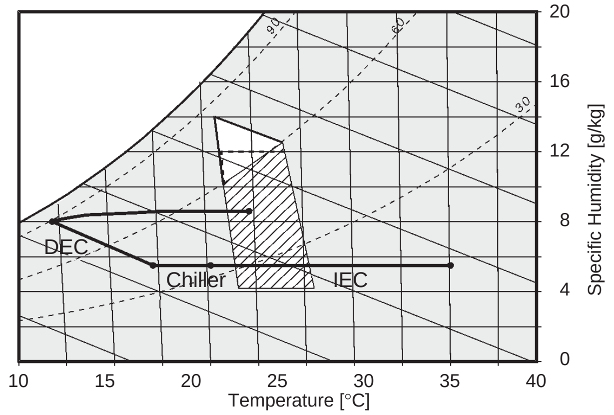


Figure 4: Psychrometric process at design dry-bulb condition

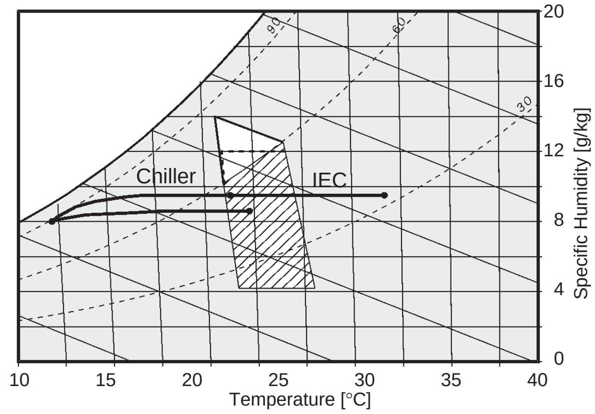


Figure 5: Psychrometric process at design wet-bulb condition

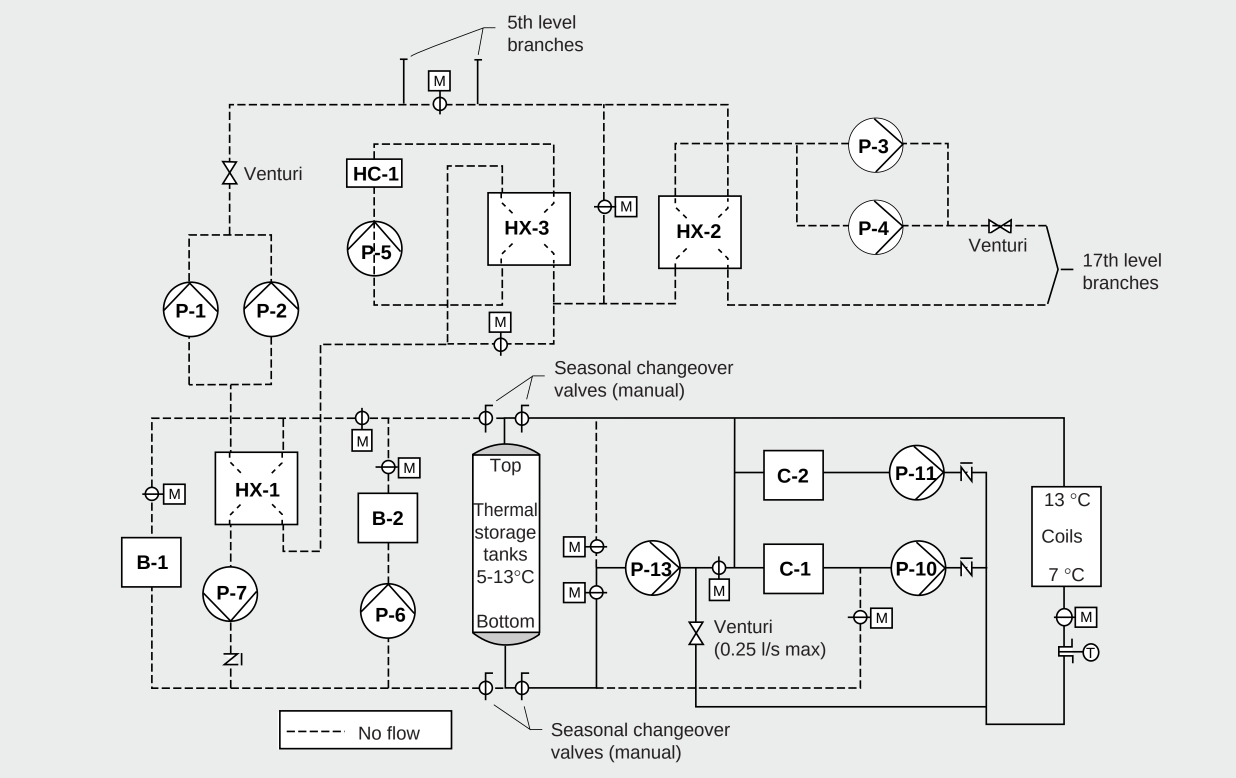


Figure 6: Flow schematic for summer occupied hours

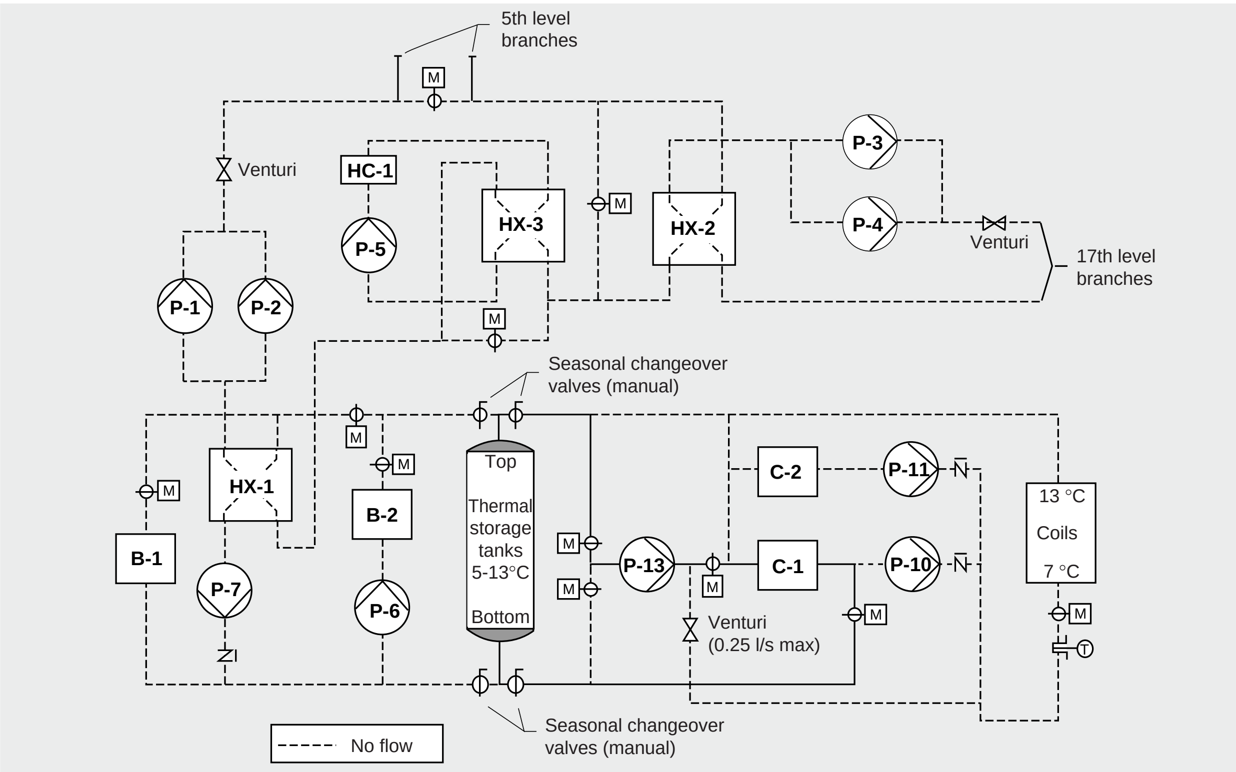


Figure 7: Flow schematic for summer unoccupied hours

Other Benefits

The direct evaporative media serves as an excellent air washer and removes microscopic pollen and dust that would otherwise be circulated with the supply air. For this reason, the indoor air contaminants measured by an independent testing agency during the summer of 1993 were significantly lower than the norm for commercial office buildings.

The building also has a fresh air injection fan/coil system that operates at a fixed volume during all occupied hours. This system has a glycol heating coil controlled by the temperature in the mixed air plenum. The injection fan speed is set to provide a minimum of 9 L/s per person for a fully occupied building. The cooling towers for the *One Utah Center* are located within the adjacent 1,000-car underground parking garage. As an additional energy conservation measure, the cooling tower enclosures were designed to provide garage ventilation for all three parking levels as a part of normal tower operation.

Energy Strategy during the Heating Season

The heating system in the *One Utah Center* gives the building owner the option of operating either gas or electric boilers, and to use the thermal storage system to minimize utility costs.

The thermal storage system utilizes hot water with a 55 °C temperature drop. When the electric boilers are used, the storage tanks are heated to 94 °C during off-peak hours (11 pm to 7 am) without incurring demand charges and provide heating water for the following day.

By avoiding demand charges, the annual cost premium for the use of the electric boilers is only about $ 16,000, or less than $ 0.40 per m^2. The electric boiler availability allows the building owner the option of selecting interruptible gas service with no danger of loss of heat, while providing long-term fuel source flexibility as local gas and electric rates fluctuate.

Performance Data

Because the *One Utah Center* is a privately-owned commercial office building, there has been no effort made to gather detailed monitored data on the energy use or performance of the HVAC system. However, the overall energy performance of the building and the innovative cooling system can be estimated from utility bill data and the engineer's records of the chiller run times.

In 1993, when the building was at 75 % occupancy, the chiller was not started until July, and the total run time was less than 100 hours on the smaller chiller only. During 1994, a record hot summer for Salt Lake City, the maximum chiller load did not exceed 1,478 kW while outdoor temperatures reached 41 °C on several days. The chiller ran a total of 250 hours, although there were several days when the outside temperature exceeded 38 °C and the supply air temperature was maintained below 12 °C without the chillers. For the six years since the building has been fully occupied, the engineer reports that the chiller operating hours (not full-load operating hours) averaged 450, compared to 1,500 hours for a typical mechanical cooling system in a commercial office building in the same area.

The utility expenses (electric, gas, water) for the *One Utah Center* for 1993 were $ 11.73 per m^2. This amount is on average $ 5.00 per m^2 lower than that of typical modern office buildings in the Salt Lake City area. It relates to an annual savings of $ 109,000 to $ 323,000 for the *One Utah Center*. Figure 8 compares the total energy use in 1993 for the *One Utah Center* (in dark-grey) to that of six other offices in Salt Lake City.

Compared to a nearby office building of the same size, the electricity use intensity (kWh/m²) for the *One Utah Center* is lower by roughly a third (see Figure 9).

Figure 10 shows the estimated monthly electricity in 1994 used by the cooling tower in *One Utah Center*. From this information, the engineer estimates that the total annual electricity for the cooling tower and pumps is 5.98 kWh/m² per year.

The engineer estimates that the annual savings from the evaporative cooling system due to reduced chiller operation is $ 51,000 even in Salt Lake City which has an unusually low electricity rate of $ 0.03/kWh. Compared to the higher initial cost of this system, this annual savings rate translates to a payback period of less than four years.

Construction and Operating Costs

The overall construction cost for the building mechanical systems including the thermal storage, indirect/direct evaporative cooling and fully finished tenant spaces was approximately $ 137 per m² in 1991 dollars.

The added cost for the indirect/direct evaporative cooling system, larger cooling towers, and thermal storage system is estimated by the contractor as $ 160,000. The engineer notes that this amount does not include the savings from downsized chiller, so that the actual cost increase may be substantially less. Based on his later experience in other buildings, the engineer feels the payback period for such a cooling system should vary from 3 - 4 years for a 25,000 l/s system to less than 2 years for a 50,000 l/s or larger system.

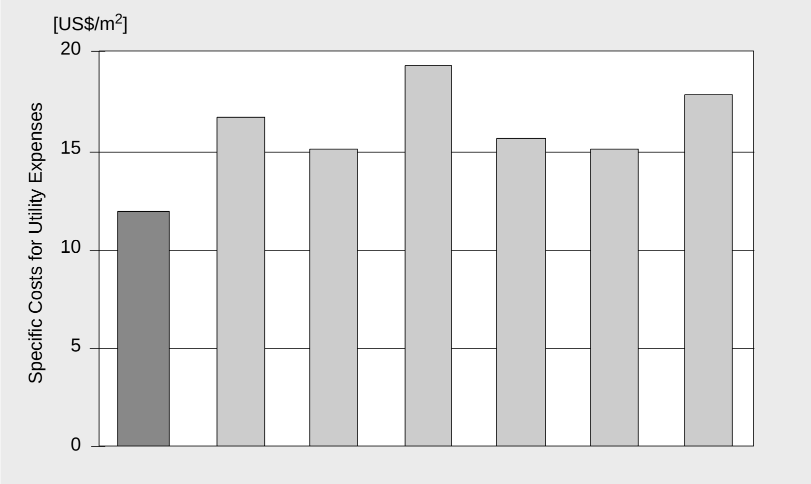


Figure 8: Office building energy use comparison (1993) of the One Utah Center (dark grey) and six typical modern office buildings in the Salt Lake City area

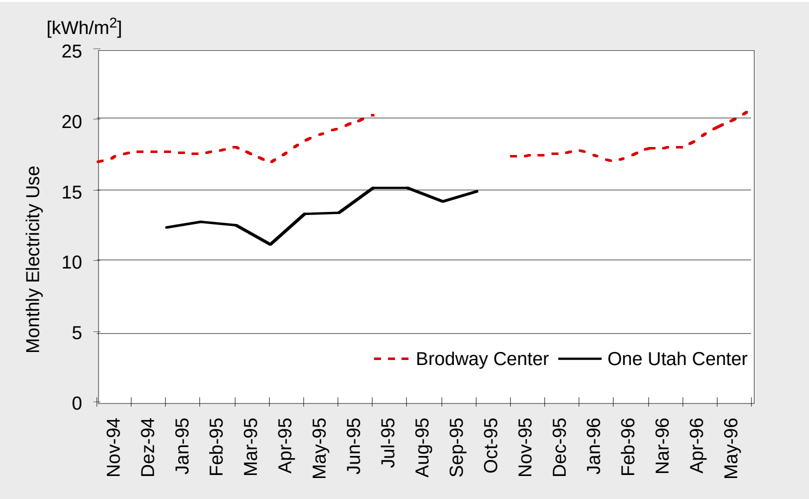


Figure 9: Comparison of electricity use intensity (kWh/m²) of One Utah Center to a nearby office building

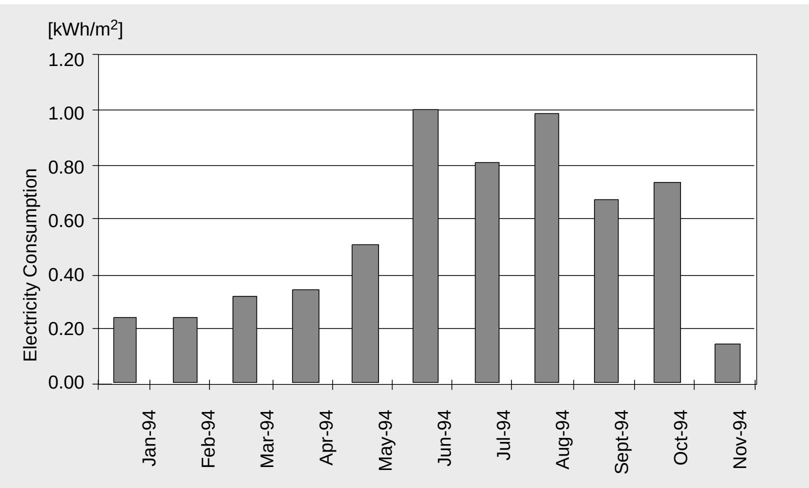


Figure 10: Estimated monthly cooling tower electricity use

Summary

An analysis of make-up air requirements and annual operating hours versus outdoor wet bulb temperature data can show a viable payback period for this system in many locations and applications. Because the system uses 100 % outside air during all cooling hours, buildings requiring large amounts of make-up air have experienced exceptionally low power costs.

The two-stage evaporative/chilled water system demonstrated here provides improved indoor air quality and economical cooling even in areas with low power costs.

References

[1] T. D. Colvin, 1995. ”Office Tower Reduces Operating Costs with Two-Stage Evaporative Cooling System”, *ASHRAE Journal*, March 1996, pp. 23-24, American Society of Heating, Refrigeration, and Air-conditioning Engineers, Atlanta GA

[2] Private communications with T.D. Colvin by J. Huang, 1995-1996. 1996

Practical Experience

After seven years of operation, the mechanical engineer reported the system had been operating satisfactorily, with no major problems. The biggest challenge in the initial control of the system was the poor operation of the chiller on start-up due to the unusually low temperature of water supplied by the oversized cooling towers. This problem was solved by adding a bypass valve to recirculate the condenser water on start-up and thus moderate its temperature.

The bypass air damper on the direct evaporative cooler was found to be only partially effective at low air flow rates because the supply static through the media was so low that an additional face damper would be needed. In later designs, the engineer found a more effective way to control the amount of direct evaporative cooling by resetting the water temperature from the cooling tower through use of variable-speed fans.

Another modification in later designs was to eliminate the centrifugal solids separators for removing dirt from the sump water, and instead automatically drain and refill the sump water at the end of every day. Although the solids separators worked well at the One Utah Building, they did present maintenance problems at other smaller installations, so the engineer felt the modified design eliminated a potential problem, albeit at the cost of increased water consumption.

The *Industry Division Office* Gaz de France Research Centre, Paris, France

Indirect Evaporative Cooling

Architect: Cabinet JPM,
Jean-Paul Marielle
Energy design: Gaz de France
Engineer: Cabinet BFD,
Victor Fedkiv
Reporter: Pierre Picard

Date: August 1998

- Natural gas heating system with hot water radiators
- Balanced ventilation with air-to-air heat exchanger
- Forced mechanical night cooling in summer
- Indirect evaporative cooling
- Year round comfort at low operating and maintenance costs

Background

The design of this building is a trade-off between energy-efficiency for heating, summer comfort and investment cost constraints.

Introduction

Since the beginning of the 80's, *Gaz de France* favoured the development of energy-efficient systems for the heating of commercial buildings, such as condensing boilers, balanced-ventilation with heat recovery, and optimal controllers. In the meantime, a stricter energy legislation induced tighter building envelopes. As internal loads were rising due to the development of office automation systems, some new buildings proved uncomfortable in the summer. A co-sponsored research project was conducted with the *CSTB (Centre Scientifique et Technique du Bâtiment)* to favour the design of balanced ventilation systems, in order to improve summer comfort in office buildings, without using a chiller [1].

First, an extensive sensitivity analysis was performed using thermal modelling and the thresholds of minimum air flow rates necessary to ensure summer comfort were tabulated for various design parameters such as the climate zone, load levels, glazing ratio, humidifier and heat exchanger efficiencies. Then, indirect evaporative components were tested at a *Gaz de France* research building. Finally, they were installed and monitored. The demonstration showed that a 4 ACH flow rate should be sufficient to maintain summer comfort in a low-load building in the temperate zones of France. This basic design was adopted for a new office building being planned on the site of *Gaz de France* research centre in Saint-Denis, on the northern outskirts of Paris, France.

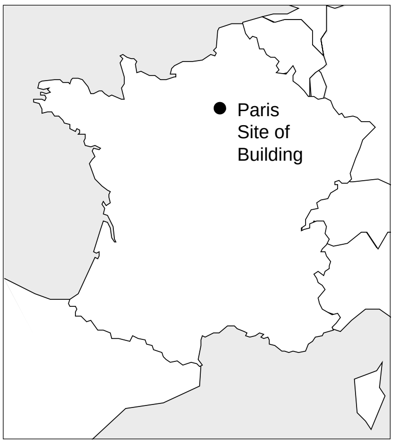


Figure 1: Location of demonstration building near Paris

Building Description

The *Industry Division* building consists of a 2-storey part with offices and laboratories, and a large hallway for experiments and testing of prototypes. This open area is equipped with infrared radiant heaters; ventilation when necessary is provided by opening doors and skylights.

Project Data	
Location	Saint-Denis/Paris
Altitude	70 m
Year of construction	1991/1992
Number of offices and labs	40
Number of working spaces	35
Cooling degree days (18)	144Kd
Heat. degr. days (20/12)	2,600 Kd
Heated floor area	1,000 m^2
Heated space	3,000 m^3
Inst. heating capacity	80 kW

Building Layout

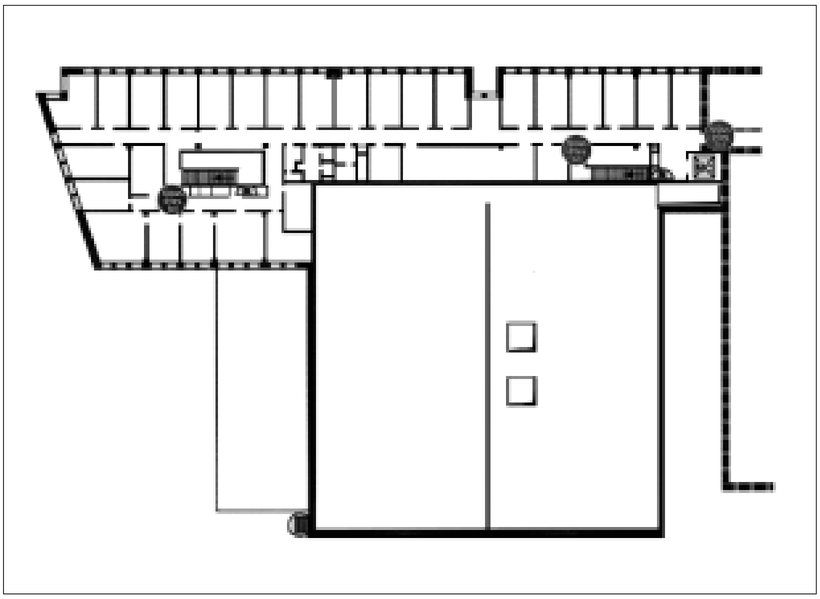


Figure 2: The "GDF Industry Division" office building is adjacent to a hallway used for experimental work.

Design Concept

General Energy Concept

The building envelope thermal characteristics have been chosen to comply with the 1988 French energy legislation levels: overall heat loss coefficient «G» is 0.7 W/m^{3}K.

The glazing area is about 25 % of the façade surface. Internal shades are provided on each window, although most of them face north. A large stairway with a roof clerestory provides daylight into the corridors.

Maximum internal load due to lighting and equipment was estimated at 20 W/m^2. The total daily load on a warm day was estimated at 250 Wh/m^{2}day.

The heating for each office is provided by a hot-water radiator located under the windows and equipped with a thermostatic valve that is connected to a hydronic network designed to operate at 80/60 °C for a temperature of -7 °C. The hot water is heated by a natural gas furnace.

The air is supplied to the rooms via registers located above the corridor door, and exhausted at one of the room corners. The ducts of the balanced ventilation system are connected to an air handling unit located at the basement. The air handling unit comprises an air-to-air plate heat exchanger, a heating coil, two-speed fans, high-efficiency air filters and a wetted-pad humidifier on the exhaust air side.

The nominal air flow of the air handling unit is 12,000 m^3/h (3.3 m^3/s) .

Demonstrated Energy Technology

This building provided an opportunity to further test indirect evaporative cooling in the French climate. The gas heating system coupled with balanced ventilation was already well known for its energy performance, low costs and high indoor air quality. This installation was also designed to enforce night cooling and indirect evaporative cooling when necessary. The control strategy is implemented in a building energy management system (BEMS).

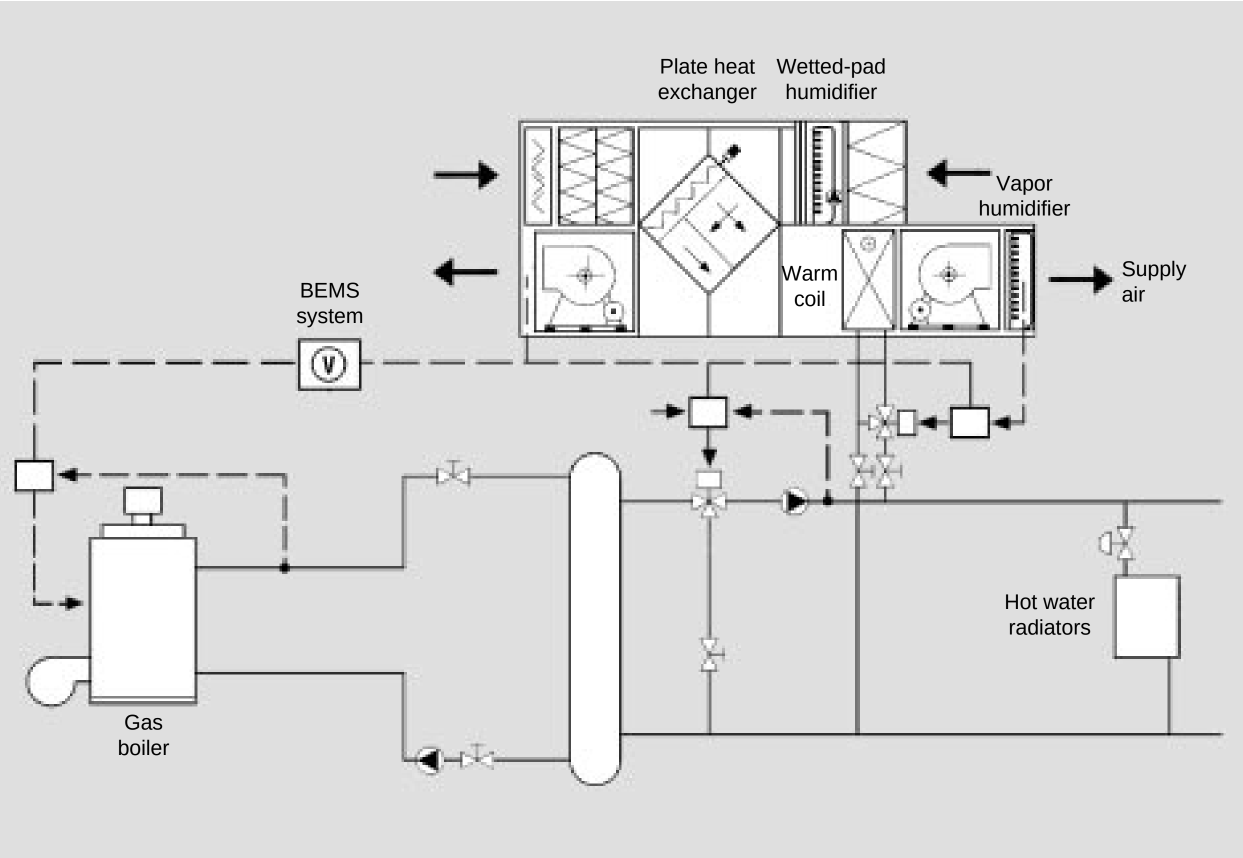


Figure 3: Schematic of the system

Design Details

Ventilation Strategy

In winter, the radiators provide the base for the heating load in each office. This is complemented by tempered ventilation supplied at 2 ACH and 20 °C. In the air handling unit, air is preheated in the heat recovery unit with a 55 % effectiveness, and its temperature is controlled by a 2-way valve throttling the flow rate in the warm coil. A separate steam humidifier maintains the indoor humidity above a minimum of 30 % r.h. in the building. Heating and ventilation are stopped when the building is unoccupied. The balanced ventilation system permits a shorter start-up period as warm air is mixed into the building.

During the change-over seasons, heating is first stopped on a high outside temperature limit. Ventilation at full speed (4 ACH) or indirect evaporative cooling are allowed on two higher limits.

In summer time, the aforementioned strategy is complemented by forced night cooling when the outside temperature is lower than that indoors.

Control Strategy

The control strategy is implemented in the BEMS local controller as four modes of operation: winter/summer, occupied/unoccupied. The temperature inside the building is measured in two rooms located on the north and the south sides. Sensors in and around the air handling unit measure the characteristics of the outdoor, supply and exhaust air.

When direct outside ventilation is mandated, louvres are controlled to bypass the plate heat exchanger. This component is bulkier than a rotary heat exchanger but it ensures total separation of the fresh and exhaust air streams.

The control of the indirect evaporative cooling stage is based on the comparison between the outside air temperature and a fictitious return temperature assuming the humidifier is turned on. This fictitious temperature is calculated from the temperature and humidity of the exhaust air and the humidifying effectiveness of the wetted pads. As soon as the "humidified air" temperature is lower than the outside air temperature, the pump is turned on. A 2-hour operation is then enforced to take into account the hygroscopic inertia of the media.

Each night, the tank of the humidifier is emptied by opening of a bypass valve to avoid accumulation of salt, dust and other materials. Sensors on the filters also indicate any clogging.

Performance Data

Overall Performance

The overall performance of the installation was judged satisfactory as it provided a good comfort and indoor air quality during the heating season, as well as an improved summer comfort.

Cooling Performance

Analysis of the data collected with the BEMS permitted the detection of several flaws in the system:

- the need for a louvre to cover the plate heat exchanger when bypassed to avoid parasitic heat recovery,
- insufficient wetting of the media at times due to clogging in the spaying ramp of the humidifier,
- a subnominal supply flow rate due to underestimating the head losses in the ducts,
- bad sensor positioning making it difficult to take accurate measurements in the air flow,
- a bug in the algorithm for the dead-band controllers. A subsequent period was necessary to fine tune the various temperature thresholds.

During a warm period, the system operates almost continuously with day and night indirect evaporative cooling (Figure 5). The exhaust air temperature of the building is lowered from 27 °C to 19 °C, while the fresh air temperature is reduced 4 K at peak time (16:00). The temperature rise over the fan is estimated to be 2 K at high speed.

The limits of the system were reached during the very warm summer of 1995. The maximum indoor temperature increased regularly over a five-day warm spell, at a pace of more than 1 K per day. The night-time temperatures did not drop low enough for a discharge of the absorbed energy in the building structure.

The overall performance of the building was hampered by insufficient solar protection on the south-façade and on the clerestory windows.

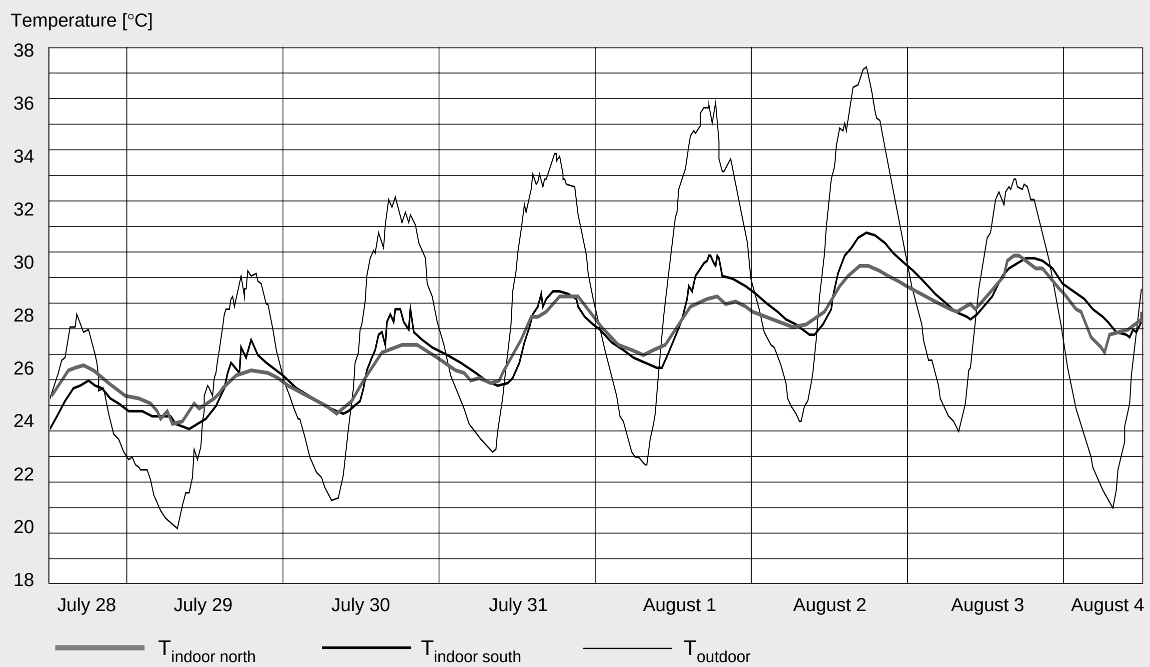


Figure 5: Indoor temperature profiles under a warm spell (August 1995)

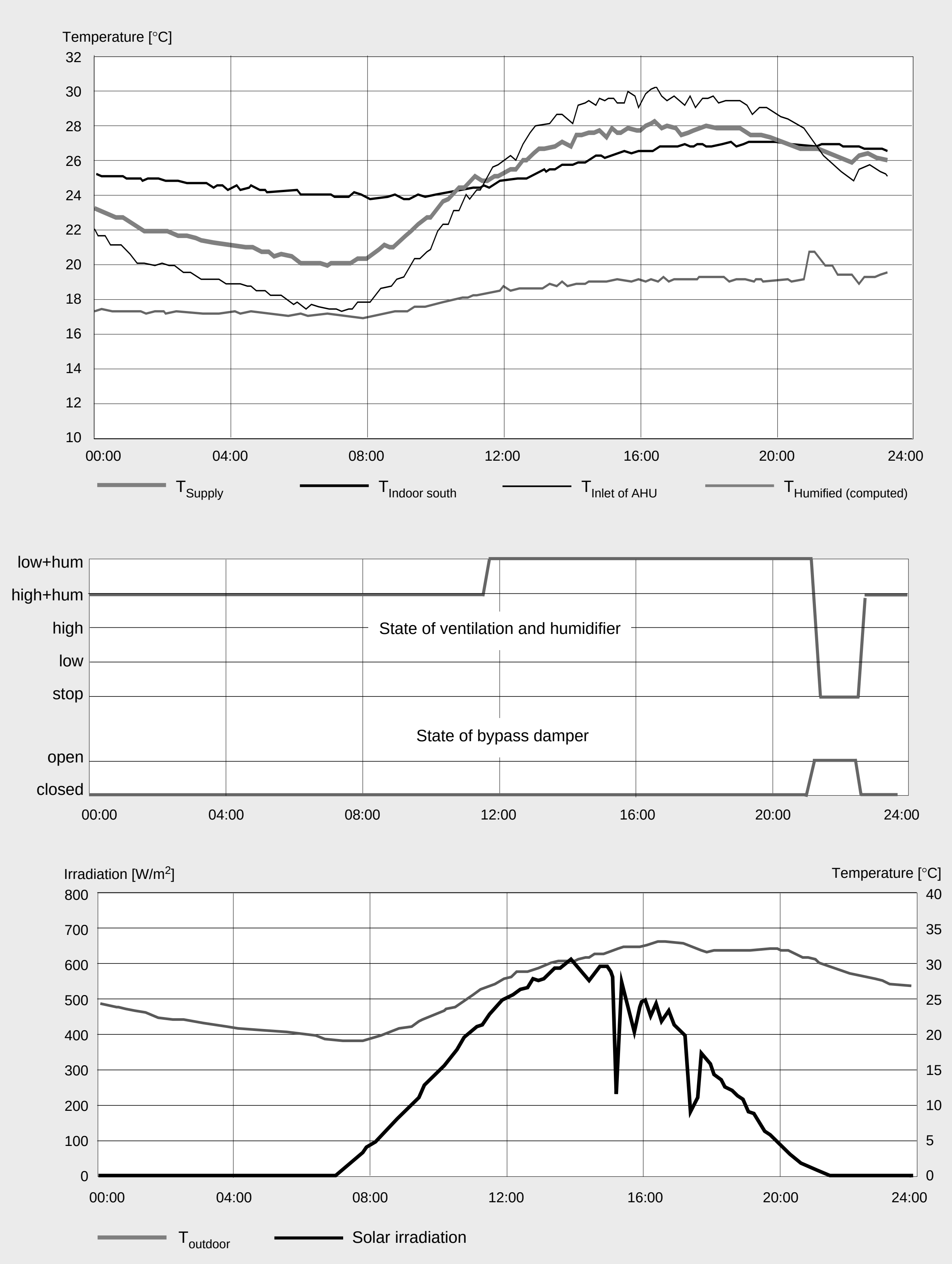


Figure 4: Temperature profiles, component states and climate on a typical warm day (August 11)

Construction and Operating Costs

The initial cost of the installation was estimated at 100 ECU/m^2, of which 25 ECU/m^2 were due to the balanced ventilation system and the improved air handling unit (when compared to single-flux ventilation). The designer felt the 4 ACH flow rate was the maximum upper limit for the integration of a low-velocity duct system without major changes to the building structure.

The annual operating cost for the heating system was measured at 5 ECU/m^2, of which 20 % was fan electricity. The summer operating costs were measured at 0,5 ECU/m^2, of which 85 % was electricity (at a consumption rate of 11 kWh/m^2) and 15 % was water (at a consumption rate of 20 l/m^2).

Maintenance costs were low, although it was not possible to isolate the overhead cost of the indirect evaporative system on this site as it was included in a large contract. It was suggested that one man-day is required to clean the humidifier tank and the nozzles once a year. This cost would increase in case water treatment was necessary to avoid scaling. Air filter costs depend on the filter type and class and on the air pollution at the site.

Summary

The monitoring of the building performance over several seasons showed the advantages of balanced ventilation and indirect evaporative cooling for a building with a low cooling load. One very warm summer spell allowed the system to be tested at its limits. As it might be difficult to predict the exact performance of such systems by modelling, it is recommended that indirect evaporative cooling be considered as a first stage before air-conditioning. In this case, an empty section was left in the air-handling unit for a cooling coil to be connected later to a chiller. Its capacity will be reduced at least by 30 %, therefore reducing either the use of HCFC in a conventional chiller or the overhead initial cost of a gas-fired absorption chiller

Practical Experiences

When considering indirect evaporative cooling and forced mechanical ventilation, the designer should first deal with the integration of the ducts into the building structure. Then, it is recommended to make an accurate calculation of the effective head losses of the network to properly size the fans (flow rate, acoustics, temperature rise).

Future French air quality regulations might forbid rotary heat exchangers although their efficiency is much higher than those of plate heat exchangers (80 vs 55 %). Similarly, fire regulations might forbid plastic wet-plate heat exchangers, although they combine the two main components into one (reducing size).

The requirements for water treatment has to be assessed. If necessary, it might be combined with other usages as the indirect system has a low consumption.

Information on the cooling system should be provided to the occupants that it is indeed a low-grade air conditioning system and that overheating might thus occur. There should also be restrictions on the amount of window openings to avoid uncontrolled air entry into the building.

In terms of economics, a sensitivity analysis based on the French database showed that the air flow of 12,000 m^3/h (3.3 m^3/s) was a lower limit to get an acceptable pay-back time when compared to direct cooling with a water chiller.

Reference

[1] Pierre PICARD, Jean-Robert MILLET, « Evaporative Cooling », FBF Seminar on Innovative Cooling Systems, Birmingham, May 1993, IEA.

The *InfraCity* Commercial Centre Stockholm, Sweden

Desiccant Cooling

Architect: Interplan AB
Energy design: PQR Consult
Engineer: Jan Wikmar
Reporter: Johnny Andersson

Date: August 1998

- Desiccant cooling used for providing a renovated office building with comfort cooling
- System provides building with high outside air flow, no return air needed for economical reasons
- Simple integration in ventilation system
- High peak load performance
- Low operating costs
- Environmental friendly system without refrigerants

Background

Only a small portion of the Swedish office buildings up to the mid 1970's were equipped with comfort cooling. Increased thermal insulation and tightening of buildings was a result of the energy saving retrofit methods prescribed after the first oil crisis of 1972/73 to ensure a reduced energy use in winter time. This however, together with an increased use of computers and other heat releasing office equipment has often lead to unacceptable high indoor temperatures in summer.

Many of these, now 20 to 30 year old office buildings, have today to be renovated. In the mean time the ban on older type of refrigerants used in mechanical refrigerating systems and discussions about the ozone layer and the green house effect have opened up the need for new alternatives to provide comfort cooling.

Desiccant cooling, in combination with evaporative cooling, is one of these interesting alternatives to conventional mechanical cooling that has been used in the renovation of an office building north of Stockholm.

Project Data

Location:	Upplands Väsby
Year of construction:	1972 (renovated 1994)
Number of office rooms:	250
Heat. degr. days (20/12):	5,480 Kd
Cool. degree days (18):	42 Kd
Heated floor area:	7,000 m^2
Heated space:	18,900 m^3
Installed heating capacity:	
• summer	300 kW
• winter	70 kW
Cooling capacity:	
• design (25 °C/10 g/kg)	130 kW
• achieved (34 °C/11g/kg)	130 kW
Cost in MSEK (MUS$)	3.5 (0.6)

Figure 1: Location of InfraCity, 30 km north of Stockholm

The Building

InfraCity, situated 30 km north of Stockholm, is Sweden's largest group of commercial real estate. The area comprises of twelve buildings with a total floor area of 190,000 m^2 of offices, hotel and shops.

The management of *InfraCity* has the policy of providing the area with an environmental profile. In one of the office buildings, built in the late 1960`s without any comfort cooling, the tenants had been complaining for many years about the high room temperatures in summertime. As the air handling unit had to be replaced anyway in order to improve the heat recovery efficiency, this created an opportunity to comply with the request of the tenants. The owner of the building therefore decided to add comfort cooling to the air handling unit but keeping the ducts for the ventilation system in order to reduce the costs for the renovation.

Design Concept

Demonstrated Energy Technologies

Desiccant Cooling

Desiccant cooling is used as an abbreviation for the combination of desiccant dehumidification and evaporative cooling in this report. The unit for desiccant cooling therefore comprises of a dehumidifier part and a cooling part. The dehumidifier lowers the water content of the supply air which then passes through the humidifiers where it is cooled. Figure 2 shows a simple schematic.

Evaporative Cooling

Evaporative cooling means that the temperature of the air is lowered when it collects water vapour. The energy needed to vaporise the water is taken from the surrounding air whose temperature is thus lowered. The humidification of the air is normally done at constant wet bulb temperature of the air and can continue until the air is saturated as shown in Fig. 3.

With indirect evaporative cooling no moisture is transmitted during the process. Supply and extract air are passing on separate sides of a heat exchanger. As no moisture is added to the supply air only the air temperature, and not its water content, will be changed.

To result in a large temperature decrease the air has to be "warm and dry" before the evaporative cooling and to be cooled to as low a temperature as possible the air has to be "cold and dry".

The relative humidity of the air controls the size of the temperature decrease. The relative humidity of the air can be lowered by heating the air. This leads to a higher temperature decrease but also to a higher temperature after the humidifier. To get a lower temperature after the humidifier the entering air should also have a lower water content.

Ambient air enters the desiccant wheel (A) (Figure 2), where part of the moisture content is removed from the air. During the adsorption process the temperature of the treated air rises but it is then cooled in the energy recovery unit (B). The air is now drier and cooler as it enters the evaporative humidifier (C) where it picks up moisture and the temperature is reduced still further. The air is now cold and is introduced to the area to be temperature controlled where it takes care of the internal heat load.

Extract air leaving the area, first enters a second evaporative humidifier (D), where it picks up moisture resulting in a drop in temperature. This cooled humid air then enters the rotary sensible energy recovery unit (E) which acts as an air cooler for the incoming supply air reducing its temperature. The supply air has the effect of increasing the temperature of the extract air which is further increased in the heater (F). From here the air passes through the desiccant wheel (G) serving as reactivating air. To reduce the energy consumption, part of the air can bypass both the heater (F) and the desiccant wheel (G). The two air flows are then combined and discharged to the outside. The system can easily be built into a conventional air handling unit operating as a supply and exhaust unit. The changes of the conditions of the supply air in the three parts of the air handling unit - dehumidifier (dehumidification and heating, A), heat exchanger (dry cooling, B), and humidifier (humidification along the line for constant wet temperature (C) (Figure 3). The dashed lines show the extract air changes.

In winter both rotors are used for heat recovery from the extract air which leads to a very small need for after heating. The design of the heating system will therefore be based on the need for regenerating heat in summer.

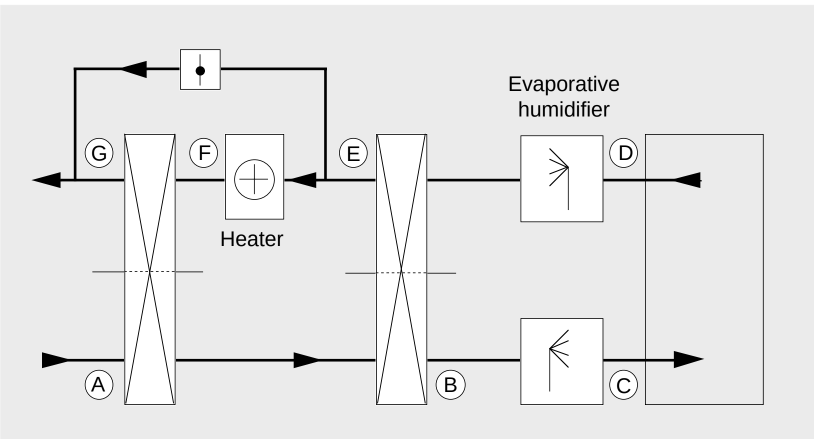


Figure 2: Schematic view of the desiccant air handling unit

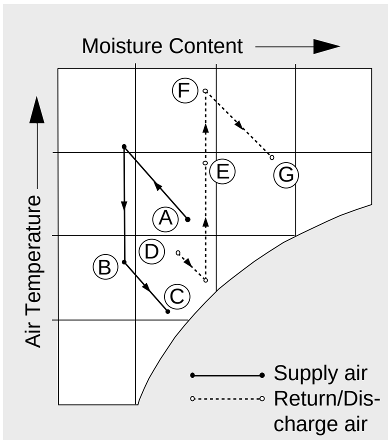


Fig. 3: The process in the xh-diagram

Design Details

The basis for the new system was given by the limits presented above. A renovated system where only the central air handling system was to be exchanged and the rest, e.g. the ductwork was to be kept. The cooling power at maximum conditions was calculated to be 130 kW and the hygienic outside air flow needed for the building was calculated to be 5 m^3/s. (For hygienic reasons return air is not accepted today in Sweden, supply air has to be 100 % outside air.)

The desiccant cooling system used at InfraCity comprises a desiccant wheel, an energy recovery unit and two evaporative coolers which are installed in an air handling unit with fans, filters and dampers.

Figure 4: The unit was lifted on to the roof ready for operation

Cooling Performance

Owing to its method of operation the performance of the desiccant system, like any other cooling system, is dependent on ambient conditions when the capacity is calculated. A desiccant cooling system handles latent heat better than a mechanical compressor system does.

The cooling capacity for ambient and internal heat load is controlled by changing the temperature of the exhaust heater for the reactivating air. For southern and central Europe, heating to about 95 and 75 °C respectively is required for peak conditions whilst 55 °C is sufficient to achieve the best results in Scandinavian applications.

The performance is also dependent on the efficiency of the energy recovery system and the humidifiers. To achieve the correct conditions and temperature reduction of the supply air, the temperature efficiency of these components should not be less than 75 % and 85 % respectively.

The unit is located on the flat roof top of the building easily accessible via a staircase. The unit is located adjacent to a technical room housing the control equipment, pumps, piping, etc., allowing easy access to the different parts of the unit.

By using the desiccant wheel in conjunction with the energy recovery system and evaporative humidifiers, a supply temperature of 12 °C to 19 °C (depending on climate) and a supply moisture content close to ambient conditions can be achieved. In cooling mode the supply air flow of 5 m^3/s outside air is increased (Figure 11).

Figure 5: The rotary desiccant wheel

Desiccant Dehumidification

Lithium chloride is an example of an absorbing desiccant physically and/or chemically when it picks up moisture. At high relative humidity it will become fluid. Molecular sieves and silica gel are examples of absorbing desiccants having a solid porous structure of microscopic pores resulting in an extremely large moisture receiving surface. In the microscopic pores the partial pressure of the water vapour will sink to a lower value than normal. At this lower partial pressure the water vapour will condense as a result of the adsorption to surface of the pores.

The efficiency of different desiccants depends, among other things, on the relative humidity of the air. During the drying process heat from the condensing water vapour is always released and transmitted to the air. To handle the problem with the desiccant being saturated with moisture and having to be changed at intervals the desiccant can be regenerated by heat that is supplied to the desiccant and evaporating the moisture out of the desiccant. Several different methods for regeneration are used.

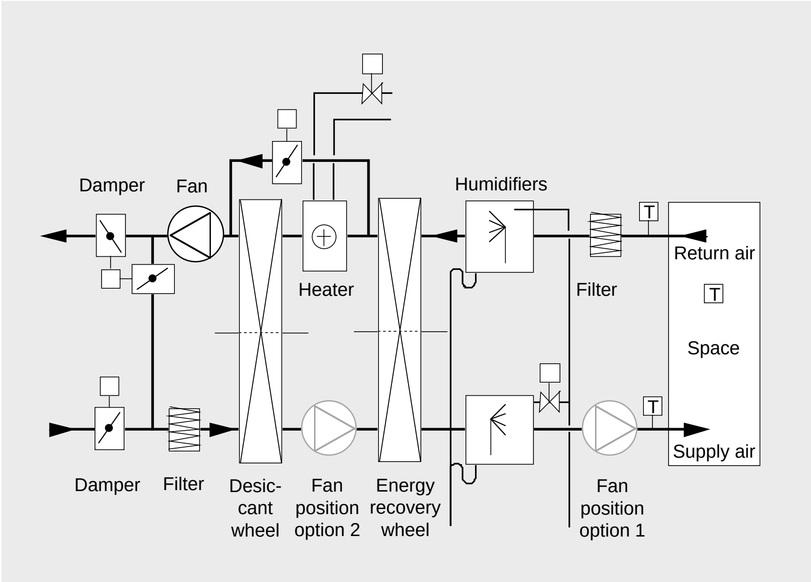


Figure 6: Water and heating installations for the complete desiccant cooling system

Winter Operation

During winter at low ambient temperatures the system operates in heat recovery mode with a total temperature efficiency in excess of 86 %. Even in winter mode the system operates with 100 % outside air and thus no return air.

The high temperature efficiency is achieved by making the desiccant wheel operate as a sensible and latent heat recovery unit in conjunction with the second sensible energy recovery wheel. This has the effect of dramatically reducing the energy consumption and thereby the costs during the heating season.

By operating the system in this way 75 % of the extract air moisture is recovered and returned to the supply air. This reduces the feeling of dry indoor conditions during the winter.

System Operation

The air handling unit at InfraCity has a rotating dehumidifier with silica gel as a desiccant. The drier wheel is passed by two air flows in counter flow separated from each other by seals. It rotates slowly while the part of the rotor that is exposed to the supply air adsorbs moisture that is then released to the heated extract air, "the regenerating air" in the other half of the rotor (Figure 6).

While the supply air is dried its temperature rises, partly due to the added condensing heat from the water and partly because the rotor is working as a common rotary heat exchanger. The heating of the regenerating air, the extract air, is done in a heating coil (that can be heated in different ways. In InfraCity district heating is used having a favourably low cost in summer when the cooling is needed and the demand on district heating is low from other customers).

Figure 7: The auxiliary equipment is located in a service corridor outside the unit.

The system is equipped with two humidifiers, one for the supply air and one for the extract air. The extract air humidifier is used as an indirect evaporative cooler as the air cooled by the humidifier passes through the rotary heat exchanger and cools the supply air passing through the other side of the heat exchanger.

The humidifier for the supply air is used as a direct evaporative cooler. To get it as efficient as possible the air should be as dry as possible. This is the reason for the location "down stream" of the dehumidifier and energy recovery rotors having the functions already described.

Operating Results

The installation was tested thoroughly in 1994, its first year of operation, when Stockholm enjoyed the warmest summer for 200 years. During all of July and half of August the daily temperature was between 30-35 °C and even the nights were warm which is very unusual in Sweden (Figure 8).

Swedish houses are built to retain heat. Consequently in premises with no cooling the temperature went up to and above 35 °C during this unusual hot period.

The results presented here were recorded during the summer 1994 when an assessment was carried out on the installation in InfraCity [1].

Although the ambient temperature varied between 17 and 35 °C during a typical week the supply and return air temperatures remained stable and acceptable (Figure 9).

Figure 8 also shows the stable supply air temperature for a typical hot summer day with increasing ambient temperature during the day. The water content (presented as dew point temperature) was however fairly constant both for the ambient air and the supply air.

The design of the system calls for an increased supply air flow when the outside temperature rises above 15 °C (Figure 10). The supply air flow (comprising of 100 % outside air) is increased from the minimum hygienic flow of 5 m^3/s linearly with the ambient temperature from 15 °C and upwards. As shown the measured hourly mean values are slightly below the design value at temperatures below 20 °C and above from 25 °C and higher.

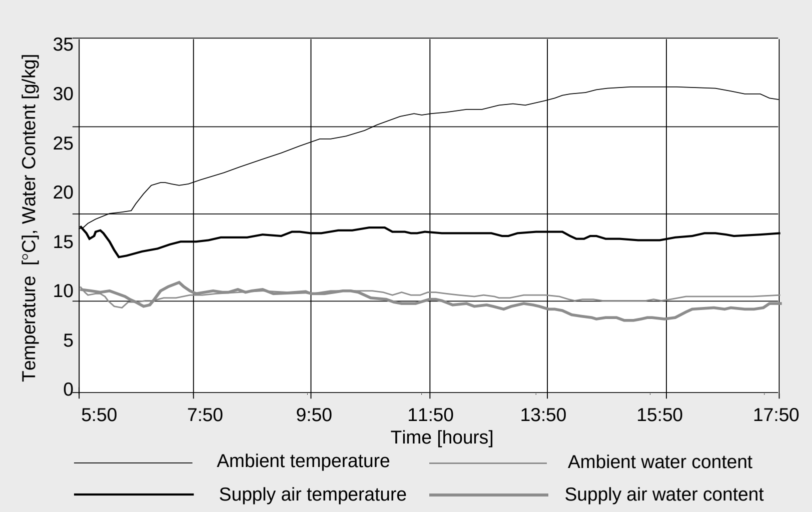


Figure 8: Temperatures and water content during a hot summer day 1994

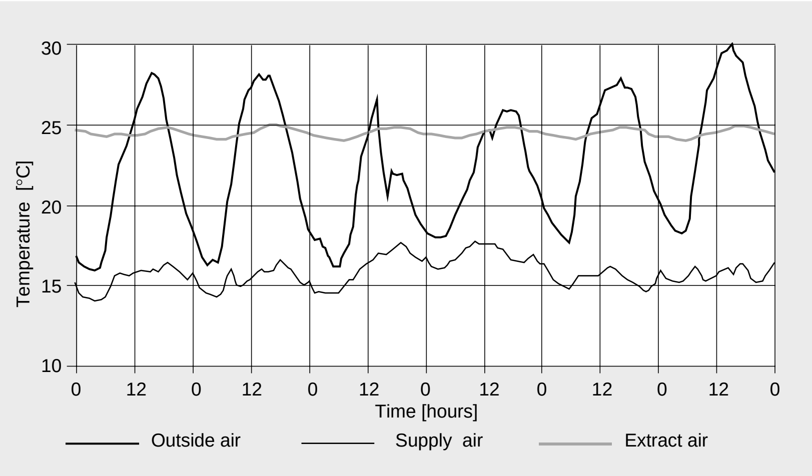


Figure 9: Temperatures during the period July 31 to August 5, 1994

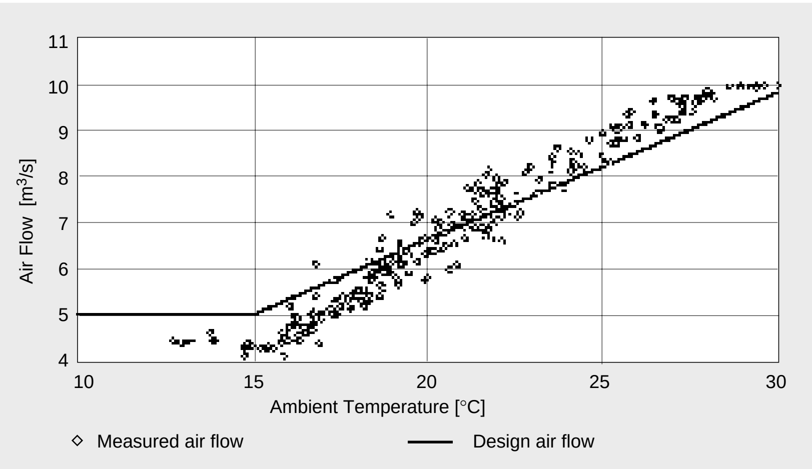


Figure 10: The supply air is increased at higher outside air temperatures

Energy Consumption

The plant is supplied with electric energy needed mainly for the operation of the two fans. The power supplied to the motors for the heat exchanger and desiccant wheels, and the circulation pump for the regenerating heat coil is a small part of the total electric power, only about 1 kW.

The fan motors are speed controlled by frequency converters resulting in a drastic reduction of the electric power at reduced air flows (Figure 11).

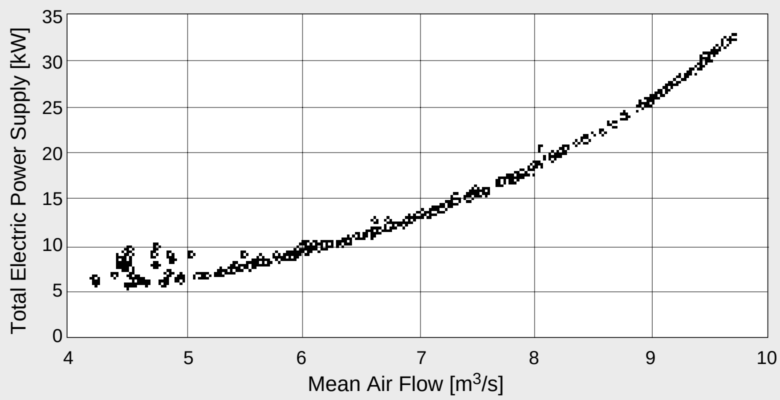


Figure 11: Total electric power consumption of the plant

The main part of the energy supplied to the plant is however the heating energy needed for regenerating the drier. As this is needed during cooling mode in summer and can be done with low temperature heat energy, district heating at low summer prices was used for the plant which reduced the cost for energy dramatically.

The energy needed in winter is lower, the air flow is reduced to the minimum hygienic air flow and both rotary wheels are used for heat recovery.

Costs

The choice of system type was based on investment and operating cost calculations for two alternatives, conventional mechanical cooling and desiccant cooling. All costs for the two alternatives were added and based on the local costs for electricity, water and district heating at the site (1994), Table 1.

The costs were based on an operating time of 3,390 h/year corresponding to week day occupancy between 6.00 - 19.00. The comparison showed that both investment and operating costs were lower for the desiccant system than for the conventional system.

For the desiccant unit the cost for producing the regenerating heat needed for the drier rotor has to be added (this is needed during summertime and for this case district heating could be used at low summer rate). Likewise the cost for fresh water to the two humidifiers must be included.

Local costs (1994) excl. VAT but incl. energy tax	
Electricity - summer (May-August)	0.203 SEK (3.17 US cent) /kWh
Electricity (April, September, October)	0.266 SEK (4.16 US cent) /kWh
Electricity - winter (November-March)	0.408 SEK (6.38 US cent) /kWh
District Heating - summer (April- October)	0.073 SEK (1.14 US cent) /kWh
District Heating - winter (Nov.-March)	0.292 SEK (4.56 US cent) /kWh
Water	3.52 SEK (55 US cent) /m^3

Table 1: Local costs for energy and water

	Conventional Cooling	Desiccant Cooling
Unit, chiller and installation	4.5 MSEK (700 000 US$)	3.5 MSEK (550 000 US$)
Operation and maintenance	56 000 SEK (8 750 US$)	36 000 SEK (5 625 US$)
Heat recovery efficiency	75 %	91 %
Source of energy	Electricity	District heat
Max., energy consumption period	Winter	Summer
Cooling capacity *	130 kW	130 kW
Control of air humidity	Extra cost, not incl.	Included
Statutory inspection	Needed	Omitted
All assembled in the installation	No	Yes

* At an outdoor temperature of 34 °C and a water content of 10 g/kg of air

Table 2: Result of cost calculations

Summary

The energy system at *InfraCity* has proven to be a suitable solution for retrofitting buildings with comfort cooling. The experiences from this installation has shown that desiccant cooling systems can be both reliable and economic.

The assessment report [1] states:

"The calculations show - with the assumptions being made - that the desiccant cooling system is fully compatible with a conventional comfort cooling system. This means that this type of comfort cooling represents a valid alternative to the common cooling systems with compressors used today. This also represents a "Freon-free" alternative which could be considered as a main argument for choosing this type of installations in the future."

The plant is only using outside air and no return air as supply air to the rooms which ensures good air quality. With mechanical cooling systems use of return air is often needed for economic reasons.

The owner states it to be important that the desiccant system was a lot easier to install. The complete roof unit with cooling and control equipment, piping, etc., was made ready for delivery and tested at the factory. Thus the reconstruction of the building could be reduced to a minimum. The order was given in March 1994. On June 6th the whole installation was put into operation. The installation itself was finished in one day only.

The owner of *InfraCity* is very satisfied with the performance of the system and has ordered similar installations for other office buildings to be renovated. Currently (January 1997) *InfraCity* has five desiccant systems installed and a sixth plant is under planning.

Practical Experience

The two rotors and the two humidifiers in the desiccant air handling unit resulted in a higher pressure drop for the air and therefore requested more fan power during summer at maximum cooling power (when the desiccant unit worked with an outside air intake 10 m^3/s) than for the conventional unit only using a heat exchanger for chilled water.

On the other hand no power is needed for cooling compressors and their auxiliary equipment which leads to a radically lower installed electric power for the desiccant unit.

The energy supplied to the plant is mainly the energy needed for regenerating the drier. As this is needed in summer and can be done with low temperature heat energy district heating was used for the plant which reduced the cost for energy dramatically.

The calculation of the operating costs showed some interesting differences between the two compared systems, e.g.:

- The pressure drop is higher for the desiccant air handling unit mainly due to the two rotary wheels and the extract air filter protecting them.

Part of this extra pressure drop can however be reduced if the air bypasses the desiccant wheel during winter.

- The maintenance cost is higher for the conventional plant which also requires an annual inspection and leak test according to the Swedish refrigeration code.

As a conclusion also the operating costs were lower in this case for the desiccant unit than for the conventional system with compressors.

Figure 12: Evaporative humidifier

References

[1] Assessment of desiccant cooling installation at Upplands Väsby (in Swedish): Sven Hallgren, Chalmers Industriteknik, 1995

[2] Air Quality, Desiccant and Evaporative Cooling Systems: Johnny V. Andersson, BFR/IEA-EUWP, 1991

[3] DesiCool, Desiccant Cooling: (Munters, 1994) and discussions with Hans Hagberg and Torgil Stark, Munters, 1995-96

[4] The Dehumidification Handbook, 2nd edition, Lewis G. Harriman III (Editor), Amesbury, MA, USA: Munters Cargocaire, 1990

[5] Desiccant Cooling and Dehumidification, Lewis G. Harriman III (Editor), Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1992

The *Granlund* Office Building Helsinki, Finland

Architect: KVA Oy
Energy design: Olof Granlund Oy
Reporter: Tuomas Laine

Date: August 1998

Ventilated Chilled Beams

- Energy and cost efficient air conditioning system
- Free cooling without extra cost
- Modular and highly integrated room unit
- Plastic cooling water pipes
- Good indoor air quality

Background

Previous studies have shown the cooling beam system to be the lowest cost alternative for office building air-conditioning systems, when individual room temperature control and good indoor air quality are required. However, additional development work was required to improve the energy-efficiency of the system.

In Finland the material of cooling water pipes has always been copper or steel. Plastic pipes have not been used in cooling systems. So there was no experience about plastic pipes in cooling systems. Therefore designers had a very prejudiced attitude in using plastic cooling pipes.

Introduction

The building was designed and constructed in years 1989 -1991.

Cooling demand calculations showed that cooling was required during a long period of the year.

The cooling beam system was selected for an air-conditioning system to achieve individual room temperature control and good indoor air quality. The cost analyzation showed that cooling beam system was the least cost alternative for individually controllable air-conditioning system.

When the project started, earlier concepts for water-based systems using free-cooling with outside air had all required an extra heat exchanger and could thus be used only at ambient temperatures below 0 °C. This ruled out free-cooling as not being cost-effective.

Cooling beams are dimensioned for using higher operating temperatures than e.g. typical fan coils (+14 to 18 °C vs. +7 to 10 °C). The higher operating temperatures increases the available free cooling time. In Scandinavia this means about 20 % and in Central Europe 30 % more free cooling operation time.

Halton Oy started 1993 a research project to improve the energy-efficiency of the cooling beam system. A new concept for ventilated cooled beam system with free cooling (called in this report as the low-energy system) was introduced in the end of year 1993.

To demonstrate the new system concept, the air-conditioning system of this building was renovated. Free cooling loop was carried out without extra heat exchangers. New low-energy room units were installed in two test rooms. The room unit is highly integrated, combining supply and exhaust air distribution, cooling and heating or heat recovery into the same unit.

The cooling water pipes in the test rooms were made of plastic (PEX) material. The better natural insulation of plastic was demonstrated.

Building Description

Project Data

Location	Helsinki, Finland
Altitude	46 m
Year of construction	1989/1991
Number of Working spaces	300
Degree days (17/12)	4,366 Kd
Heated floor area	6,998 m^2
Heated space	35,850 m^3
Inst. heating capacity	1,370 kW
Inst. cooling capacity	400 kW

The *Granlund* building is located in Helsinki, about 15 km north of the city.

Figure 1: Location of the demonstration building in Helsinki, Finland

In the building works about 300 employees, about 100 employees on every floor, mainly in several consulting offices.

Building Layout

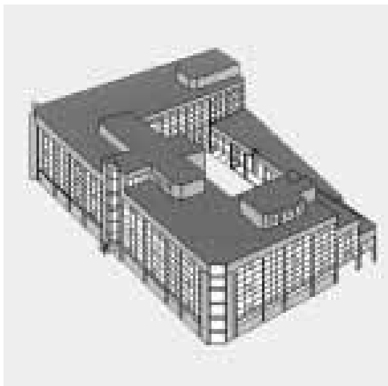


Figure 2: The office building has four zones and a courtyard

The building has three storeys and a parking area in the basement. There are four zones on the first floor and three zones on the other two floors. A courtyard is located between the zones.

Design Concept

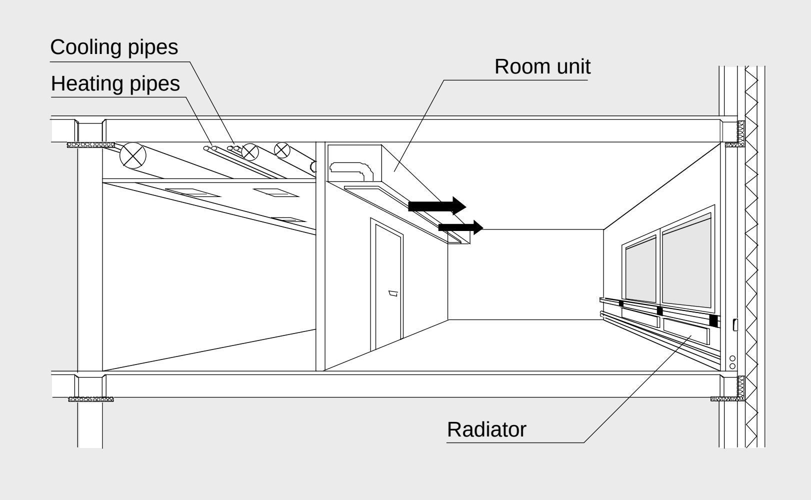


Figure 3: The new low-energy room unit in a test installation. Cooling, heat recovery and both supply and exhaust air distribution are integrated in the room unit. Existing radiators are used for heating.

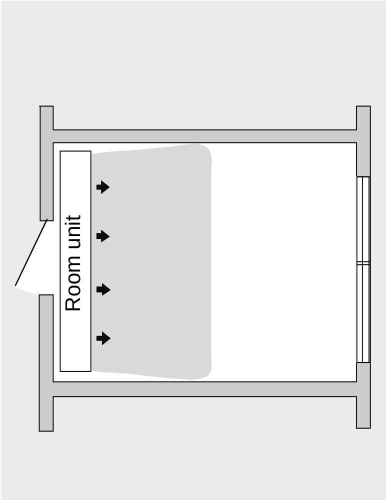


Figure 4: The air distribution in the test room (floor plan)

General Energy Concept

The building envelope is of concrete and glass. Standard sandwich elements are insulated according to the regulations (U-value 0.28 W/m^{2}K).

The windows are triple glazed, U-value about 1.8 W/m^{2}K. The outside glass is absorptive type of glass and every window is equipped with manual blinds for solar and overheating protection.

Lighting and computers with peripherals form the main electrical load in this building. The lighting is dimensioned for 1000 lux and the load is about 18 W/m^2. The lighting appliances are controlled manually. After normal working hours an automatic switching impulse is given in every other hour. No occupancy or daylighting control is used.

Over 80 % of the employees have a personal computer. Every printer is shared with about 10 persons. The total load from these equipment is about 10 W/m^2.

Demonstrated Energy Technology

In developing of a new water-based air-conditioning system, a goal was set to improve energy and cost-efficiency of water-based systems by using free cooling and low-energy technologies.

Using a single coil for heating, cooling, and as heat exchanger for the free cooling in the air handling unit lead to a simple and cost-effective solution. The primary system diagram for the demonstration building is presented in Figure 5.

The system concept has an air-conditioning unit equipped with a heating coil and a cooling coil and heat recovery unit. Heat is produced by using existing radiators. The existing heating coil is only used in extremely cold weather. During the free cooling operation the cooling coil is used for pre-heating the outside air. So many different functions were integrated in the same coil.

A good indoor air quality (IAQ) and possibility for individual indoor temperature control is achieved by using new highly integrated room units.

The air flows were dimensioned for fulfilling the IAQ-requirements. The cooling capacity of the room unit is used for controlling the indoor temperature during summer, spring and autumn. The radiators with room thermostats maintain adequate temperature during the heating season.

Design Details

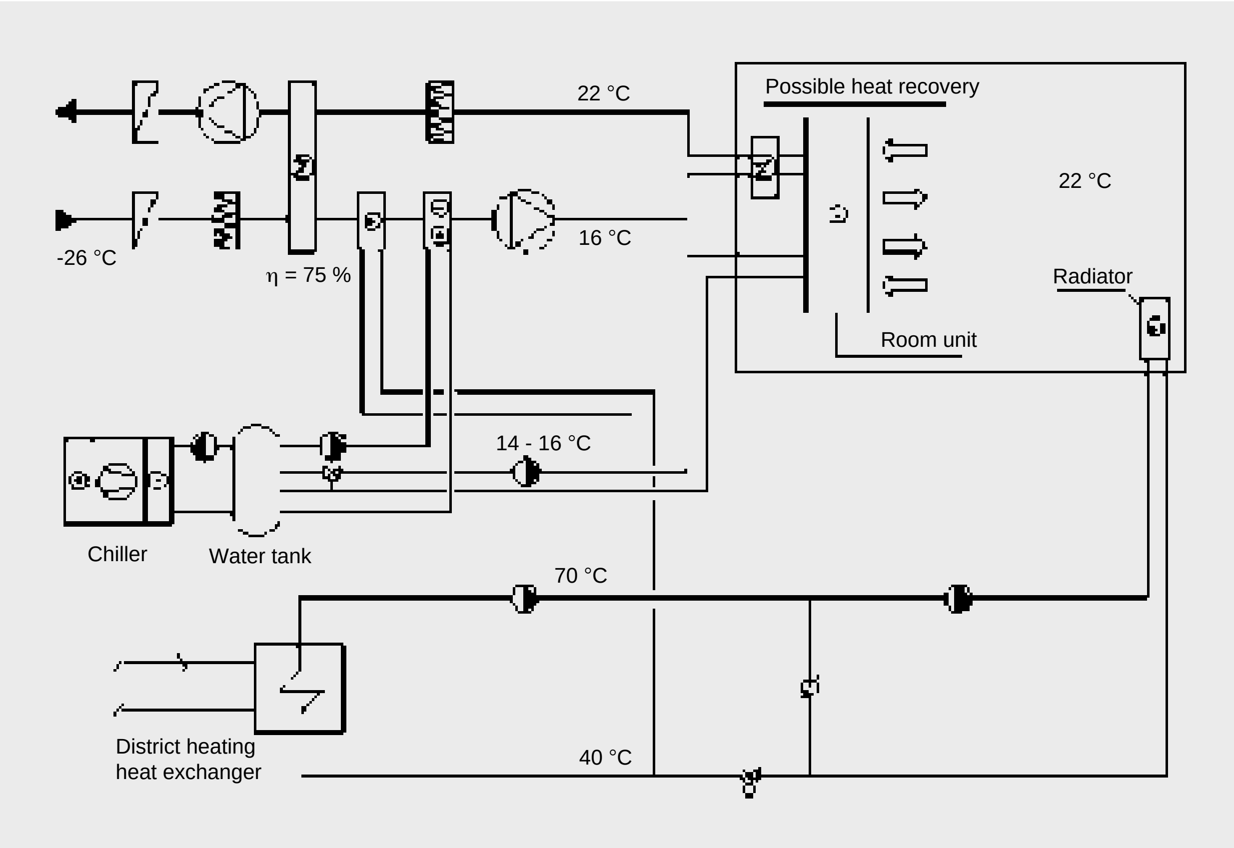


Figure 5: Principle system diagram of the "Granlund" demonstration building

Low-Energy System

During free cooling operation the cooling water from the water tank is circulated through the integrated cooling/free cooling coil. The free cooling coil transmits heat from cooling water to colder outside air, which is at the same time pre-heated (see Figure 5).

Using low-energy system surplus heat in part of the rooms can be transferred into rooms that need to be heated at the same time.

Air temperature after the heat recovery unit is +12 °C to +13 °C in free cooling operation.

After the free cooling coil the temperature rises to minimum + 14 °C and after fan to minimum + 15 °C.

Low-Energy Room Unit

The highly integrated room unit is installed in two test rooms. One of the test rooms is a typical office room (1 room unit in the window wall) and the other a meeting room (2 room units in the corridor wall).

Both air supply and exhaust, cooling and heat recovery functions are integrated in the room units. In the meeting room only one of the room units has the heat recovery function.

Cooling Water Pipes

The cooling water pipes in the test rooms were made of plastic material to demonstrate the better natural insulation of plastic compared to typically used copper.

Surface temperature of the plastic cooling water pipe was 17 °C (cooling water 14 °C) without insulation according to the field measurements. Using a separate mounting pipe the surface temperature is even higher 19.5 °C. So no condensation occurs with uninsulated plastic pipes.

Control Strategy

The central equipment's operation sequences can be divided into three different modes. The annual hours of operation for each mode during normal office hours (weekdays 8:00-16:00) are as follows (Figure 6):

- Summer (260 h/year): Cooling energy is produced mechanically using a chiller.
- Free Cooling (1,180 h/year): Outside air, which is simultaneously preheated, is used for cooling. There is no need for mechanical cooling.
- Winter (650 h/year): No cooling required.

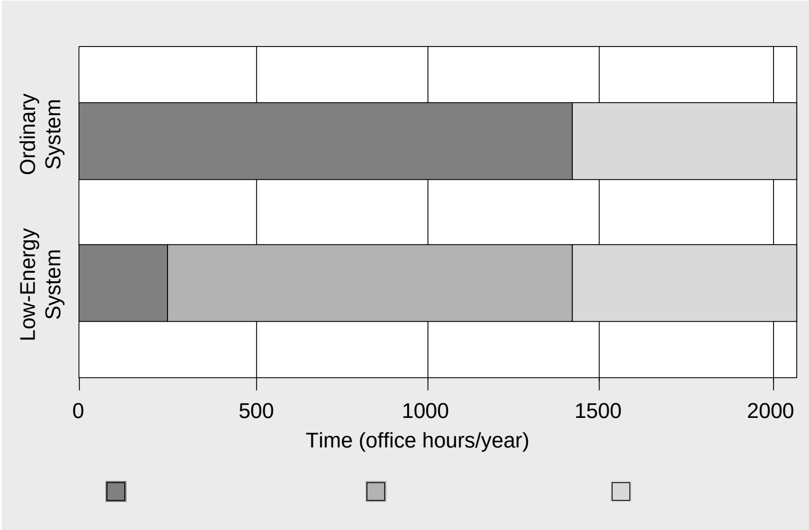


Figure 6: Low-energy systems operation sequences compared to ordinary water-based system

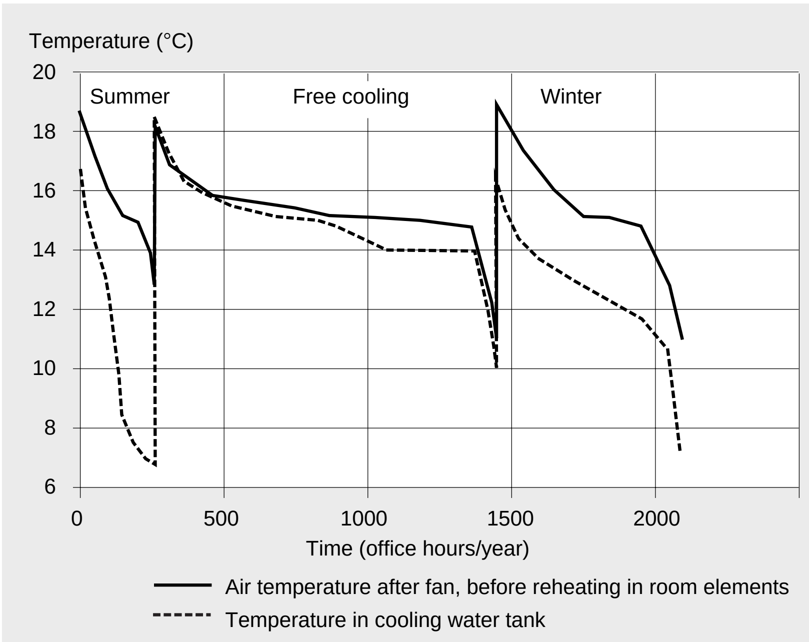


Figure 7: The system temperature during different operation sequences. Outside air, which is simultaneously preheated, is used for cooling. There is no need for mechanical cooling.

Performance Data

Overall Performance

The building was designed using normal constructions and U-values according to the regulations. No special constructions were used.

The heating and cooling systems are energy-efficient. The AC-heating system has an efficient (efficiency 75 %) heat recovery. The free cooling energy is used to preheat the outside air.

The measured specific heating energy consumption has been only about 21 kWh/m^2. This is about 50 % less than in a typical office building of that age.

Cooling Performance

The cooling performance of the low-energy system was measured during November 1993 and May 1994.

During the first measurement period the outside temperature varied between 0 °C to +5 °C. The results showed that there was cooling need in the building but no mechanical cooling was required. In Figure 8, the measured free cooling energy is shown during a typical day in November 1993.

The second three week measurement period was in May 1994. The outside temperature varied between 5 to 17 °C. This period was used to test the highest temperatures in free cooling operation. In Figure 9, the measured temperatures are shown during a typical work day in May.

The results show that free cooling can be used up to about 15 °C outside temperature.

On an average year the outside temperature is below 15 °C during 83 % of the annual hours.

The measurements with plastic cooling pipes showed that using the integrated protective installation pipe no need for insulation was recorded.

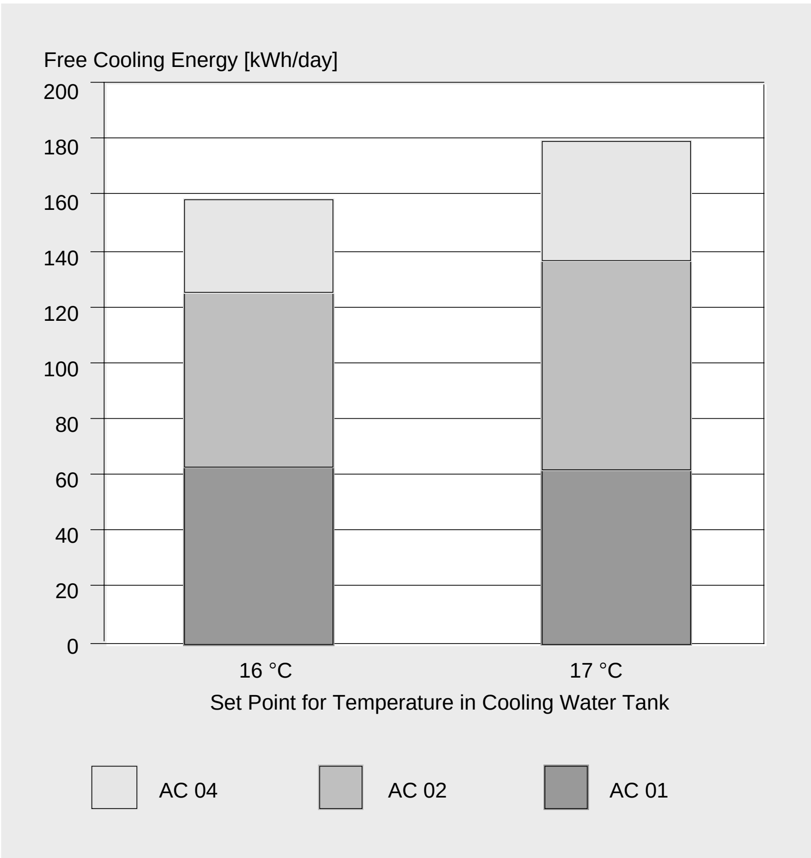


Figure 8: The measured free cooling energy is shown during a typical day in November 1993 (three AC units).

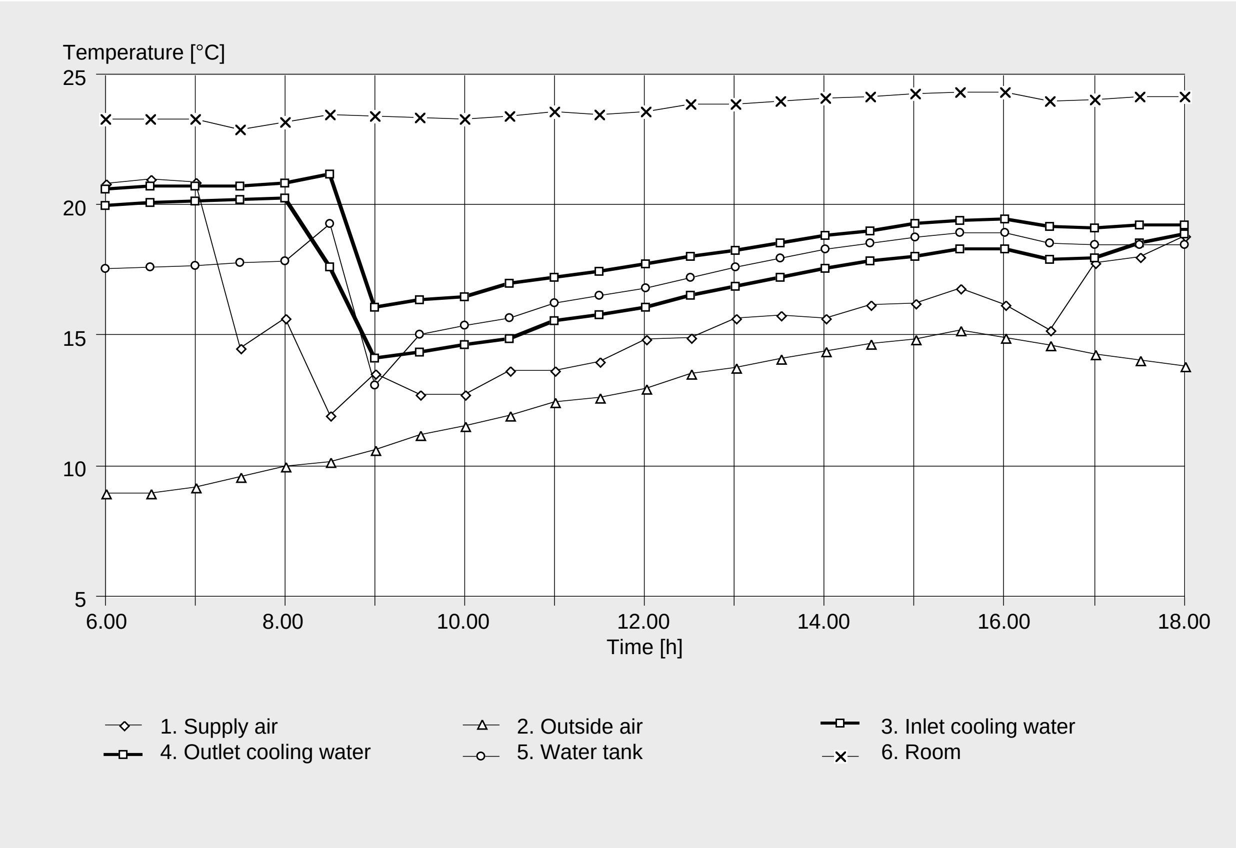


Figure 9: Measured operating temperatures in the "Granlund" building during a typical work day (26th May 1994)

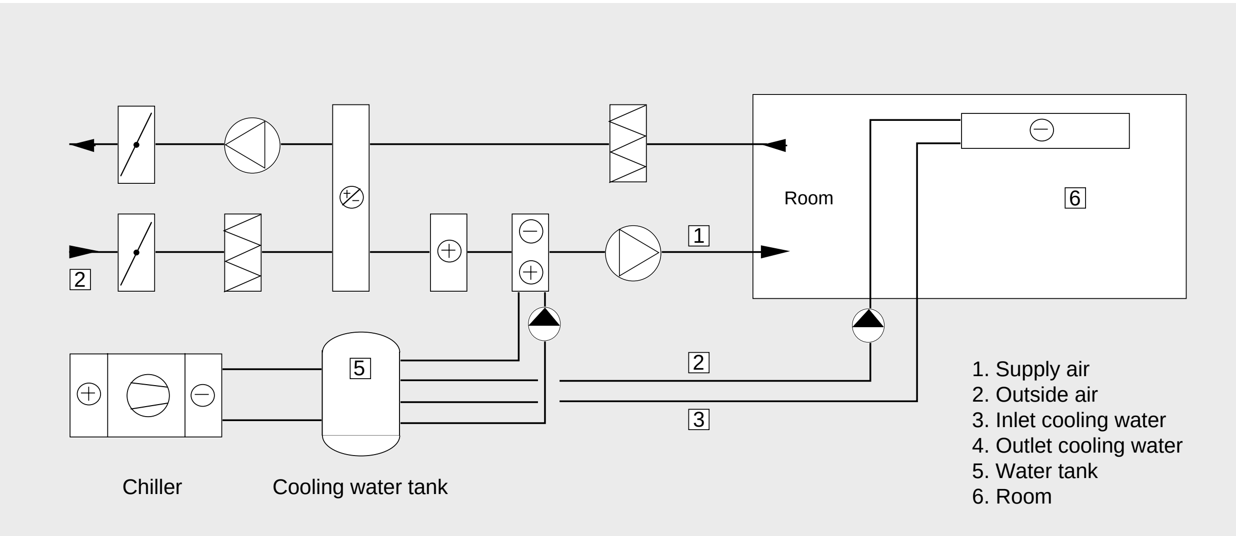


Figure 10: Installation scheme of the "Granlund" building and measured temperatures (see Figure 9 for temperatures)

System Costs

No extra costs are required for the low-energy systems free cooling loop. The highly integrated room units are more expensive than the ordinary cooling beams without any extra functions. However the total costs for all functions are comparable with the low-energy room unit.

Plastic cooling water pipes were demonstrated in the test rooms. Economical calculations were made to calculate the savings potential in the cooling water pipe network using uninsulated plastic pipes (Figure 11).

In the *Granlund* building plastic pipes with separate mounting pipes would save about 160,000 FIM.

Calculations showed that the free cooling function of the low-energy system reduces mechanical cooling energy consumption of room elements by nearly 50 %. The total cooling energy consumption (both cooling coil and room units) can be reduced by 38 % (Figure 12). In the "Granlund" building the energy savings potential would be 0.93 FIM/m^{2}year, totally about 6,500 FIM/year.

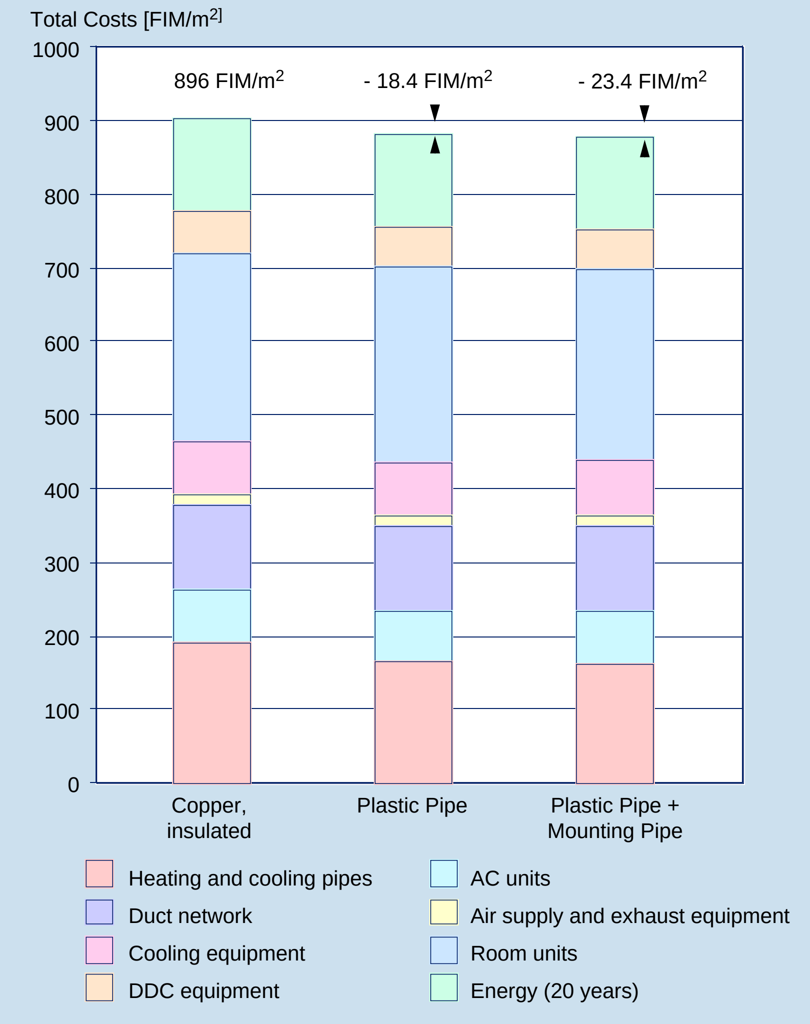


Figure 11: Savings potential of plastic cooling water pipes compared to insulated copper pipes

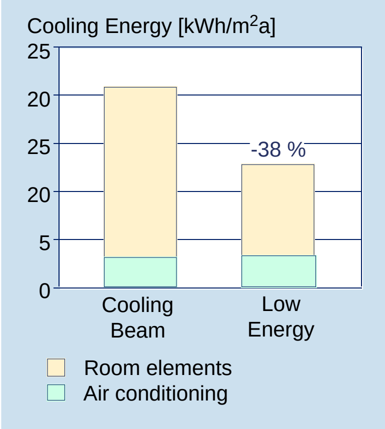


Figure 12: Cooling energy consumption of the low-energy system compared to ordinary cooling beam system

Summary

The new ventilated cooled beam system concept with free cooling can be applied in both new and renovated buildings.

It offers:

- Good indoor air quality and individual control possibility
- Up to 50 % cooling energy savings due to free cooling
- Cost reduction and system simplification

Reference

[1] T. Laine, J. Pekkinen: Low-energy, water-based air conditioning system, CADDET Newsletter 1/1995

The *Wärtsilä Diesel* Building Vaasa, Finland

Ventilated Chilled Beams (Renovation)

Owner: Wärtsila Diesel Oy
Energy design: Olof Granlund Oy
Room units: Halton Oy
Reporter: Tuomas Laine

Date: August 1998

- Energy and cost efficient air conditioning system
- Free cooling without extra cost
- Modular and highly integrated room unit
- Good indoor air quality

Background

Previous studies have shown the cooling beam system to be the lowest cost alternative for office building air conditioning systems, when individual room temperature control and good indoor air quality are required. However, additional development work was required to improve the energy efficiency of the system.

Introduction

In 1993 Halton Oy started a research project to improve the energy efficiency of the cooled beam system. A new concept for a ventilated cooled beam system with free cooling (here called the low energy system) was introduced in 1994.

Cooling beams are dimensioned for using higher operating temperatures than e.g. typical fan coils (+14 to 18 °C vs. +7 to 10 °C), which increases the available free cooling time. In Scandinavia this means 20 % and in Central Europe 30 % more free cooling operation time.

Theoretical calculations and measurements in the first demonstration building in Helsinki had shown the new low energy system to be energy and cost efficient.

During 1995 the whole air conditioning system of one office floor in the large industrial area of *Wärtsilä Diesel Oy* was renovated. The new low energy system was selected to achieve good indoor air quality with minimum energy use.

The air conditioning system was renovated and new integrated room units (manufactured by Halton Oy) were installed.

The *Wärtsilä Diesel* building was selected to be the demonstration building in the new development project that was started at the beginning of 1996. The project was financed by TEKES (Technology development centre of Finland) and Halton Oy.

Building Description

The demonstrated system was installed in one part of the office floor. The demonstration building is located in an area of mainly industrial buildings.

The office building was built in 1950. The demonstration area is an open plan space for about 60 employees.

Typical for the office area is a high indoor cooling load from office equipment. Most employees have two computers with peripherals on their desk. The outdoor cooling load is much lower and therefore cooling requirements are very stable through the whole year.

Project Data

Location	Vaasa, Finland
Altitude	6 m
Year of construction	1950
Year of renovation	1996
Number of Working spaces	60
Degree days (17/12)	4,730 Kd
Heated floor area	1,020 m^2
Heated space	3,672 m^3
Inst. cooling capacity	63 W/m^2
• low energy beams	32.7 kW
• air conditioning	31.6 kW

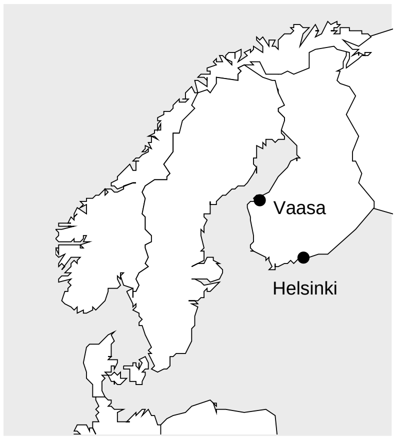


Figure 1: Location of the demonstration building in Vaasa, Finland

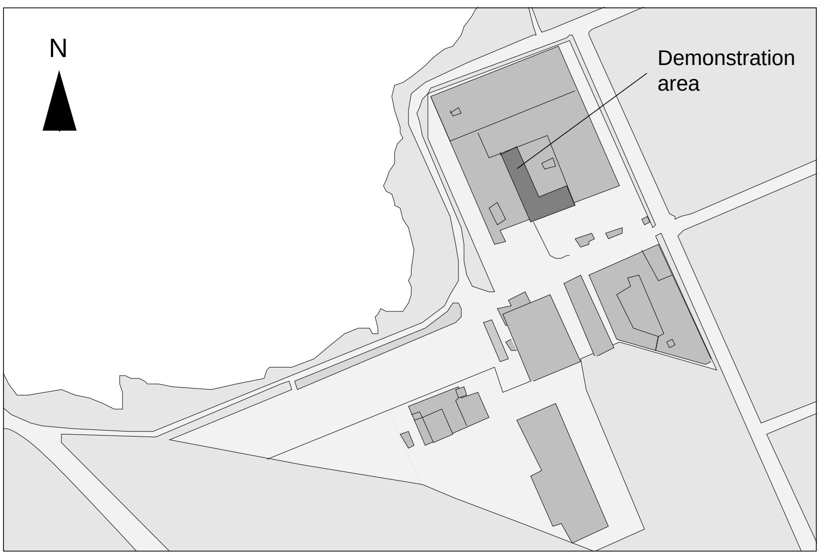


Figure 2: The demonstration area for the low energy system is one office floor (about 2,000 m^2) in a large industrial area.

Design concept

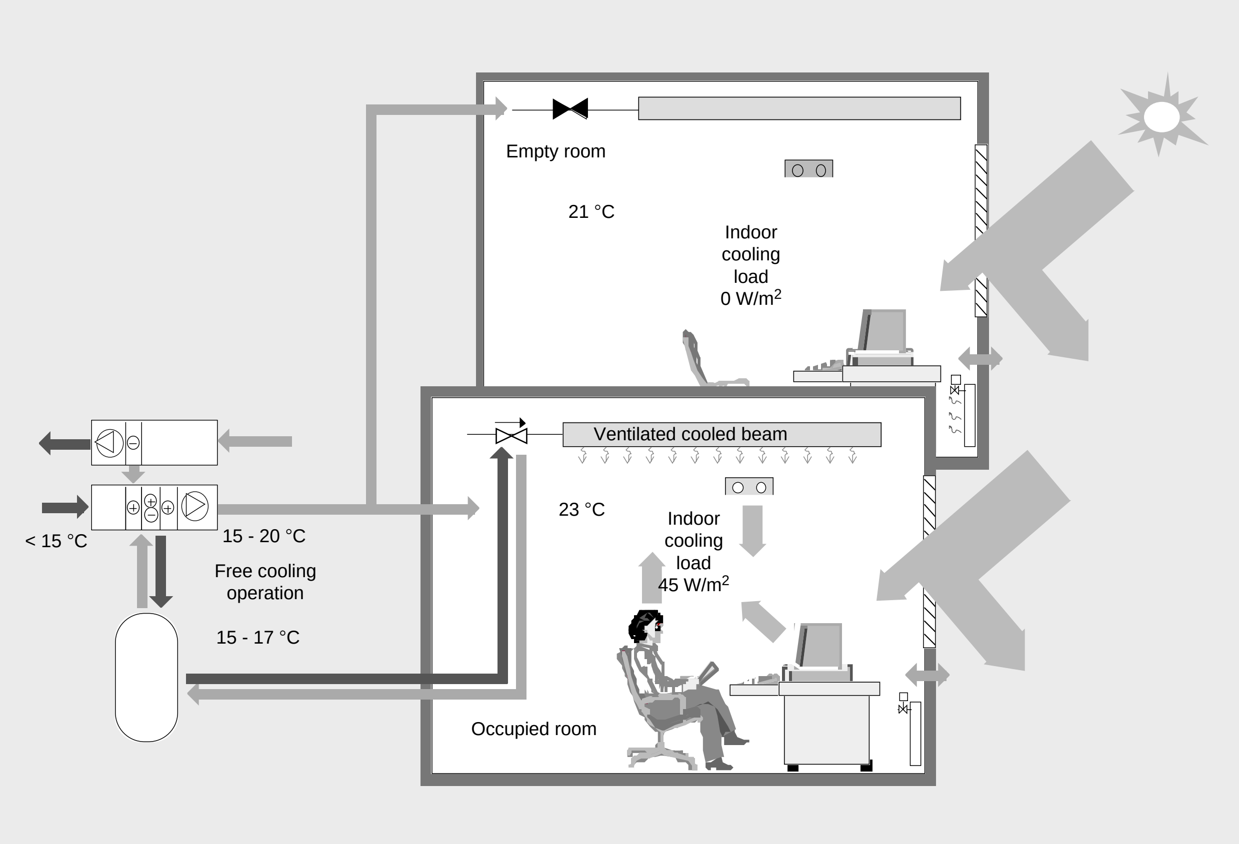


Figure 3: The principle of the chilled beam low energy system

General Energy Concept

Typical for the office area is high a indoor cooling load from office equipment. Most employees have two computers with peripherals on their desk.

Lighting appliances are controlled manually. No occupancy or day-lighting control is used.

The building envelope is constructed of concrete and glass. The windows are triple glazed and solar radiation is efficiently shielded by using reflective coatings.

Radiators are used for heating and new low energy room units for cooling and air conditioning.

Demonstrated Energy Technology

The energy and cost efficiency of the water based air conditioning system was improved by using free cooling and low energy technologies.

A system simplification was achieved by integrating the typically separate air handling unit's cooling and free cooling heat exchanger functions into a single coil (Figures 3 and 5). The system concept has an air handling unit equipped with a water-glycol heat recovery unit and integrated cooling/free cooling coil. Because the heat recovery efficiency is rather low (50 %), there is a small heat exchanger in the heat recovery loop. The existing heating coil is now used for reheating.

Good indoor air quality and individual room temperature control is achieved by using low energy room units (Figure 4). The room unit does both cooling and supply air distribution. Heating is produced by using existing radiators.

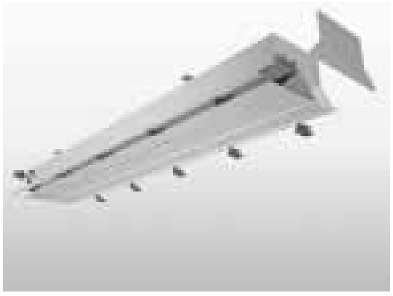


Figure 4: The integrated room unit for the demonstrated low energy system. The room unit has both cooling and supply air distribution functions.

Design Details

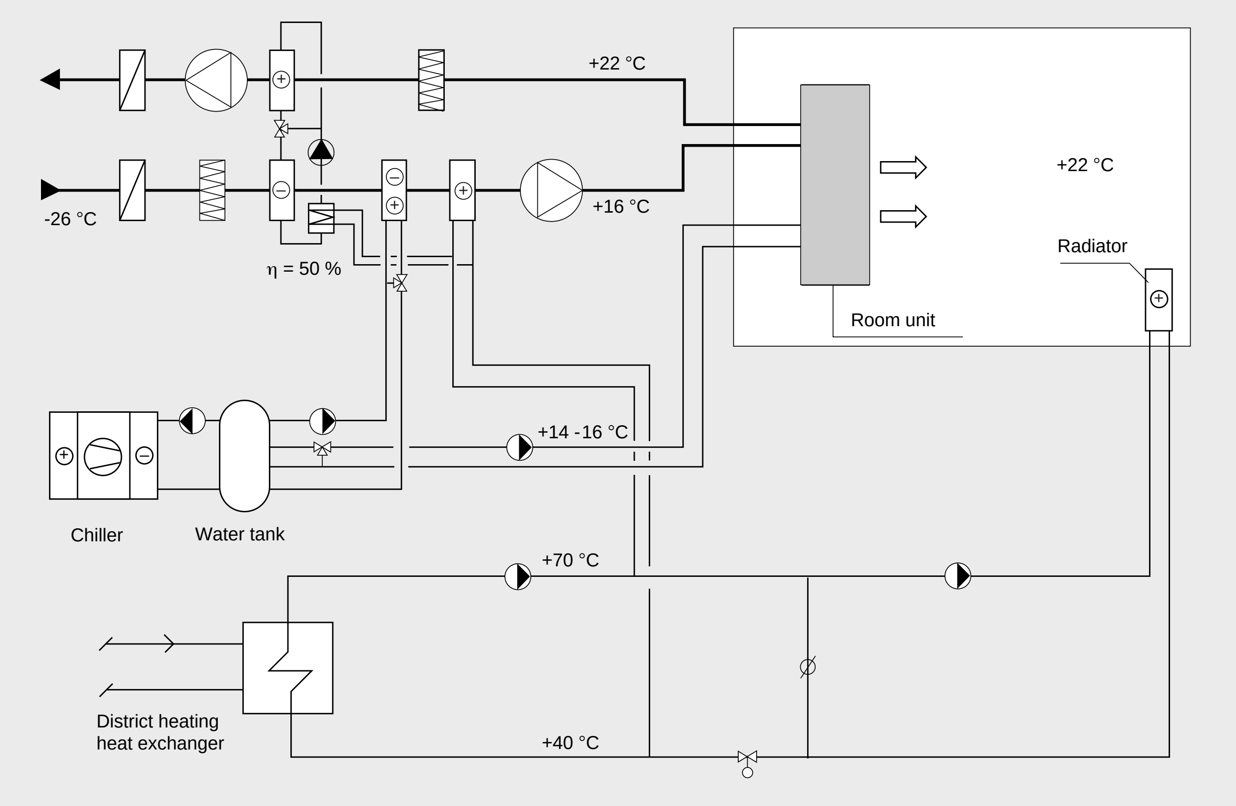


Figure 5: Principle system diagram of the Wärtsila Diesel demonstration area (winter situation)

Low Energy System

During free cooling operation the cooling water from the water tank is circulated through the integrated cooling/free cooling coil. The free cooling coil transmits heat from the cooling water to the colder outside air, which is at the same time preheated (see Figure 5).

The extra heat exchanger in the heat recovery loop is used in extremely cold weather when the temperature after the heat recovery unit would remain below 0 °C.

Mechanical and free cooling are used in parallel. Figure 6 shows the measured dependency between the outside temperature and the free cooling portion of the total daily cooling energy consumption.

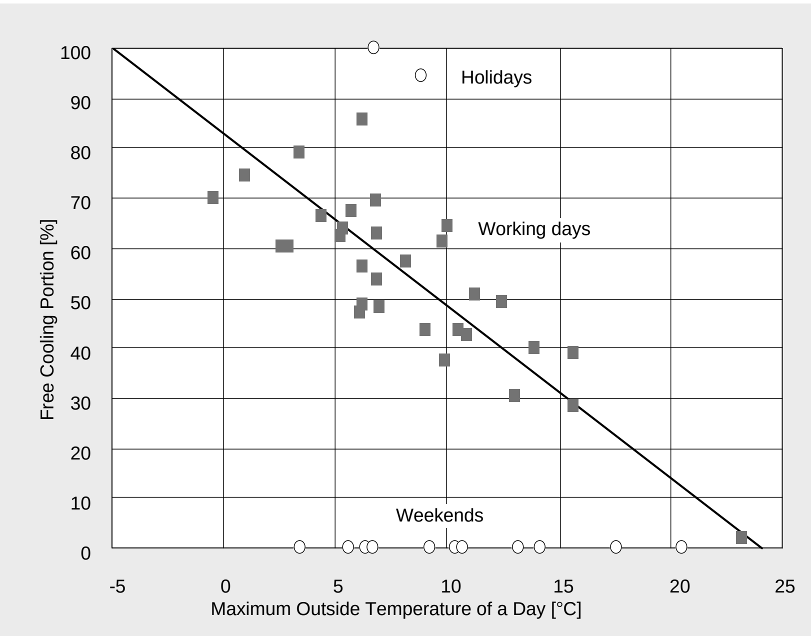


Figure 6: The measured dependency between outside temperature and the free cooling portion of the total daily cooling energy consumption

Control Strategy

The central equipment's operation sequences are divided into three different modes:

- Summer: Cooling energy is produced mechanically using a chiller
- Free Cooling: Outside air, which is simultaneously preheated, is used for cooling
- Winter: No cooling required

In this concept the mechanical cooling and free cooling sequences 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 the cooling water flow will be at its maximum. The supply air temperature is controlled by the reheating coil.

Cooling Efficiency

A conventional air conditioning system has to produce all cooling energy mechanically with a chiller (water systems) or with a chiller and a fan (air systems).

The low energy systems cooling efficiency (COP-value) is most of the time higher than the one of a conventional system (see Figure 7).

The COP of the low energy system in free cooling mode was calculated using the design values of the *Wärtsila Diesel* building. A typical fan selection was made for the air systems (CAV: constant air volume; VAV: variable air volume). The chiller COP of the water system (Cooling beam, fan coil) was dimensioned to be 3.

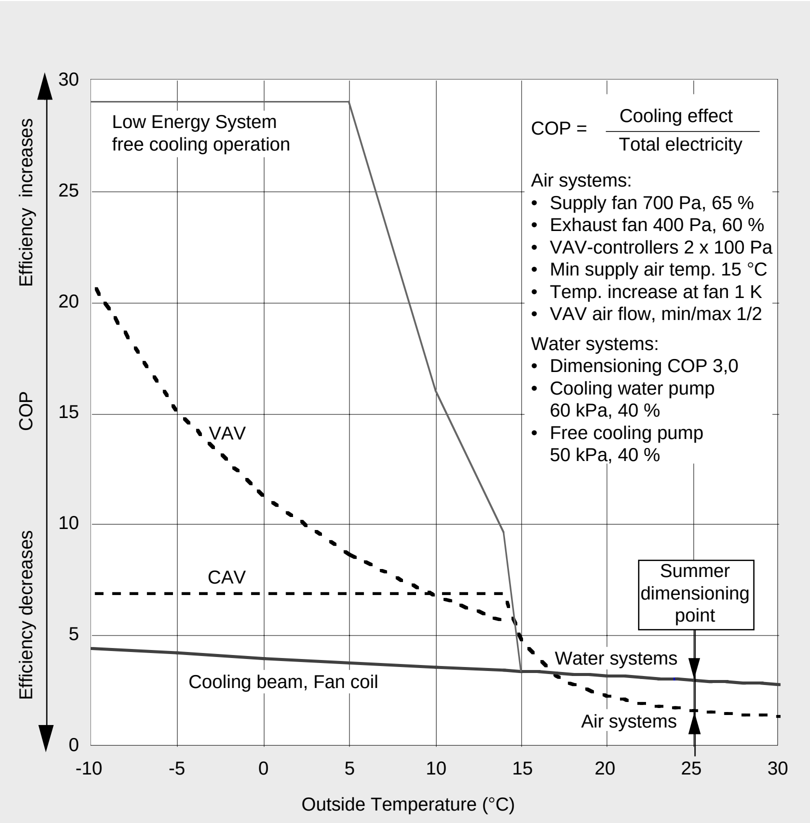


Figure 7: The cooling efficiency (COP-value) of the low energy system compared to other conventional air conditioning systems at different outside temperatures.

The free cooling mode starts below +14 °C outside temperature. Below this temperature, the low energy system is much more efficient (COP 29) than the most efficient air system (VAV-system COP 7 to 21).

During the summer (dimensioning climate for Finland: +25 °C / 55 kJ/kg) water systems require less energy than air systems to produce the same cooling effect.

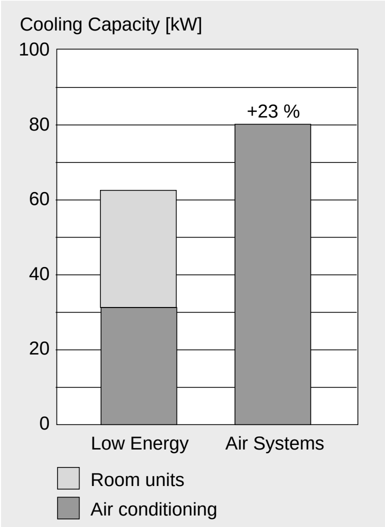


Figure 8: The required cooling capacity for the low energy system compared to air systems

In the Wärtsila building the installed cooling capacity for the low energy system is 64.3 kW of which about half is for air conditioning. Using air systems (CAV or VAV) the required cooling capacity would be 23 % higher (79.2 kW).

Figure 5 shows the measured dependency between outside temperature and the free cooling portion of the total daily cooling energy consumption.

Performance Data

Cooling Performance

The cooling performance of the low energy system was measured during the spring and summer of 1996.

The free cooling operation was measured during the spring measurement period 25.3. - 22.5. At the beginning of this period the system operation was checked to function correctly. After this temperature and fluid velocity measurement points were connected to the monitoring system. The values were read every minute and recorded automatically after 20 minutes.

The mechanical and free cooling consumption was calculated by using the measured data.

Figure 7 shows the measured daily cooling energy consumption during the spring measurement period.

The results show that the average free cooling portion of the total cooling energy consumption was 60 % when the outside temperature was below +14 °C (setpoint for summer cooling sequence). The free cooling savings potential varied between 2 to 100 % according to outside conditions.

Before the start of the autumn measurement period the set point for free cooling operation was changed: the cooling water temperature was allowed to rise to +17 °C (before +16 °C) until mechanical cooling was started. This increased the free cooling savings potential.

During the autumn measurement period the average free cooling savings potential was 71 %. The highest daily outside temperatures were between -2 and +10 °C. The free cooling savings potential varied between 53 and 89 % according to the outside conditions.

Energy Savings Potential

Using the measured data dependency between outside temperature and the free cooling portion the total cooling energy consumption can be defined. According to the measurements all the required cooling energy is produced by free cooling when the outside temperature is below -5 °C (Figure 6). On a day with a maximum outside temperature of +15 °C the free

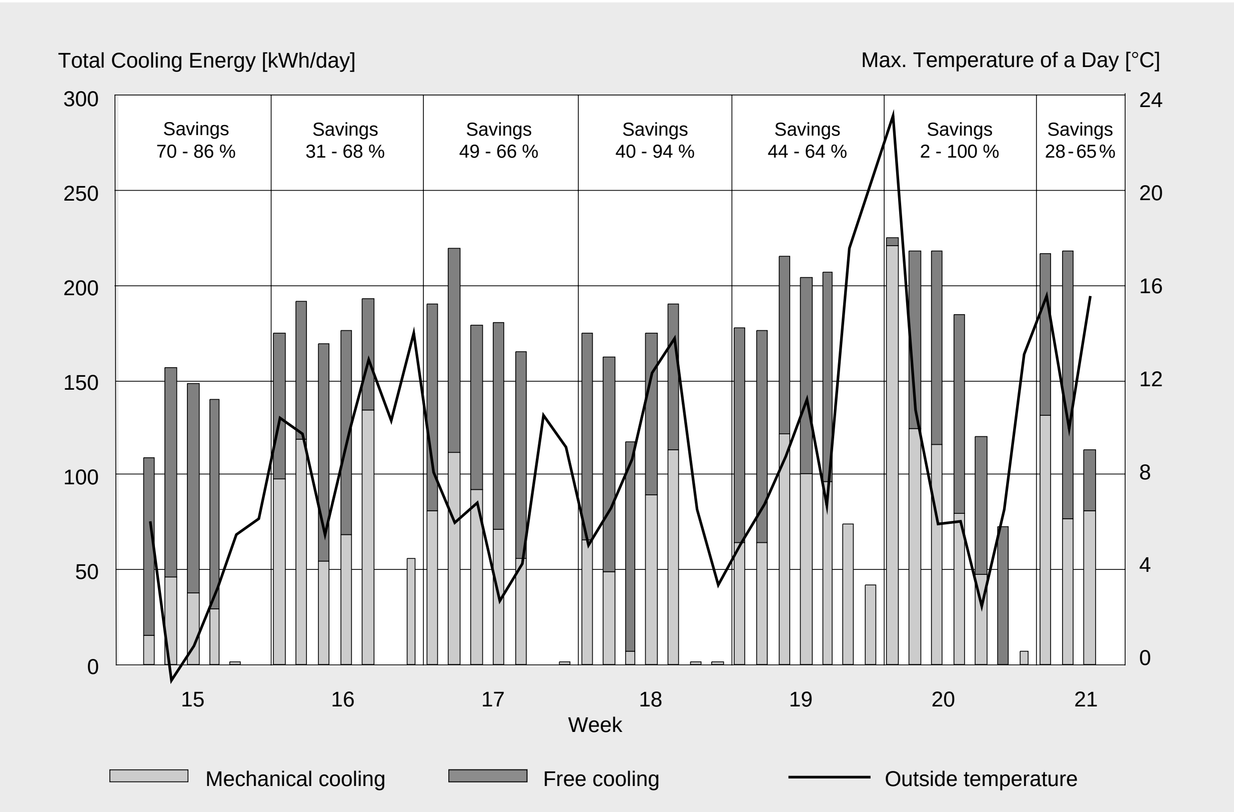


Figure 7: The measured daily mechanical and free cooling energy consumption during spring 1996 (9.4.-22.5.). The cooling energy was produced mechanically by using chiller or without mechanical energy by using free cooling.

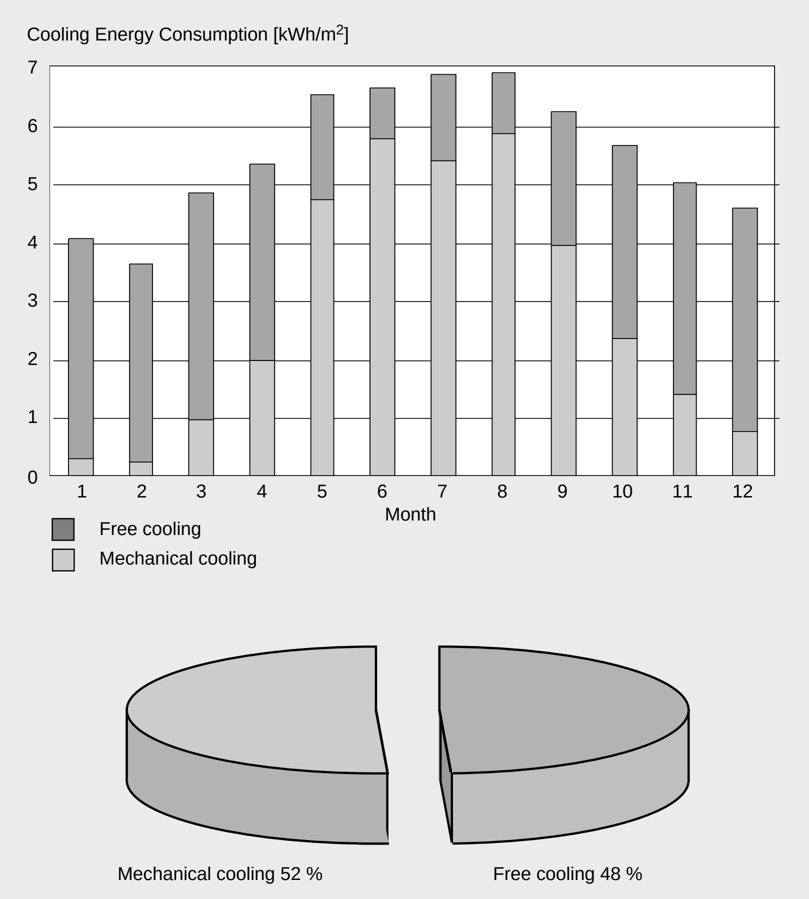


Figure 8: The annual cooling energy savings potential by using the low energy system. The low energy system decreased electricity consumption by 10.9 kWh/m²year which is 49 % less than in the traditional water based systems. The energy cost reduction was 2.88 FIM/m²year or 0.48 ECU/m²year.

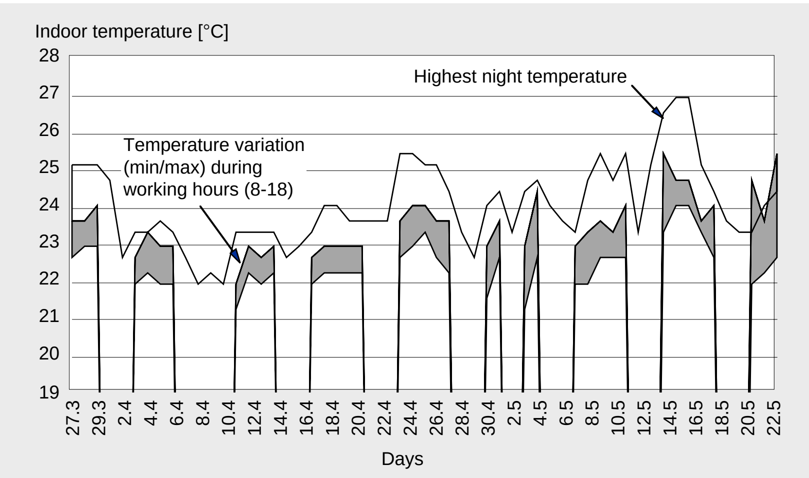


Figure 9: The measured indoor air temperature daily variation during spring 1996 (27. 3 - 22. 5.). Both the minimum and the maximum temperatures during working hours (8-18) and the highest night temperatures were recorded.

cooling portion is about 30 %. The estimation for the cooling energy savings potential was calculated by using these equations.

The annual cooling energy consumption of the room unit cooling system was estimated to be 62.2 kWh/m² of which an average of 29.6 kWh/m² can be produced by free cooling. The cooling energy saving (the free cooling portion) was about 48 % (Figure 8).

Cooling energy is required throughout the whole year because of the high indoor cooling load. According to the measurements more than 60 % of the maximum cooling power is required when the outside temperature is as low as 0 °C. Even in extreme cold weather conditions (-26 °C) about 20 % of the maximum cooling power is required. The total cooling load is rather stable because of good solar radiation shields.

The electricity consumption of the room unit cooling system is estimated to have decreased by 10.1 MWh/year and 9.9 kWh/m² per year.

Comfort

The indoor climate was monitored during the spring measurement period (free cooling operation) and during the summer period (mechanical cooling operation).

The indoor temperature varied mostly between 22 and 24 °C during the working hours in the spring period (Figure 9) and 21 to 23 °C during the autumn period. The temperature of +25 °C was exceeded only a few times.

A night time temperature increase (1 to 3 K) was recorded in spring. Night ventilation terms were checked before the start of the autumn measurement period. The night time temperature increase was much lower compared to the spring period and was recorded to be only 0.5 K.

The indoor air quality in two working places was measured in June 1996. The average indoor temperature in the occupied zone was +23.5 °C. The average air velocity was below 0.2 m/s and no draught problems existed.

Practical Experience

Indoor air quality in the renovated office area was found to be much better after installation of the new ventilated cooled beams.

During free cooling operation higher temperatures than the design inlet cooling water temperature (17 °C) were tested. The results showed that there were no negative effects on the indoor air quality. The inlet water temperature in this building can be at least 3 K higher than for design conditions.

Costs

No extra costs are required for the low energy systems free cooling loop.

Standard ventilated cooled beams were used for the *Wärtsila Diesel* low energy concept. Integrating other functions (heating, exhaust air distribution or heat recovery) for the room unit increases the cost of the room unit but may decrease the total system costs.

Operating costs are lower compared to traditional air conditioning systems. The new ventilated cooled beam system concept with free cooling saves energy costs in the demonstration area by 2,700 FIM/year and 2.61 FIM/m^2 per year (0.44 ECU/m^2).

Summary

The new ventilated cooled beam system concept with free cooling can be applied in both new and renovated buildings.

Good indoor air quality and individual room temperature control was achieved by using low energy room units. Both cooling and supply air distribution functions were integrated in the room units. No extra costs were required for the low energy systems free cooling loop.

The new ventilated cooled beam concept with free cooling offers:

- good indoor air quality and individual control possibility,
- up to 50 % cooling energy savings due to free cooling,
- cost reduction and system simplification.

References

[1] T. Laine, J. Pekkinen: Low energy, water based air conditioning system, CADDET Newsletter 1/1995

[2] T. Laine, J. Pekkinen, P. Horttanainen: Low energy water based air conditioning system, Indoor Air 96 proceedings, vol. 2, page 759

Figure 12: Interior view of renovated offices

The
Nestlé - France Head Office
Noisiel, France

Architect: Reichen and Robert
Energy design: OTH Bâtiments
Reporter: Christian Feldmann

Date: August 1998

Chilled Ceiling and Displacement Ventilation

- Chilled ceiling using plastic capillary tubes integrated into metallic panels
- Same system for cooling and heating

Background

Nestlé France, the French Sister company of the famous Swiss firm has decided to establish its Head Office in an old chocolate factory whose buildings have been registered as historic sites by the French government.

Most of the retrofitted buildings are equipped with chilled ceilings. In France, the concept of chilled ceilings is not yet a current technology.

Nestlé France Head Office is the very first site where this type of air conditioning system is used on a large scale.

Introduction

When considering the different ways of renovating all the buildings on the site it was decided to use a technology new to France: a chilled ceiling air conditioning system in combination with displacement ventilation.

The main reason for this choice was the low energy consumption of this system, the silent operation and the reduced floorspace required by terminal devices.

Building Description

Project Data

Location	Noisiel/Paris
Altitude	130 m
Year of renovation	1994
Cooling degree days (18)	144Kd
Heat. degr. days (20/12)	2,600 Kd
Number of working spaces	142
Heated floor area	6,936 m^2
Cooled floor area	3,856 m^2
Building envelope, U-Value	≈ 0.5 W/m^2K

All windows facing east, south and west are equipped with external shading devices that can be automatically operated according to the degree of solar radiation.

Solar factor of shading device: 0.2

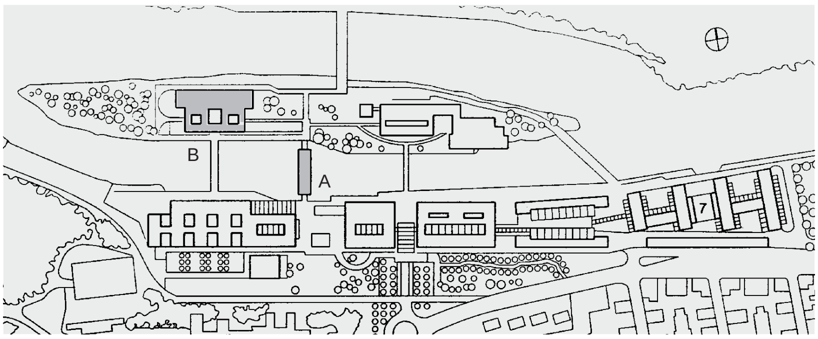


Figure 1: Site plan. The building on page 12-1 is A, the monitored building is building B.

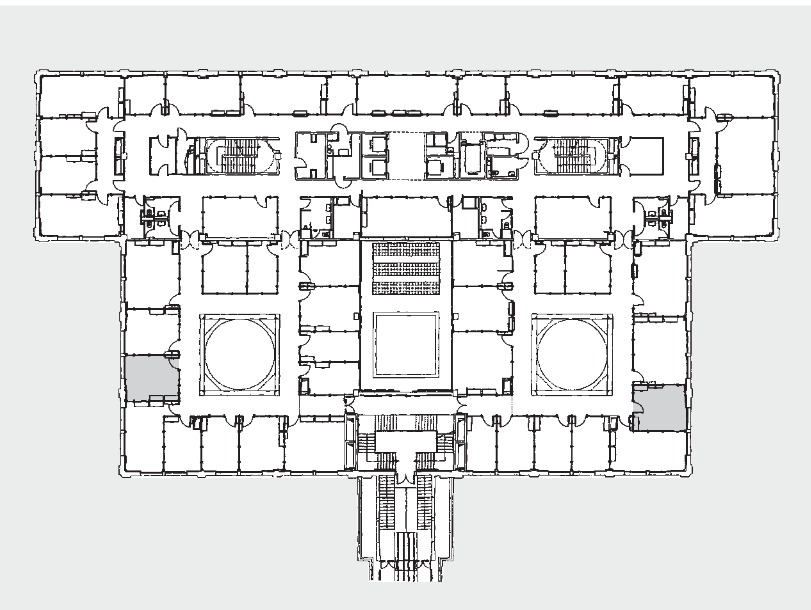


Figure 2: Plan view of the building. The monitored rooms are shaded.

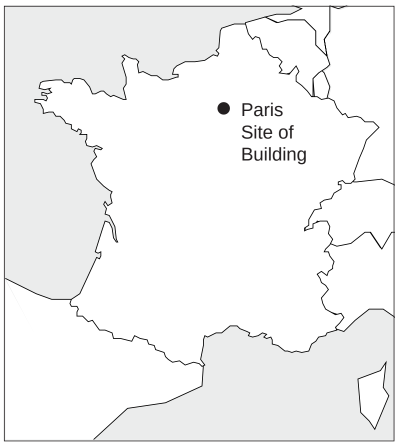


Figure 3: Location of the demonstration building in Noisiel, 25 km east from Paris

General Energy Concept

The system concept is based on metallic ceiling panels chilled by capillary tubes in which cold water is circulated.

Rock wool insulation covers the panels to reduce the heat transfer from the ambient air to the tubing. The panels are fed with cold water (supply temperature 15.5 °C, return 18.5 °C).

Water Network

Panel supply loops are separated from the main warm and cold water network by heat exchangers. The main hot and cold distribution networks are fed from a central heating and chiller plant building which supplies individual building sub-stations. Each office has an individual cold water supply loop with up to 15 connecting panels.

Air Network

Outside air is pre-cooled and dehumidified by an Air Handling Unit (AHU) before being supplied to the offices. This is achieved by means of low air velocity grilles fitted in the false floor of the offices.

Extract air transfer vents to corridor are positioned at high level on the opposite wall (see Figure 5).

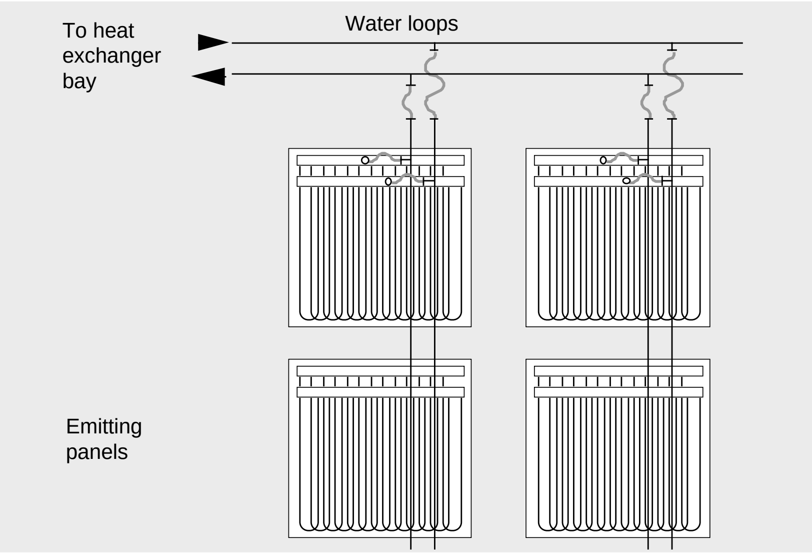


Figure 4: Emitting panels seen from above. Up to 15 panels can be supplied from a common cold (or warm) water loop.

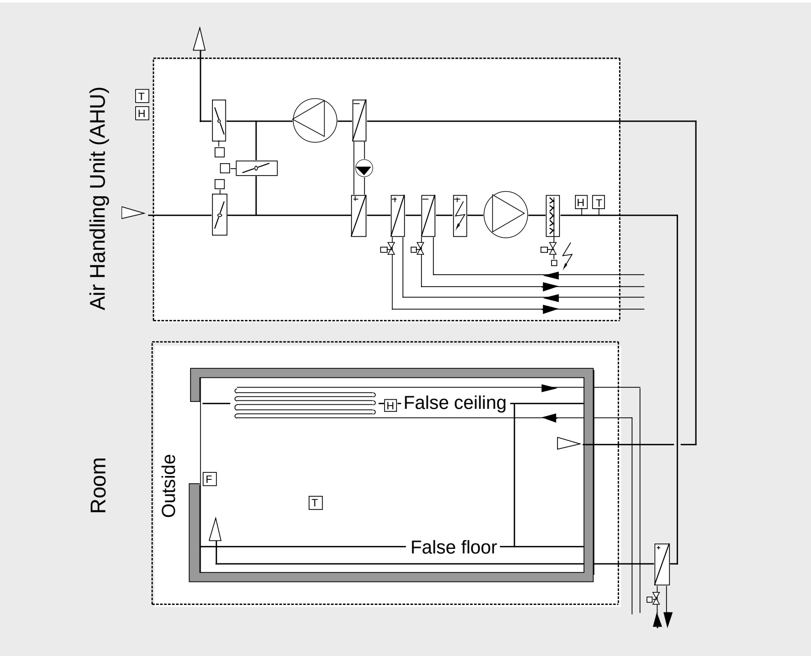


Figure 5: In summertime fresh air is pre-cooled and dehumidified by an Air Handling Unit

Control Strategy

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 ceiling of the rooms of the offices shuts off the cold water supply when the room air dew point temperature approaches the panel surface temperature.

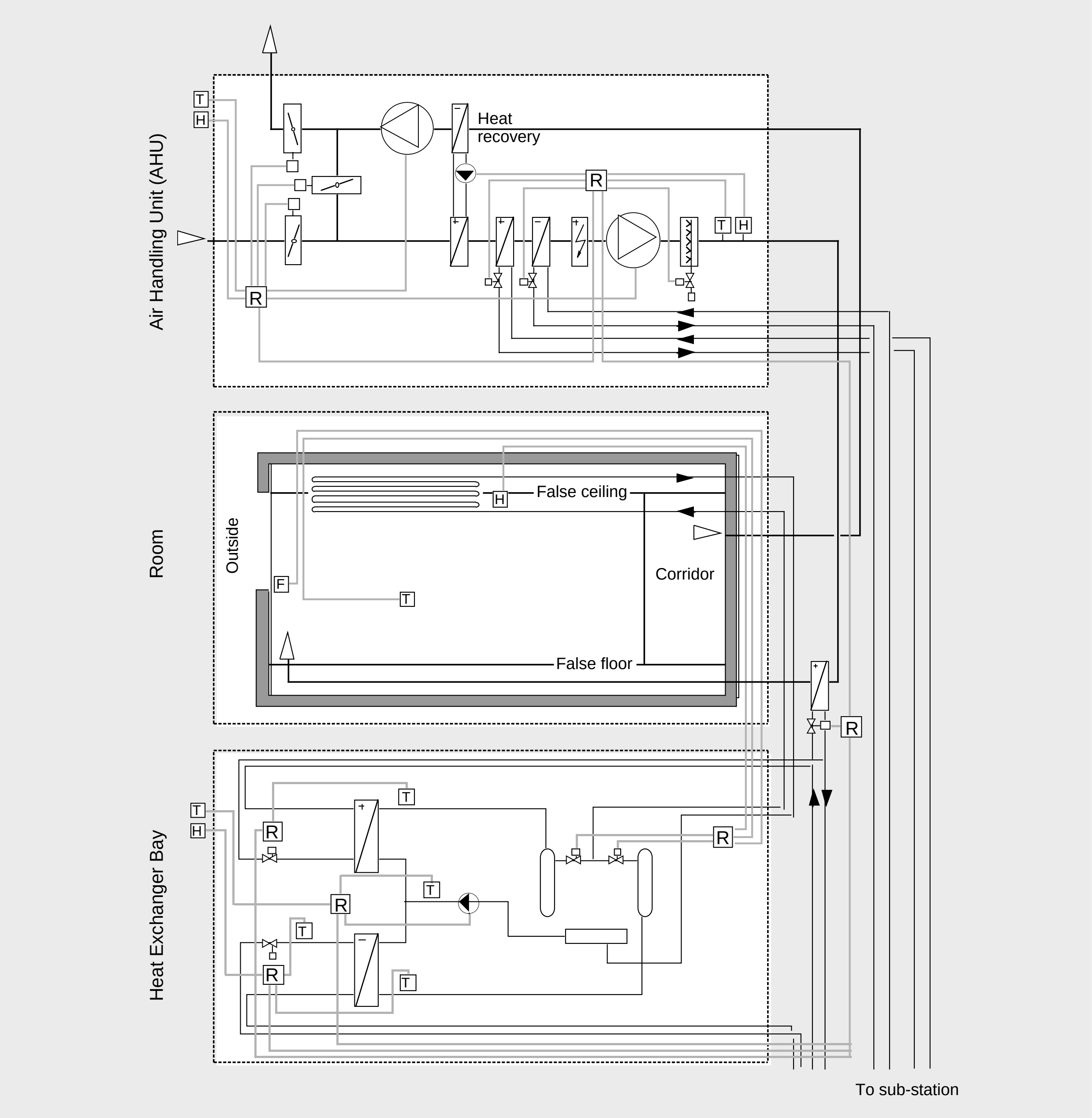


Figure 6: Control schematic (gray lines)

Design Details: Heat Exchanger Bay

For each level of the building a heat exchanger bay supplies warm and cold water to the different office loops (up to 24).

Nominal cooling capacity: 25 kW
Nominal heating capacity: 10 kW

Nominal Cold Water Supply Temperature
Heat exchanger primary: 11 °C
Heat exchanger secondary: 15.5 °C

Nominal Cold Water Return Temperature
Heat exchanger primary: 16 °C
Heat exchanger secondary: 18.5 °C

Nominal Warm Water Supply Temperature
Heat exchanger primary: 50 °C
Heat exchanger secondary: 30 °C

Nominal Warm Water Return Temperature
Heat exchanger primary: 40 °C
Heat exchanger secondary: 27 °C

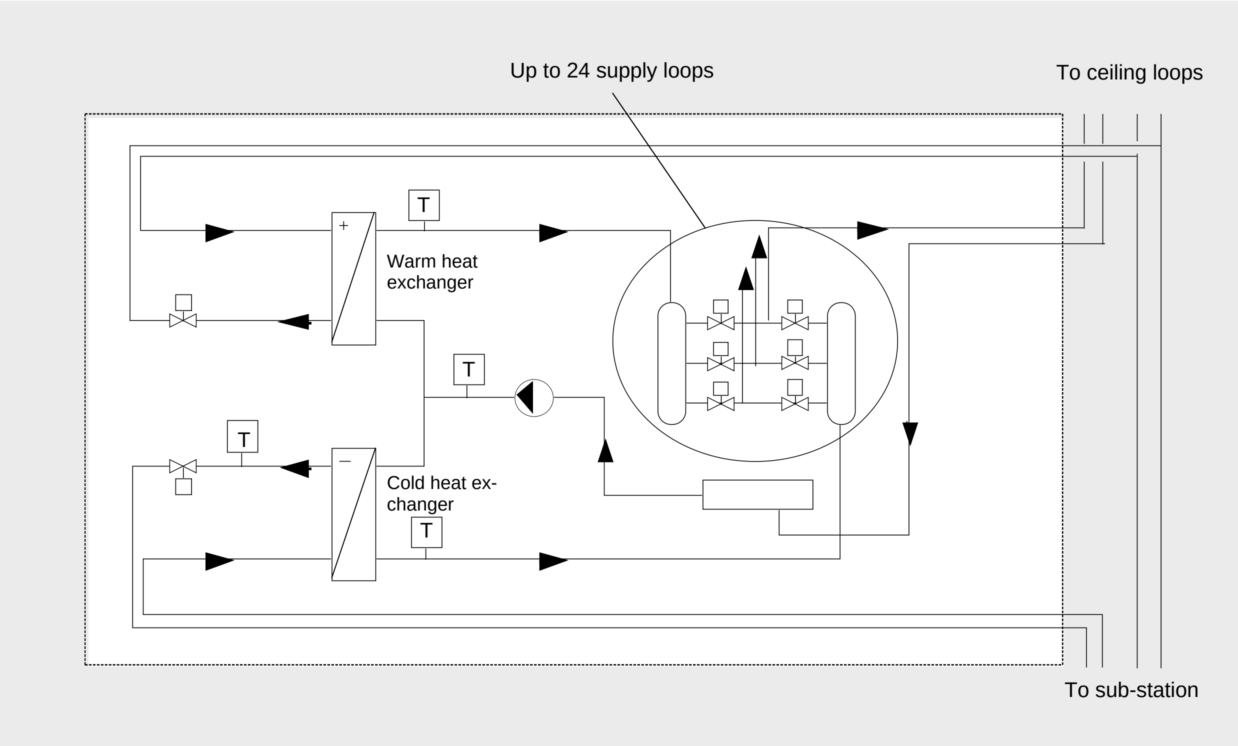


Figure 7: Heat exchanger bay

Performance Data

The main operating parameters of the system were logged during three representative periods of the year.

Figures 8 and 9 below display main running parameters versus time for both monitored rooms, on a summer day.

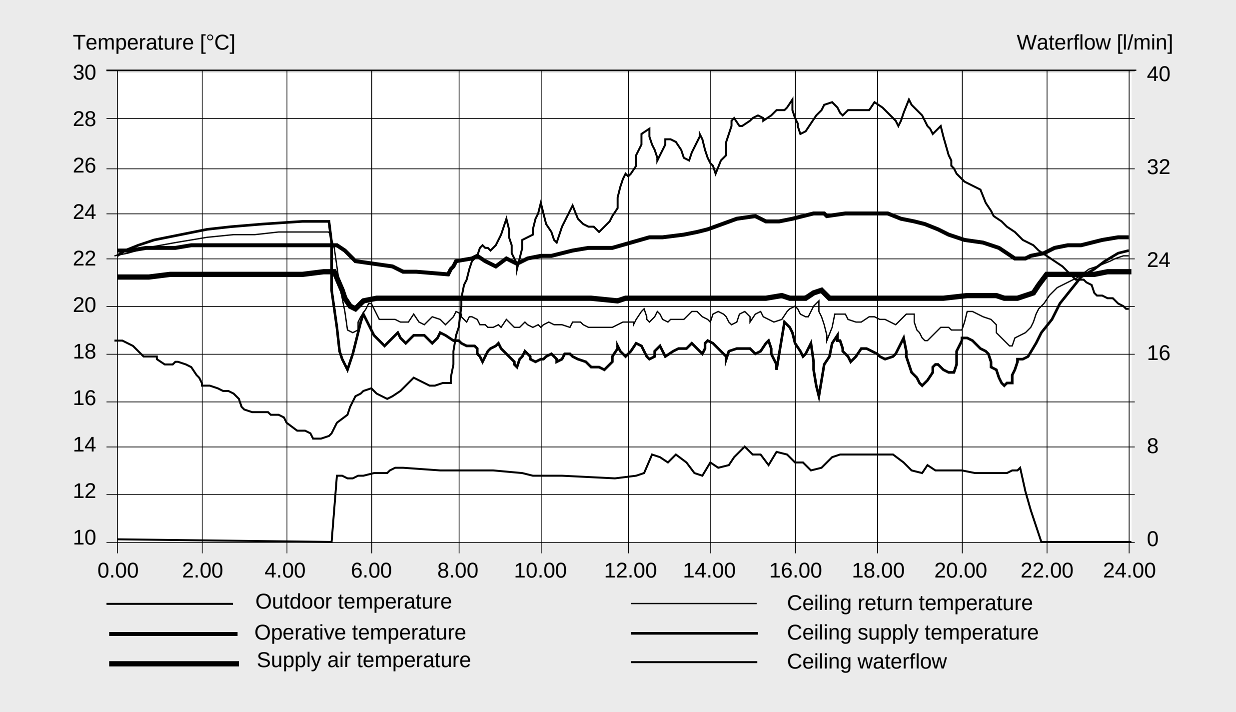


Figure 8: Measured operating parameters in a room facing east

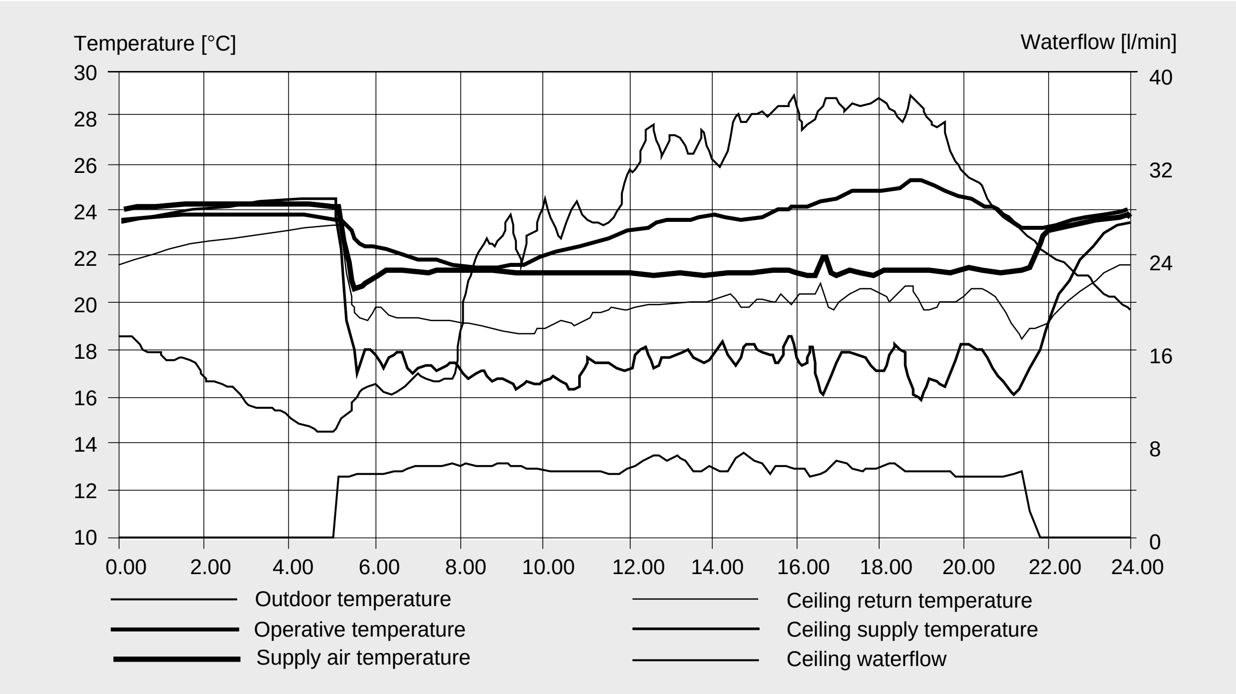


Figure 9: Measured operating parameters in a room facing west

Cooling Operation

Typical values of operating data are given in Table 1.

This table gives mean measured values during one month in summer between 12 o'clock and 6:00 pm for both a room facing East and a room facing West.

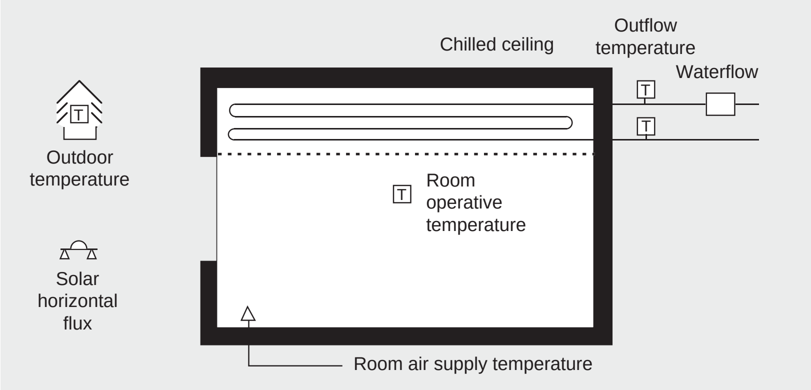


Figure 10: Schematic section through cooling and ventilation system. See Table 1 for measured mean values of indicated measurement points.

Heating Operation

The ceilings are also used for extra-heating during winter, the base heating is ensured by terminal heating of the supply air. The AHU is equipped with pre-heating coils and run-around heat recovery coils which enable the reduction of heat losses in the exhaust air.

Terminal heating coils are fitted to the ducts which deliver air to the offices.

These coils are fitted with control valves which provide automatic adjustment of supply air temperature as a function of outside air conditions.

Mean values	Room facing East	Room facing West
Outdoor temperature [°C]	27.5	27.5
Ceiling inlet temperature [°C]	18.0	17.7
Ceiling return temperature [°C]	19.5	20.2
Room air supply temperature [°C]	20.9	21.4
Operative temperature [°C]	23.6	24.0
Mean vertical air temperature [°C]	23.4	23.8
Ceiling water flow [l/min·m^2]	6.6	5.2
Solar horizontal flux [W/m^2]	602	602
Ceiling cooling rate [W/m^2]	616	832

Table 1: Mean measured values

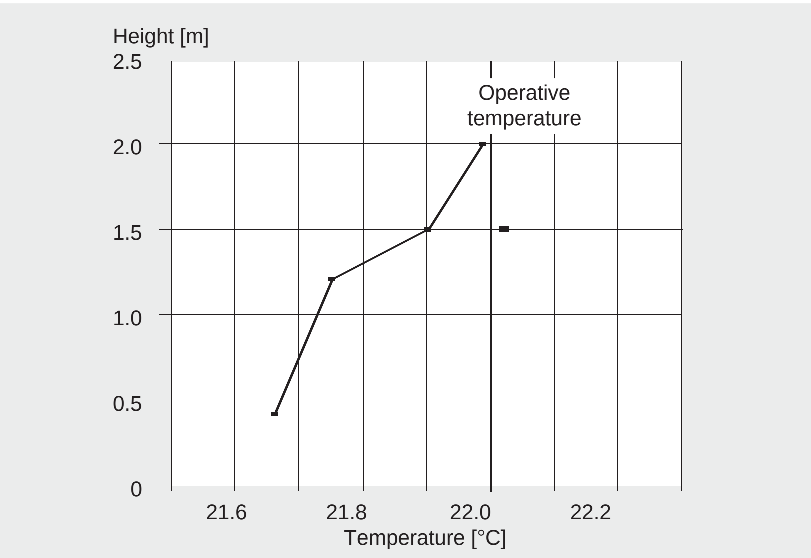


Figure 11: Vertical air gradient (mean ceiling temperature = 18.7 °C, supply air temperature = 20.7 °C)

Energy Consumption

For the cooling mode, the global energy consumption, including auxiliary devices (i. e. fans, pumps) for a four month operating period (from June till September) does not exceed 37 kWh/m^2 (139 MJ/m^2).

Summary

The monitoring of the Nestlé headquarters building plant has shown that chilled ceilings coupled with displacement ventilation can be a convenient technology for the retrofitting of old buildings.

Up to 40,000 m^2 has been equipped with such a system in the *Nestlé* Building.

The system concept is based on metallic ceiling panels chilled by capillary tubes in which cold water is circulated.

Outside air is pre-cooled and dehumidified before being blown into the offices.

Air is supplied to the room through low air velocity grilles fitted on the floor (displacement ventilation).

One of the retrofitted buildings has been monitored and results of a one year measurement period are presented in this paper.

Practical Experience

The comfort in the building was very much appreciated by office occupants.

Measurements done in summer and winter periods show that air temperature levels reached in the rooms are in close accordance with design values and comply with comfort criteria.

Energy consumption for cooling does not exceed 37 kWh/m^2 (139 MJ/m^2) for the summer period. Reduction of this first values may be expected by improving the tuning of the different components of the plant.

Figure 12: The former Nestlé mill during renovation. Today the building is used as museum and office space.

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[1] M.-P. Jouan: Plafonds rayonnants rafraîchissants pour un Siège social, Les Cahiers Techniques du Bâtiment Nr. 160, Mars 1995

[2] C. Feldmann (CoSTIC), D.T. Young (OTH): La climatisation par plafonds rayonnants, L'exemple du Siège social de Nestlé-France, Promoclim Nr. 5, 1995

[3] C. Feldmann, E. Mortier, E. Nyobe: Evaluation des performances d'un système de climatisation par plafonds rafraîchissants, Rapport d'étude ADEME, Décembre 1996

[4] D. Begoc, J. Miriel, I. Soide: Analyse des performances des plafonds rafraîchissants, Chaud Froid Plomberie Nr. 571, Juillet/Août 1995

[5] C.K. Wilkins, R. Kosonen: Cool ceiling system - A European air conditioning alternative, ASHRAE Journal, August 1992

[6] M. Fraass: Untersuchungen zu Kapillarrohr-Decken-Kühlsystemen, HLH Nr. 10/11, 1993

[7] G. Mertz: Chilled ceilings and ventilating systems - Thermal comfort and energy saving, Air infiltration Review No. 3, June 1992

[8] Detail, Zeitschrift für Architektur und Baudetail, 1998/4, page 600-605, June 1998

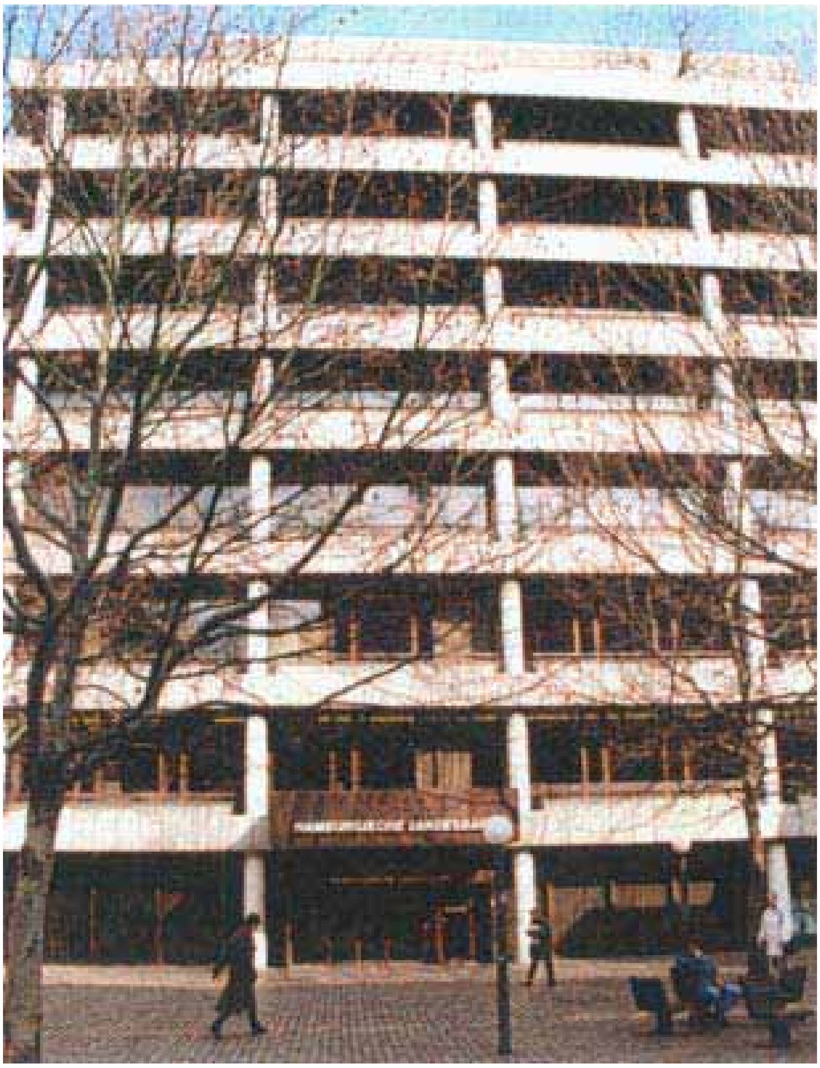
The *Hamburg Regional Bank* Hamburg, Germany

Architect: Fritz Rafeiner
Energy design concept: STULZ GmbH
Engineers: HSP Eng. Group
Reporters: K.-D. Laabs, H. Wolkenhauer, F. Joseph

Date: August 1998

Chilled Ceilings and Displacement Ventilation

- Dissipation of cooling loads up to 80 W/m^2
- Flexible installation technology
- Meeting the demand for a high level of comfort
- Reduced investment and operating costs
- System rebuilt during continuous operation of building



Background

In the past 5 years water cooling systems have been increasingly designed to dissipate cooling loads while maintaining the degree of comfort e.g. according to CEN TC 156 WG 6 "Ventilation of Buildings" and DIN 1946 Part 2 [2]. These systems are installed independently or in combination with air systems.

Boundary Conditions

The *Hamburg Regional Bank* building was constructed in 1974. Asbestos in the building has necessitated restoration. In the course of restoration, consideration was given to modernisation of the installation, renovation taking place in stages while the other storeys are fully operational. The surface to be restored over the 6 storeys is approx. 12,000 m^2. The building façades are completely glazed. The central ventilation system is located on the 8th storey.

The following was installed in the renovated areas:

- Outer zone: High-pressure induction system with 4-conduit system, flap-actuated including heating
- Inner zone: Double duct high-pressure system, blow-out via slot outlets.

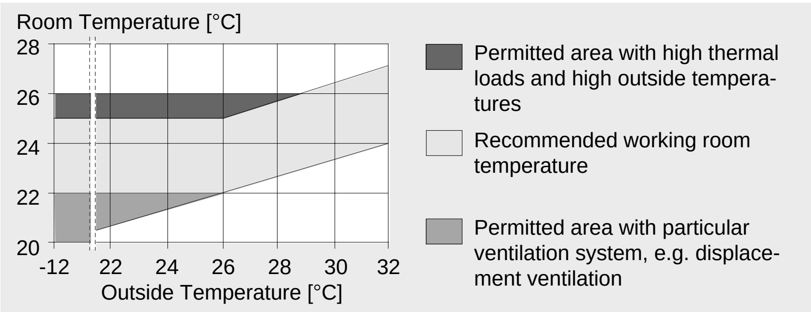


Figure 1: Comfortable working temperature range for offices. Temperatures are controlled by limits in accordance with DIN 1946 Part 2 [2]. Brief deviations are permitted during operation in summer, if high outside temperatures and high thermal loads occur.

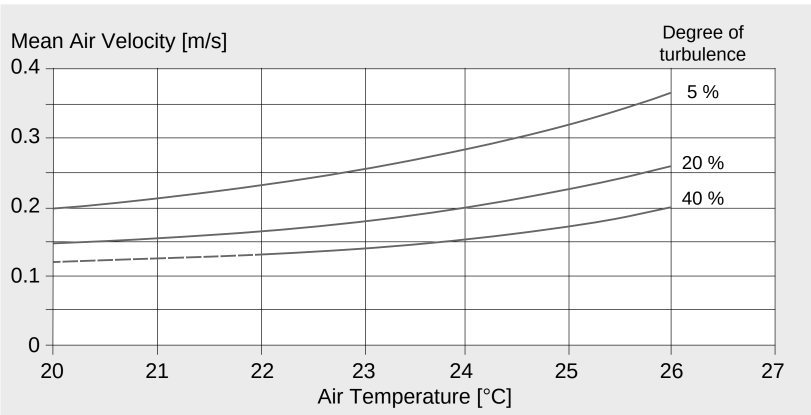


Figure 2: Mean air velocity values as a function of temperature and degree of air turbulence within the comfort range (DIN 1946 Part 2 [2])

Figure 3: Location of the building in the Federal Republic of Germany

Taking into account the operating and investment costs, the following installation system was considered:

- Outer zone: Local heating surfaces, displacement ventilation system on the façade in conjunction with a chilled ceiling.
- Inner zone: Displacement ventilation system in conjunction with a chilled ceiling. An appropriate installation system which meets the comfort criteria.

Project Data

Location	Hamburg
Altitude	10 m
Year of construction	1974
Modernised:	1994-1996
Cool. degree days (18)	215 Kd
Heated floor area	12,000 m^2
Inst. cooling capacity	1,300 kW

Costs in US$

- Low-temp. generation 1,190,000
- Chilled ceiling 4,300,000
- Ventilation 1,600,000

Design Concept

The design concept was based on a detailed modernisation study. The findings of this study are summarized below.

Outer Zone
The high-pressure system no longer meets the requirements in respect of:

- Fire protection: Ceramic nozzles instead of plastic nozzles are required.
- Additional fire protection dampers between floors are required in the air system.
- The comfort criteria of DIN 1946 Part 2 in respect of permissible air velocities, penetration depth of the winter/summer room air distribution varies.
- Economic efficiency – the flaps have air leakage rates of 15 to 20 % (distorted flaps and damaged seals).

Inner Zone
The air outlets do not meet the requirements of DIN 1946 Part 2 January 94.

General

- The control system is antiquated (electro-pneumatic).
- The fire protection dampers do not bear any test mark and have bound asbestos, ventilation box units are single-wall, thus questionable in terms of hygiene and acoustics.
- Heat recovery is only possible to a limited extent by the mixing of recirculated air. A *rotary heat exchanger wheel* with a design efficiency above 75 % would be better.
- Cooling was generated by means of refrigerant R 12 which contains CFC's.
- The existing air systems are wasting energy and should be replaced by modern systems.

Proposed Systems

- Installation of displacement ventilation system – air rate 6 m^3/h and m^2 floor area, chilled ceiling for outer and inner zone.
- Outer zone static heating to cover transmission losses.

Given Boundary Conditions

- The modernisation had to take place floor by floor, keeping the other storeys in full operation.
- An asbestos renovation was underway.
- On the 6^{th} storey the duct supply air line for the 7^{th} storey including heating and cold water lines had to remain.
- The ceiling cassettes of the chilled ceilings should be non-directional.
- The chilled ceiling cassettes must meet acoustic requirements.
- The chilled ceiling cassettes should have as large a surface area as possible, taking into account good handling and accessibility, preassembled in the workshop.

Factors During Planning Stage

- After completion of the installation specifications, decision was made to cover the inner court with a glass roof (the façades were previously outer zones).
- All floors were now connected to the atrium. A glass roof was required to reduce transmission losses.
- A sprinkler system using wide-angle nozzles and installations for the removal of exhaust air in the glass roof area were needed.
- The installation of a sprinkler system was essential due to the connection of the inner court to all floors.
- The presence of a central sprinkler system required a larger water reservoir.

Figure 4: Atrium with open access to the office floors

Planning Data

Performance Data

Overall air quantity	74,900 m^3/h
Refrigerating capacity of displacement ventilation	399 kW
Heating capacity of central unit	175 kW
Heating capacity of recovery units	175 kW
Heat recovery capacity	949 kW
Humidifying output	179 kg/h

Specific Data for 6th Storey

Floor area:	2,500 m^2
Displacement ventilation:	
• Air volume	16,500 m^3/h
• Outside air rate (10 m^2/person)	>60 m^3/h·p
• Cooling capacity	12-15 W/m^2
Chilled ceiling:	
• outer zone	83 W/m^2
• inner zone	62 W/m^2

Design Criteria

Figure 5: View of retrofitted office with chilled cassette ceiling and displacement ventilation system

The following design principles were strived for:

- Removal of the exhaust air via exhaust air fittings, in order to minimise the thermal load.
- Operation of displacement ventilation solely with outside air.
- Use of *rotating wheels* as a regenerative heat recovery system with design data efficiency of at least 75 %, i.e. 75 % of the energy contained in the exhaust air is transferred to the supply air so that the energy required for using 100 % outside air is only 25 %.
- Making use of the storage effect of concrete ceilings by installation of a chilled ceiling provided with open joints.
- Insulation of the complete supply and exhaust air system in the ceiling cavity as air circulates in the ceiling cavity to utilise the storage effect of the ceilings. The minimum saving in cooling capacity by making use of the storage effect is about 15 %. The saving should tend to be even higher.
- Equipping the radiators with electronic radiator valves which are operated in sequence with the outer zone chilled ceilings. As experience with installations which are in operation has shown, users expect a *hot radiator* with low outside temperatures. This is ensured by minimum flow rate control.
- The water installation should be separated from the ceiling cassettes, i.e. the chilled ceiling elements must be connected to the water-conducting pipes by the factory, so that only a water connection to the water piping on the primary side is required for each ceiling cassette.
- The ceiling cassettes of the chilled ceilings should be non-directional.
- The ceiling elements should consist of powder-coated aluminium or sheet steel.

Control Strategy

Room conditions

- Summer 26 °C/50 % rel. H.
- Winter 22 °C/50 % rel. H.
- Windows not to open

Ventilation equipment on level

The supply air is processed centrally in the primary air system, i.e. heating, cooling, humidifying and dehumidifying. From a control point of view, the level consists of:

- 10 individual room circuits
- 35 zone control circuits (large area)

Cooling water regulation

The cooling water inlet temperature is controlled for the entire level via a counter-flow heat exchanger and a straight-through valve. The minimum inlet air temperature is:

T_{min} = dew point + 1.5 K

The DDC substation calculates the dew point based on the humidity of the exhaust air and the room temperature.

Dew point monitoring

When humidity builds up, the humidity sensor in the common cooling water supply switches off the secondary pump by means of hardware and closes the straight-through valve.
An immersed temperature regulator (thermostat) has the same function at temperatures below 15.5 °C of the cooling water supply.

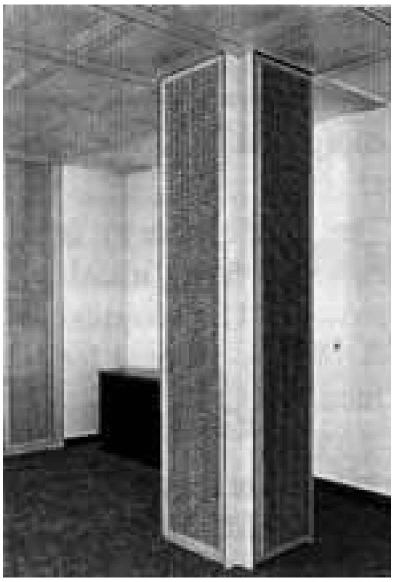


Figure 6: View of displacement ventilation outlet. Air flow 100 m^3/h per side, total 400 m^3/h

Figure 7: View of radiator and façade displacement ventilation outlet. Air flow 100 m^3/h

Figure 8: Installation of chilled ceiling panels

- The provided control units of the control zones must be established before the final design of the ceilings.
- In order to carry out the renovation storey-by-storey, all installations should be within the storey concerned.
  It is to be ensured by suitable measures that the supply air temperature at the displacement ventilation outlets is *not* above room temperature (installation of recovery units, insulation up to the displacement ventilation outlets).
- Particular attention must be paid to the ventilation of the water network of the chilled ceilings.
- In order to prevent any great loss of water in the event of leakages, heat exchangers should be provided for disconnection on a storey-by-storey basis. Primary cold water temperature range is generally 6 to 12 °C. Secondary cold water network for the chilled ceilings is generally 16 to 18 °C.
- The office furniture provided for the installation should be placed away from the displacement ventilation outlets (at a distance of at least 1 m) and have a clearance to the floor of 20 - 25 cm.

Operating Data

Cooling Performance of Chilled Ceilings

With chilled ceilings the cooling performance is dependent on the location in the building. Therefore measurements on site or at the research centre should be made. The important reason for taking a measurement is the simulation of the cooling loads in an enclosed area. We can use a space in the inner zone or outer zone, simply by enclosing it with light walls or paper. The airtight limit of the floor space must be guaranteed. The simulation of external cooling loads, lighting, people and machines result in the expected data of a real-life situation. The cooling performance is the result of water mass flow rate and the temperature difference.

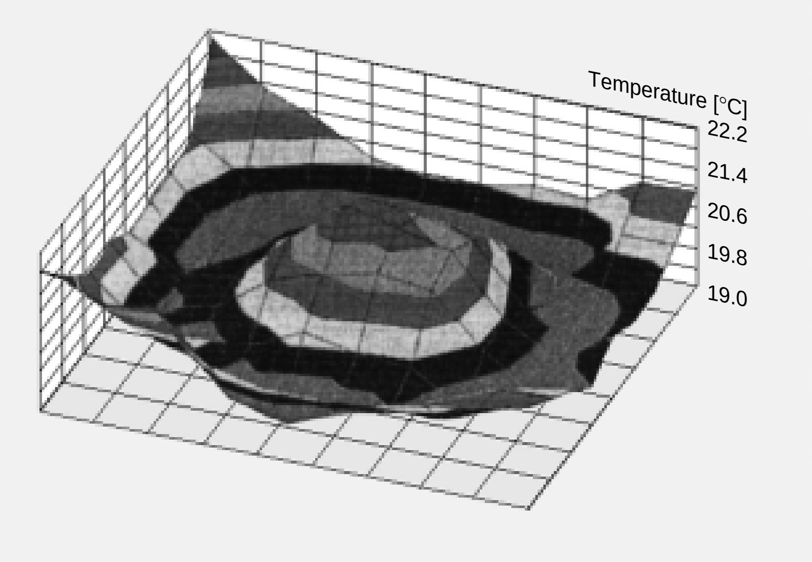


Figure 10: Performance measurements and temperature distribution of cooling cassettes

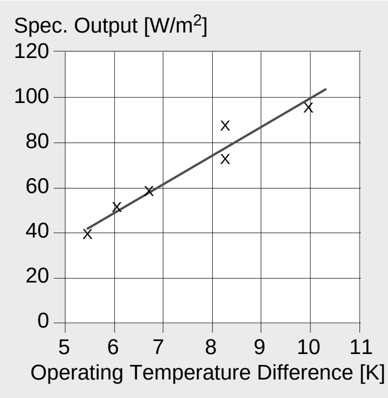


Figure 9: Performance curve of 4th floor (outer zone)

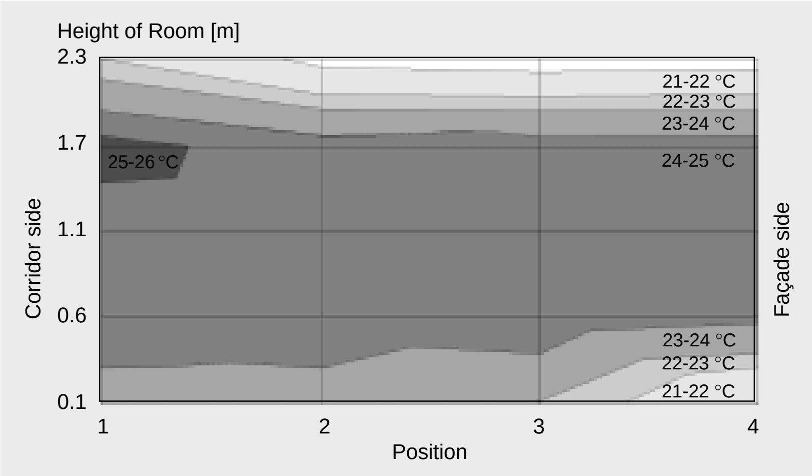


Figure 11: Temperature stratification in the room (section from corridor to façade)

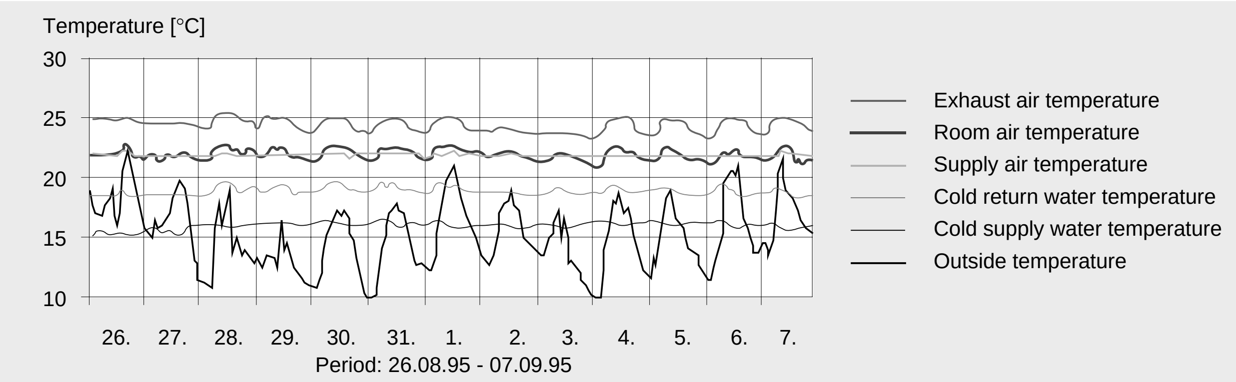


Figure 12: Operating characteristics

Energy Savings

The considerable savings in operating costs by comparison with conventional systems are due to the reduced air flows and thereby reduced heat energy requirement.

To compare air-only systems, with a displacement ventilation system in combination with chilled ceilings, the cost of the recirculating pumps for the cooling water circuit of the chilled ceilings must be included in the calculation. The comparable cost of this combined displacement ventilation system will be approx. 2.90 $/m^2$ and annum.

The differences in costs as shown in Table 1 should be seen as energy cost savings in favour of the displacement ventilation system.

The costs for building transmission heat losses, dissipating excess heat (cooling costs) are not included in this calculation, nor the costs of humidification, as in this respect there are no significant differences between the various systems.

Figure 13: View of glass covered courtyard

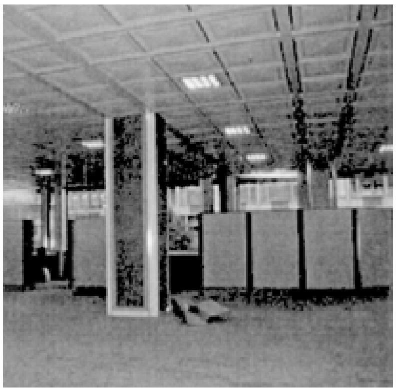


Figure 14: Open floor office area with chilled ceiling and displacement ventilation

	Air flow[1)] [m^3/m^2h]	Power only ventilation energy[2)] [MJ/m^2a]	Energy cost[3)] [$\$/m^2a$]	Thermal energy cost[4)] [$\$/m^2a$]	Total energy cost[5)] [$\$/m^2a$]
Conventional ventilation	24.5	217	≈ 9.6	≈ 6.6	≈ 16.2
Variable volume ventilation	17.0	153	≈ 6.8	≈ 4.6	≈ 11.4
Displacement ventilation + chilled ceiling	6.0	54	≈ 2.4	≈ 1.6	≈ 4.0

Table 1: Comparison of energy costs for conventional, variable volume and displacement ventilation systems in combination with chilled ceilings (average thermal load 65 W/m^2)

1) *52 weeks per year, 5 days per week, 11 hours per day (2860 h/a)*
2) *Pressure difference 2,500 Pa for supply and exhaust, η_{fan} = 0.8*
3) *Electricity price assumed: 0.16 $/kWh*
4) *Δt = 8 K, 1,200 full load hours, heat price assumed: 48 $/MWh*
5) *Ventilation only, without transmission losses, cooling and humidification*

Investment Costs of Installation System

Note:

For guarantee reasons and also for visual reasons, the entire ceiling including the strip grids should be supplied by the supplier of the chilled ceiling. The costs of a normal suspended false ceiling are thus dispensed with.

When considering air-conditioning costs, these costs can be deducted. This item is shown separately at the end of the cost assessment.

Specific cost of the chilled ceiling including strip grids and retaining structure as a mean value of inactive and active surface as well as the necessary inspection openings and primary piping:

- 355 $/m^2 (550 DM/m^2)

Specific cost of displacement ventilation system including air processing unit, including refrigeration, including heat recovery, 6 m^3/m^{2}h x 18.00 $/m^3:

- 110 $/m^2 (170 DM/m^2)

Specific cost of secondary piping including shut-off devices and accessories including refrigeration:

- 84 $/m^2 (130 DM/m^2)

Specific cost of control system in the form of modern DDC control as well as connection to the building services management system:

- 58 $/m^2 (90 DM/m^2)

Specific cost of radiators including piping and fittings:

- 39 $/m^2 (60 DM/m^2)

Total cost of HVAC-system:

- 645 $/m^2 (1,000 DM/m^2)

With conventional modernisation, the cost of the suspended ceiling would be estimated elsewhere so that in principle a sum of 100 to 130 $/m^2 (DM 150 to 200 per m^2) would have to be deducted. The comparable costs for the proposed system are therefore $ 515 to 545 $/m^2 (DM 800 to DM 850/ m^2).

The costs are based on a total equipped area of approx. 12,000 m^2. The value could be somewhat higher in the case of smaller areas, and somewhat lower in the case of larger areas.

Heat generation itself is assumed to be available, as is the connection of the heat exchanger on the heating side.

Heat exchanger connection = 100 Watt/m^2 (Unit + recovery unit) x 0.40 $/Watts ≈ 40 $/m^2 (DM/m^2).

This value would still have to be added, working on the "polluter pays" principle.

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Operating experience

- The 6th storey installations were commissioned without any problems in December 1993.
- The 5th storey was put into operation in September 1994, the 4th storey in December 1994.
- The installations were accepted and approved of by the users who assessed the room air conditions as being very pleasant.
- Acceptance of the built-in system right from the start of the operation is surprisingly high, whereas there are frequent problems in the case of other ventilation systems.
- Apart from slight corrections to the assembly sequence, no changes were made during the installation of the 5th and 4th storeys to the system parameters listed for the 6th storey.
- The 3rd storey was installed later and completed in June 1995.

Due to good user acceptance, an increase in height of the court and approx. 3,500 m^2 of office space will also be equipped with the system described.

The *Advanced House* in Laval, Canada

Ground Coupled Reversible Heat Pump

Design concept: Luc Muyldermans
Engineering: TN Conseil
Project Supervisor: A. Gagné
Reporters: S. Hosatte, L. Bassani, H. Bui, CEDRL-CANMET

Date: August 1998

- Wells for ground cooling and heating
- Heat recovery ventilation system
- Fenestration to optimize passive solar gains

Background

In industrialized countries, the building sector is a major energy consumer. In Canada, residential and commercial buildings consume currently more than 30 percent of the country's total energy supply. Most of this energy is derived from fossil fuels that yield carbon dioxide emissions and have a considerable impact on global warming. In response to this environmental concern, Canada has emphasized the adoption of energy-efficient technologies for housing by creating the Canadian Advanced Houses Program. Figure 1 provides an overview of Canadian energy consumption.

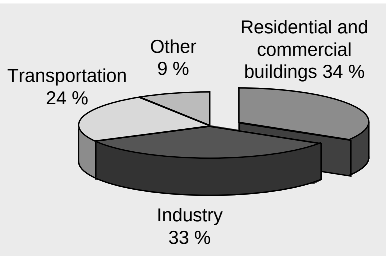

Figure 1: Canadian energy consumption

Introduction

The Canada Centre for Mineral and Energy Technology (CANMET), the research and development branch of Natural Resources Canada, in cooperation with the Canadian Home Builders Association, developed the Canadian Advanced Houses Program in 1991. The main objective of the program was to study and assess the potential of innovative technologies which had been implemented in advanced houses, in the hope that state-of-the-art residential housing in Canada would be promoted. Ten houses were built under the Advanced Houses Program, all of which were designed to minimize their impact on the environment by consuming less than one-quarter the energy and one-half the water of a conventional Canadian house built after 1985. Figure 2 compares the annual energy consumptions of these advanced houses with conventional ones. In addition to energy savings, the advanced houses offer a significantly higher level of comfort and indoor air quality to the occupants.

To qualify as an advanced house, stringent performance-based requirements in the following three categories have to be met:

- energy conservation,
- indoor air quality and occupant comfort,
- environmental concerns.

In order to reach these performance requirements, energy efficiency was considered in the following areas:

- space heating,
- space cooling,
- domestic hot water,
- lighting and appliances.

Built on the success of the Canadian R-2000 Program for energy efficient homes, the Advanced Houses Program involves assessments of designers' and builders' prototypes to meet performance-based energy targets. With such efforts, advanced houses represent a further step in environmentally appropriate and energy-efficient housing.

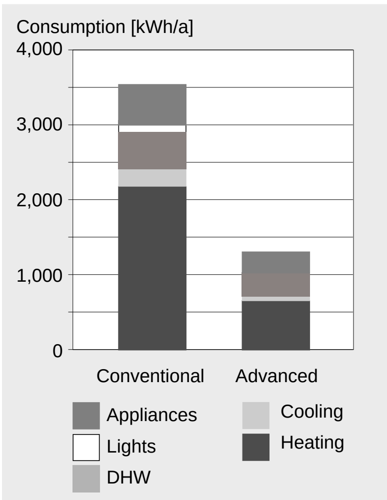

Figure 2: Annual energy consumption of conventional and advanced houses. The advanced houses are designed to be four times as energy efficient as conventional houses.

Project Data

Location	Laval, Québec
Altitude	17 m
Year of construction	1993
Cooling degree days (above 18 °C)	250 Kd
Heating degree days (below 18 °C)	4,540 Kd
Floor area	132 m^2
Space	412 m^3
Energy consumption	16,000 kWh/a

Figure 3: Location of the advanced house in Laval, Canada

Building Description

An advanced house, named the *Maison Performante*, was built in Laval, a suburban of Montreal, by the "Association provinciale des constructeurs d'habitations du Québec inc." (APCHQ), the association of home builders in Québec, in 1993. Laval is in a zone of 250 degree-days above and 4,540 degree-days below the base temperature of 18 °C. Figure 3 shows the location of the advanced house.

Design Concept

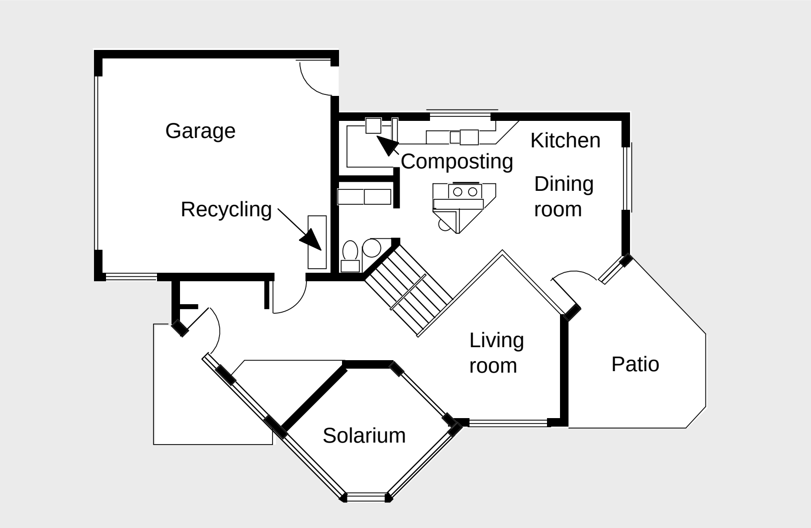

Figure 4: Floor plan of the Advanced House

This two-story house comprises mainly a basement, a garage and an insulated solarium. Figure 4 shows the floor plan of the advanced house. Several innovative technological features enhance the performance-based requirements. These features are as follows:

- Air tight building envelope
- Innovative exterior air barrier film
- High efficiency insulation
- Dry stacked insulation block foundation system
- High efficiency windows
- Fenestration which optimizes passive solar gains
- Solarium to increase passive solar gains
- Free cooling using rainwater and the ground as cold sources
- Two wells as heat sources for the heating cycle
- Heat pump for peak cooling and heating
- Heat recovery from wastewater
- Preheating of domestic hot water using evacuated-tube solar collectors
- Heat recovery ventilation system
- Efficient use of the electrical appliances
- High efficiency lighting
- Rainwater storage tanks for exterior watering

The highlight of this advanced house is the cooling system operating under three modes which involve rainwater and ground as cold sources for cooling, and a reversible heat pump.

General Energy Concept

Although Canadian houses have a low cooling load, an increasing request for a comfortable indoor environment year-round is leading to a higher demand for cooling. In the advanced house, the energy consumption required by a conventional cooling system is targeted for a 50 % reduction. To achieve this reduction, the advanced house embraces an air-conditioning system with three operating modes as well as innovative designs of the building envelope and fenestration. Figure 5 compares the results for the cooling and heating energy consumptions of the conventional and advanced house.

Building Envelope

The air tight building envelope and the insulation reduce heat losses substantially. The air barrier which is installed on the exterior of the frame walls eliminates several of the problems associated with the common interior air barrier, such as draught created by electrical outlets. Made of polyethylene and sandwiched between two layers of fibreboard for its protection and structural support, the exterior air barrier is easy to apply and saves considerably on construction time. Air tightness was measured at 0.95 air change per hour for a pressure difference of 50 Pa.

	Typical House	Advanced House
Walls	0.45 - 0.3	0.175
Roof	0.25 - 0.15	0.095

Table 1: Insulation U-values of the building envelope (W/m^{2}K)

The main type of insulation is made of recycled cellulose fibre that was blown in between the wood studs. A fibre-mesh holds the material in place to give it some air permeability, which allows a better compaction of the material. This type of insulation also has fire-retardant and insect-proof properties. Table 1 summarizes the insulation resistance values of the building envelope.

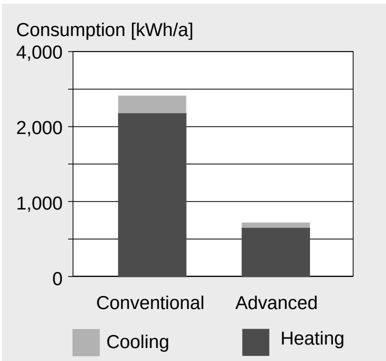

Figure 5: Comparison of cooling and heating annual energy consumption of conventional and of advanced houses

Demonstrated Energy Technology

Fenestration

In order to optimize passive solar gains, the location of fenestration was selected partly according to the house's orientation. Thus, most of the windows are on the south, southeast and southwest sides of the house where maximum solar gains are available. To reduce heat losses on the east and north façades, krypton-filled windows with triple glazing and two film coatings were chosen. On the south, southeast and southwest façades, argon-filled windows with double glazing and a low emissivity coating were the preferred choice for increasing heat gains.

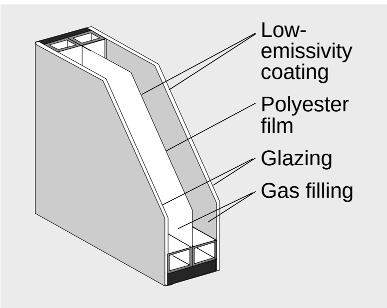

Figure 6: High efficiency windows with krypton gas filling for north and east façades

The windows were designed to maximize intakes of natural light and passive solar gains with a minimum of heat losses. The low emissivity coatings applied on the interior surface of glazing allow penetration of solar passive gains and retain indoor radiant heat. The triple-glazed units include one glazing made of polyester, which is more efficient than glass, to reduce convective heat losses. In addition, the triple-glazed units contain two low emissivity coatings that transmit most of the incident solar radiation. Reduction of convective heat losses is also obtained by introducing gases, such as argon or krypton, in the spaces between the glass panes.

Cooling Strategy

The cooling system consists mainly of two rainwater storage tanks, two wells, and a reversible heat pump which operates under specific and predetermined peak temperature levels. By exploiting rainwater and the ground as natural cold sources, this air-conditioning technology can provide an alternative to conventional systems based on chemical refrigerants, such as chlorinated fluorocarbons, thus contributing to the protection of the ozone layer. The schematic of Figure 7 describes the principles of the cooling system.

Rainwater Cooling

When the inside temperature exceeds the set point temperature, the home automation system activates the first cooling mode which uses the rainwater storage tanks. The pump, represented by P3 on the schematic of Figure 9, drives water in a closed-loop pipe from the rainwater tanks located under the garage slab to the heat exchanger E3. Fan V1 blows indoor air continuously through the heat exchanger E3 as well as E1 and E2. Pump P3 stops when the cooling demand is satisfied or when the rainwater temperature exceeds 20 °C.

Ground Cooling

The second cooling mode starts automatically when the inside temperature reaches 25 °C. If the rainwater temperature is still below 20 °C, the rainwater storage tanks operate in coordination with the ground cooling system. On the diagram, pumps P1 and P2 drive a 50 % water-methanol mixture that circulates through the wells and the heat exchanger E2. The two wells consist of one closed-loop pipe made of polyethylene, inserted into two 15 cm diameter bores with depths of 42 m and 78 m respectively. This pipe bears the mixture that ensures a good heat exchange between the house and the ground.

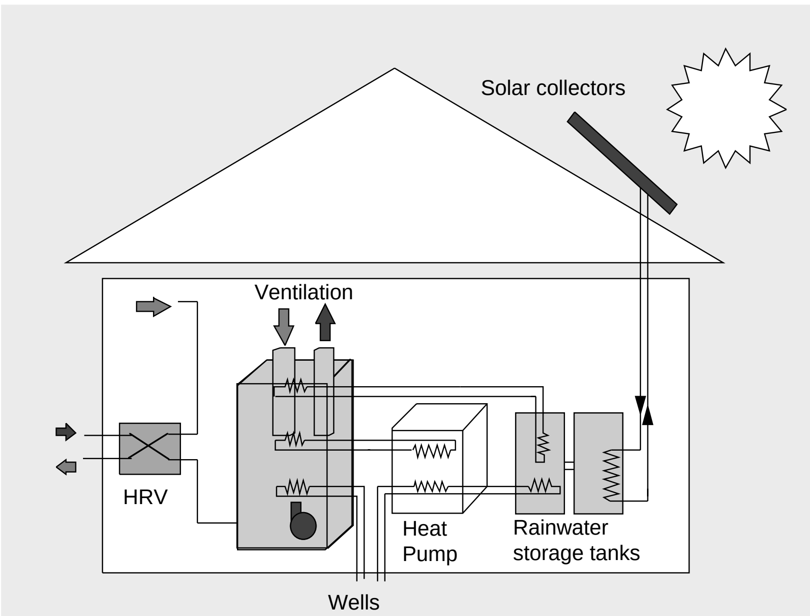

Figure 7: Advanced House mechanical system concept

Figure 8: Installation of the rainwater storage tanks under the garage slab

Heat Pump in Cooling Mode
If rainwater and ground cooling are not able to satisfy a high demand and the inside temperature reaches 27 °C, the free cooling mode stops and the heat pump in reversible mode is activated as a substitute. For personal comfort, the heat pump can also be turned on manually by the dwellers.

Heating Strategy

Space heating is also provided by the heat pump which uses both the rainwater storage tanks and wells as heat sources. During cold seasons, the rainwater intake valve is closed and the rainwater storage tanks can be used to store the excess heat collected from the house, the solarium and wastewater. This heat supplies most of the energy to the heat pump during these times. Heat is also gained through the evacuated-tube solar collectors.

Passive and Active Solar Gains
Without a system to recover passive solar gains, overheating would occur easily during daytime, due to the highly efficient fenestration. Excessive heat in the vicinity of windows, and especially in the solarium, is transferred by a closed-loop pipe to the thermal storage reservoirs and serves for night-time heating, if required. Similarly, the preheating of domestic hot water is performed using five evacuated-tube solar collectors installed on the roof. When the domestic hot water cistern reaches the desired temperature, the solar collectors are then used to heat the thermal storage reservoirs.

Heat from Wastewater
In the basement, a 190 litre tank recovers wastewater coming from the sinks, showers and dishwasher. When the tank is filled with hot wastewater, a pump drives the water of the thermal reservoirs through a heat exchanger tube located in the wastewater tank. This heat, usually lost in a conventional house, is recovered by the thermal storage reservoirs and serves for heating purposes.

Heat Pump
At first, the thermal reservoirs, namely the rainwater storage tanks, provide energy to the heat pump evaporator. However, when the thermal reservoirs cannot provide enough energy to the heat-pump, the vertical wells are connected to the heat pump cycle. If both the thermal reservoirs and the wells cannot supply enough energy to the heat pump, in order to fulfil space heating during very cold days, an electrical backup is activated to satisfy the demand.

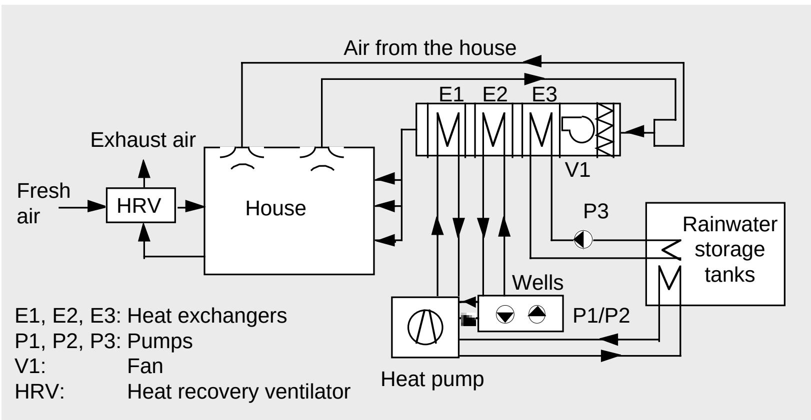

Figure 9: Advanced House cooling and heating mechanical system schematic

Performance Data

Indoor Air Quality

In addition to ventilation requirements, the Advanced Houses Program encouraged the use of healthier indoor materials. Paints, caulking, carpets, and kitchen cabinets were carefully selected to reduce formaldehyde emissions and total volatile organic compounds (TVOC's). The presence of particulates is due to the recent construction and should decrease with time. On all building parts below ground, an exterior polymer coating is applied to eliminate moisture and gas entry from the soil to the basement. Table 2 summarizes the level of contaminants which exeed considerably the ASHRAE standards.

Control Strategy

The services are managed by an integrated control system, namely the home automation system. The control system is capable of recording information such as occupancy, open doors and windows, inside temperature and relative humidity, and presence of smoke. These data enable the home automation system to regulate the different options in order to provide the best comfort to dwellers. For cooling and heating, the control system adjusts the three modes to obtain the desired indoor temperature and coordinates with occupant loads as programmed by the residents.

	Advanced House	Conventional House	ASHRAE Limit
Formaldehyde	0.054 ppm	0.058 ppm	0.4 ppm
TVOCs	0.04 ppm	0.57 ppm	n/a
Particulates	0.1 mg/m^3	n/a	0.5 mg/m^3

Table 2: Ventilation requirements of ASHRAE, for conventional houses and for the advanced house

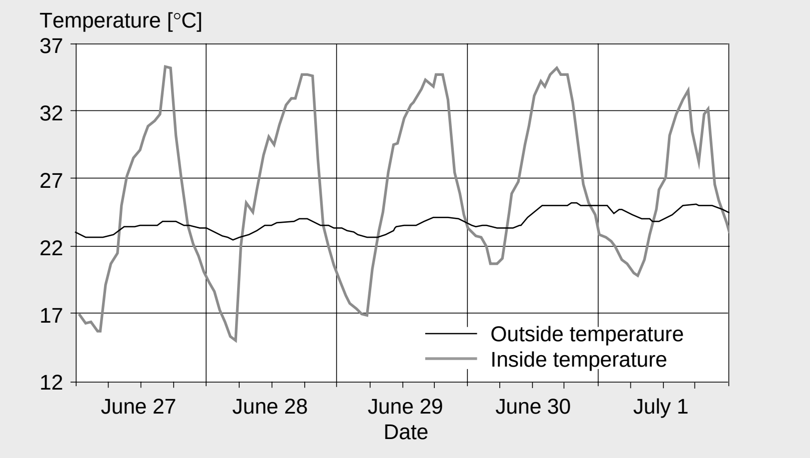

Figure 10: Inside and outside temperatures of the advanced house

Cooling Performance

Measurements of temperatures as well as flows of each closed-loop pipe were recorded between the 1st of May and 10th of July 1995. Results show that rainwater and ground cooling satisfied most of the space cooling.

Temperature
During the measurement period, the maximum inside temperature was 26 °C, and outside temperatures reached as high as 36 °C. As shown in the monitored data of Figure 10, the inside temperature was maintained relatively constant between 22 and 26 °C. Because the inside temperature never reached 27 °C, the automation system designed to start the heat pump in cooling mode at ASHRAE standards of 27 °C was never activated. In fact, the occupants always turned on the heat pump to the cooling mode manually before the temperature reached 27 °C. Nevertheless, the rainwater storage tanks combined with ground cooling could have been sufficient to maintain indoor comfort in agreement with ASHRAE standards.

Free Cooling
Rainwater cooling was mostly effective during spring. As displayed in Figure 11, rainwater cooling was inoperative between the 18th of June and the 7th of July when the rainwater temperature exceeded 20 °C. Although the wells were more useful at the beginning of June, the control system actuated the ground cooling mode as soon as the 4th of May to supplement rainwater cooling, since the indoor temperature had reached 25 °C. Figure 12 provides an overview of ground cooling. Because of their relatively constant temperature in the range of 10 to 15 °C, the wells are more reliable than the rainwater tanks: rain temperature and

occurrence fluctuate according to the weather. As shown from Figure 13, rainwater and ground cooling operate in tandem while the reversible heat pump satisfies personal comfort only during very hot days.

Removed Heat
From May to mid-July, the cooling system removed approximately a total heat of 6,720 MJ. Ground cooling satisfied most of the demand by removing 63 % of that heat while the rainwater tanks achieved 28 %, which leaves the reversible heat pump having removed only 9 % of the excessive heat load.

Coefficient of Performance
The coefficient of performance (COP) is defined as the cooling energy provided divided by the electric energy consumption for pump, fan and heat pump activation. For the period of monitoring, the cooling system exhibited an average COP of 4.8. However, during free cooling periods with rainwater tanks and wells as heat sinks for the cooling cycle, the system attained a COP of 7.3. In comparison to a conventional cooling system which has a practical COP in the range of 2 to 3, the air conditioning system of the advanced house achieves better results and hence is profitable in terms of energy conservation.

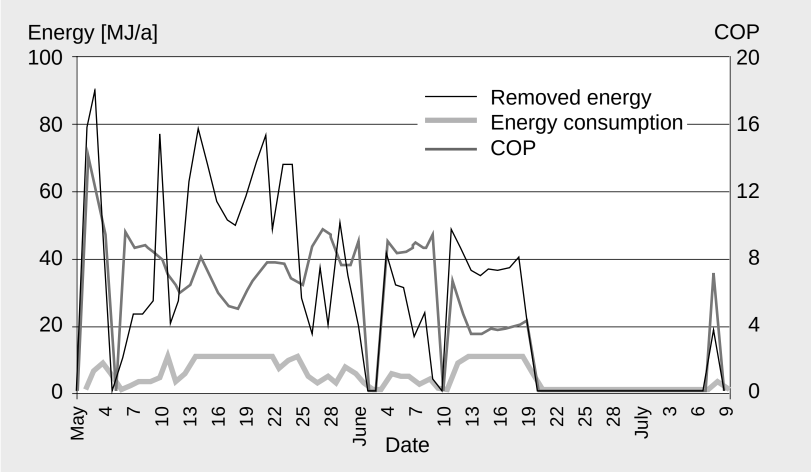

Figure 11: Rainwater cooling performance

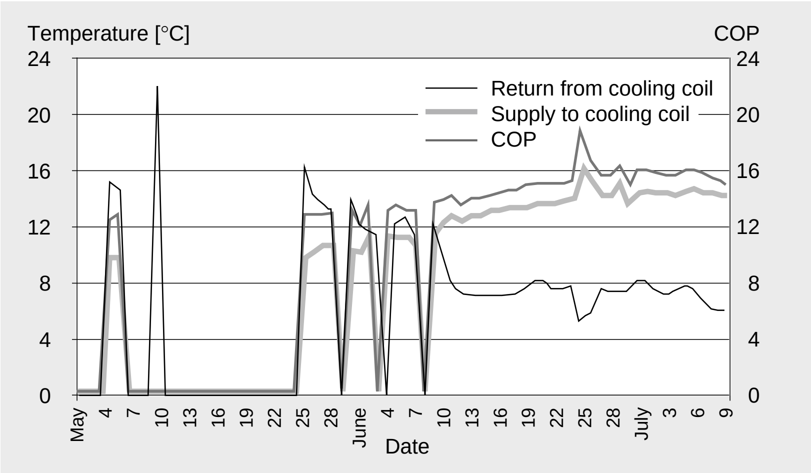

Figure 12: Ground water cooling performance

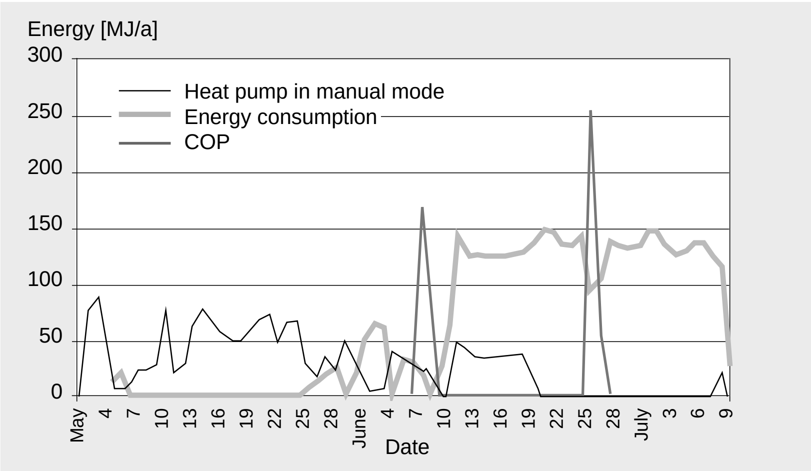

Figure 13: Removed heat by the cooling system during the period of monitoring

Costs

The entire construction cost of the house has been estimated at CND 287,000 (US$ 212,000; 188,000 ECU). This high cost is attributed to the fact that this project was a demonstration house incorporating a number of advanced prototypes and innovative design features to meet the stringent Advanced Houses Program technical requirements.

	Equip. costs	Instal. costs
Rainwater storage tanks (2)	6,000 CND 4,400 US$ 3,900 ECU	1,500 CND 1,100 US$ 1,000 ECU
Wells (2)	1,800 CND 1,300 US$ 1,200 ECU	1,500 CND 1,100 US$ 1,000 ECU
Heat pump	6,500 CND 4,800 US$ 4,300 ECU	1,500 CND 1,100 US$ 1,000 ECU
TOTAL	18,000 CND 13,000 US$ 12,000 ECU	

Table 3: Detailed construction costs (March 4, 1994 exchange rates)

Practical Experience

Although ASHRAE standards set the peak temperature for comfort at 27 °C, the occupants found this temperature too high. The heat pump was turned on manually to the cooling mode, re-adjusting the indoor temperature to an average of 23 °C. It is concluded, therefore, that the control system should also be re-adjusted at a lower peak temperature with regards to the activation of the cooling devices.

With regards to the mechanical equipment, part of the incremental costs is due to redundant design of the rainwater and ground cooling system. Table 3 summarizes the costs of each device.

Summary

The advanced house operates with an integrated system consisting mainly of two rainwater storage tanks, two wells, a reversible heat pump and a heat recovery ventilator that provide heating, cooling, ventilation, as well as fresh air tempering. The design of equipment as well as the building envelope and fenestration reflects the latest energy conservation technologies for housing.

In terms of energy management, the coordination of services by the control system and the three modes of the air conditioning device reduce considerably the household energy consumption. Free natural sources of energy, such as rainwater and ground air, are exploited to fulfil most of the cooling demand, while solar energy serves partly for heating purposes. Also the air conditioning system uses equipment with low power consumption, while the building envelope and fenestration reduce significantly the energy load. The overall low energy consumption of the advanced house, which takes advantage of natural sources, makes it indeed environmentally sensitive.

The project has been successful in that it has provided useful information for developers of residential buildings. The monitored data of the three cooling modes show that the wells coupled to the reversible heat pump yields the optimum combination, taking into consideration the construction cost of each device. Future designs may use this information to minimize further the use of the heat pump, leaving the rainwater storage tanks and the wells for most of the space cooling, with only a small electrical backup for heating during very cold days.

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The *Schwerzenbacherhof* Office and Industrial Building Schwerzenbach,Switzerland

Architect: Rolf Lüthi
Energy design concept: Bruno Wick
Engineer: Thomas Baumgartner
Reporter: Mark Zimmermann

Date: August 1998

Ground Cooling (Air)

- Seasonal heat storage in ground below building
- Same system for cooling and heating
- Simple integration in ventilation system
- High peak-load performance
- Low operating and maintenance costs

Background

Recent Swiss energy legislation, that permits active cooling only in exceptional cases, has spurred efforts to develop passive HVAC systems capable of achieving the necessary standard of indoor comfort.

Introduction

In 1986, the Canton of Zurich introduced new energy legislation resulting in far-reaching changes in building design procedures. The objectives were to promote energy conservation, to support the use of renewable energy, to reduce dependency on single energy sources and to ensure an economic supply of energy non-detrimental to the environment.

Estimates show that active cooling systems will only be permitted when the internal loads from lighting and equipment exceed 350 Wh/m^2 within 12 hours.

Energy-relevant provisions contained in the Canton of Zurich building code

- Min. requirements for insulation
- Max. supply water temperature
- Separate energy metering in buildings with five or more tenants
- Efficiency standards for domestic hot water systems
- Min. heat recuperation values
- Measurement of electrical consumption for HVAC systems
- Proof must be given of net energy savings when specified limits for air velocity in ducts are exceeded
- All reasonable action must be taken to avoid use of ventilation systems with active cooling, and especially with chillers
- Solar shading devices and windows must have a transmission factor < 15 %
- Alternatively, proof that the provisions have been met may be made by simulating the building under specified boundary conditions with DOE-2.1D.

Having recovered from their initial perplexity, an increasing number of highly qualified architects and energy designers began actively to face the new challenge, recognising that the innovative effort invested would prove an advantage in the long run. Needless to say, highly motivated owners are also a prerequisite for futuristic projects of this type.

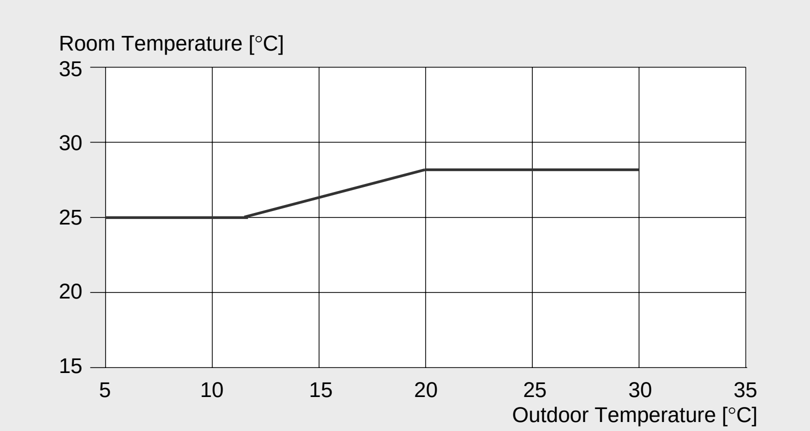

Figure 1: Acceptable indoor temperature in relation to the outdoor temperature. Active cooling is only permitted if the room temperature exceeds this limit by 30 Kh/a during office hours. Days with peak temperatures above 30 °C are not counted.

Building Description

Project Data

Location	Schwerzenbach/Zurich
Altitude	440 m
Year of construction	1989/1990
Heat. degr. days (20/12)	3616 Kd
Cooling degree days (18)	198 Kd
Heated floor area	8,050 m^2
Heated space	27,060 m^3
Inst. heating capacity	240 kW
Number of working spaces	190
Costs in CHF	
• Ground coupling	265,000
• Ventilation system	670,000
Costs in US$	
• Ground coupling	175,000
• Ventilation system	445,000

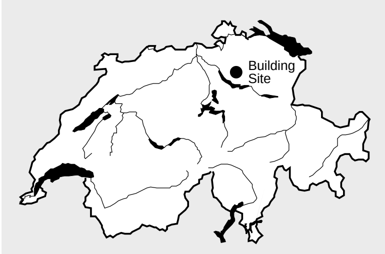

Figure 2: Location of demonstration building in Switzerland

Building Layout

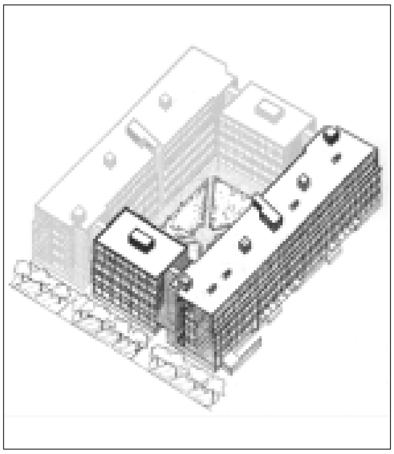

Figure 3: The Schwerzenbacherhof office and industrial building has a courtyard of 1,200 m^2. To date, about half the building has been completed.

Design Concept

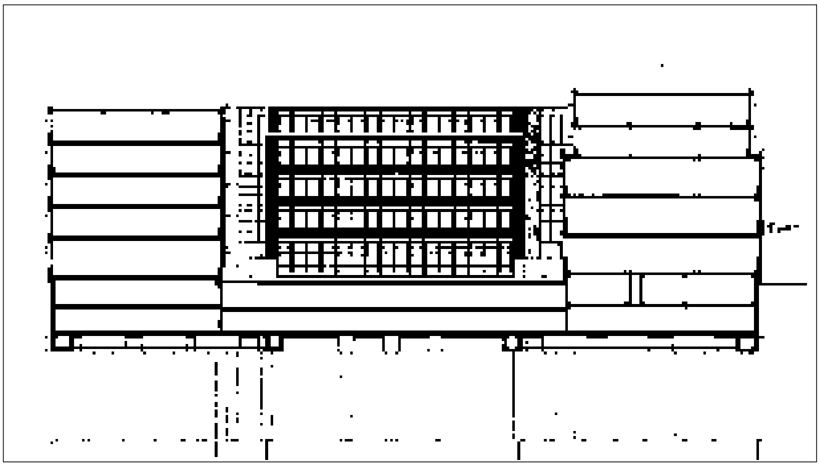

Figure 4: Section and partial view of the façade. There are two floors below ground for storage and parking. The lowest floor lies about six meters below the groundwater level. Ground and first floors are intended for industrial use only. The second floor is used for mixed industrial and office use. The third and fourth floors are for office use only.

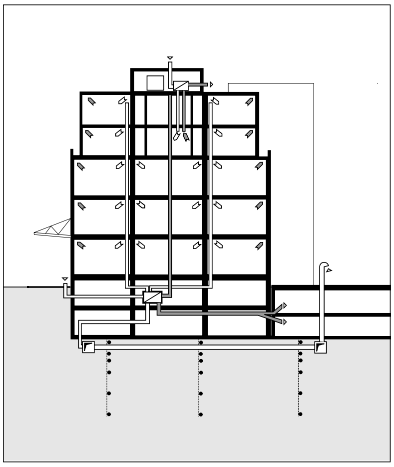

Figure 5: Schematic of ventilation and ground coupled system

General Energy Concept

Building Envelope

The building envelope of aluminium and glass, is very airtight and well insulated. The U-values are about 0.3 W/m^{2}K for the walls and 1.3 W/m^{2}K for the glazing. Thermal bridges have been eliminated as far as possible.

Solar and Overheating Protection

The entire building is equipped with automatically controlled external shading devices that are operated separately for each façade. The blinds at every second building frame location can be operated directly by the occupants.

In addition, fixed horizontal blinds are mounted on the façade. With this system, since the automatic blinds are activated only if the fixed blinds give insufficient shading, the view remains mostly unobstructed. Furthermore, should the individual blinds be incorrectly operated, the fixed blinds will prevent extensive overheating of the rooms.

The design of the façades and the use of light interior colours ensures good daylight quality. To minimize internal loads, artificial lighting has been reduced to a minimum.

To minimize air temperature variations, the room air has direct contact with the massive building structure as the concrete ceiling is not covered.

Demonstrated Energy Technology

Ground coupling of the ventilation system is one of the alternatives considered during the last decade in Switzerland for the provision of passive cooling. The concept not only allows the cooling of supply air in summer, but also the preheating of supply air in winter. Thus the ground is used twofold to store both heat and cold, and is regenerated each season. Furthermore, preheating of the supply air avoids the risk of freezing in the recuperation heat exchanger.

Particularly during colder periods in winter, but also in summer, the system achieves high peak-load performance.

The *Schwerzenbacherhof* office and industrial building was the first Swiss building to use a large ground coupled ventilation system, and enabled detailed measurements within the framework of a research project.

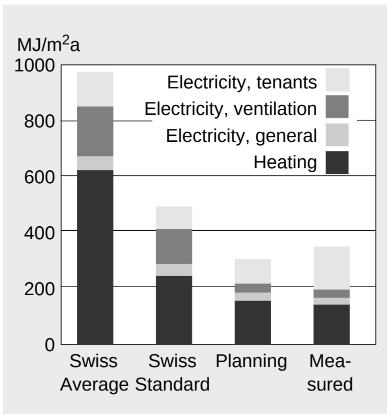

Figure 6: Specific energy consumption of Swiss office buildings compared with design and measured values for the Schwerzenbacherhof

Design Details

Ventilation Strategy

A balanced ventilation system provides both for the supply of fresh air and the extraction of used air. In winter, the necessary temperatures is ensured by the heating system (radiators). Passive cooling provides comfortable room air temperatures during summer. The supply air is not humidified.

The ventilation plant is located on the first floor below ground (Figure 5). The supply air is distributed horizontally in the corridors through metal ducts cast into the concrete ceilings. The supply air inlets are located at each second building grid. The same principle is adopted for air extraction. This allows design and installation of the system to be completed before the final requirements of the tenants are known. The supply air inlets are placed at the corridor side of the offices, the extract grilles at the façade side.

The supply air temperature is always lower than the room air temperature. For this reason, the system may also be used in displacement ventilation systems. In winter, after passing through the ground storage, the temperature of the supply air is raised to 16 °C by the regenerative heat exchanger. Further passive heating in the cast-in supply air ducts raises the final temperature to 18 °C or above.

The dimensioning of the ventilation system was based on the required outside air flow per person in summer (25-30 m^3/h). The resulting air change rates are shown in Table 1. The air change rates shown are based on using low-emission materials for interior construction. Provision for natural ventilation is made in all offices.

Ventilation schedule	Industry		Offices	
	Air change h^{-1}	Air flow rate m^3/h	Air change h^{-1}	Air flow rate m^3/h
Summer day	0.75	11,400	1.00	5,750
Summer night	1.5	22,800	2.0	11,500
Winter day	0.5	7,600	0.75	4,310
Winter night	-	-	-	-

Table 1: Ventilation schedules and air flows of the balanced ventilation system. The flow rate is doubled during summer nights to allow for mechanical night cooling.

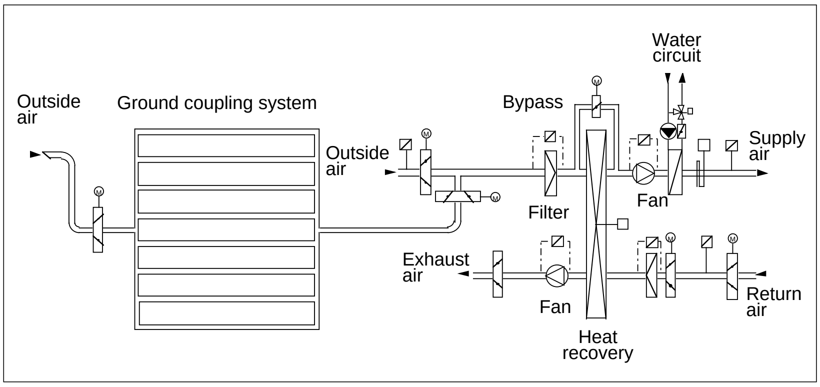

Figure 7: Schematic of the ground coupled and ventilation systems

Ground Coupled System

Without a ventilation system, internal gains from lighting and equipment would cause the temperature inside the building to rise excessively during the summer. To avoid the need for active cooling, nearly 1,000 metres of plastic piping were laid under the foundation. The plastic pipes of High Density Polyethylen (HDPE) have a diameter of 23 cm and a length of 23 m. Through these, outside air is drawn into the building. The piping is located approximately 6 m below the groundwater table, ensuring good heat exchange characteristics.

The air inlet is situated in the courtyard (see page 15-1). A metal screen prevents insects from entering the air system. A backdraft damper is installed to prevent the escape of preheat air from the ground coupled system during winter nights. Before entering the piping system, the air is passed through a large concrete distribution duct accessible for maintenance and cleaning. Because the piping system lies about 6 m below the groundwater table, all fittings have been made watertight. To account for expansion and shrinkage in the plastic piping caused by seasonal temperature variations, special seals have been used.

After passing through the piping system, the air is collected in a further large plenum duct, from where it is supplied to the ventilation plant.

Control Strategy

The ground coupled system is used when the outside air temperature is higher than 22 °C in summer and lower than 7 °C in winter.

Summer Cooling

Because of its limited cooling capacity, the ground coupled system is only used when no other cooling is available. Thus in summer, ground coupling is used only when necessary to supplement the free cooling available during the night. The latter provides about two thirds of the total cooling capacity. For this, a bypass is provided allowing cool night air to enter the building directly. Although only one third of the total cooling capacity is provided by the ground coupled system, its use is essential during daytime.

Winter Preheating

At outdoor temperatures below 7 °C, the ground coupling is used to preheat the incoming air. This also serves to discharge ground heat accumulated during summer.

Fresh air preheating also prevents freezing in the rotary wheel heat exchanger.

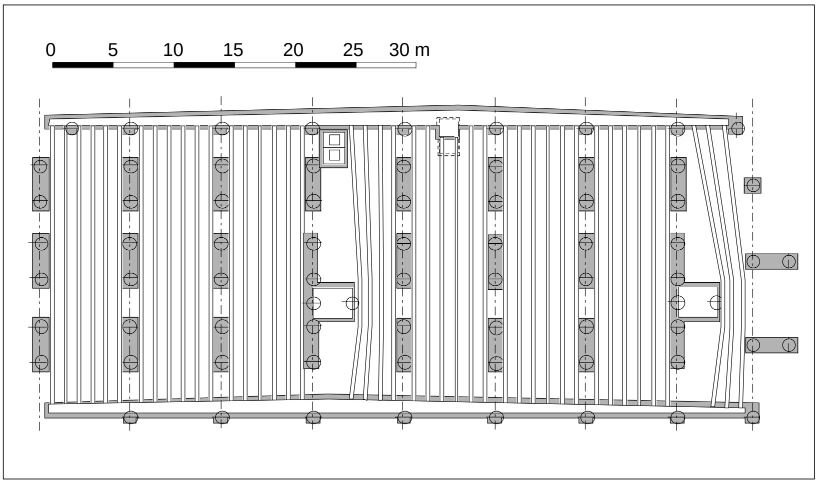

Figure 8: Ground plan of ground coupled system, situated below the basement at 6 m below ground. The watertight piping system has a total length of about 1,000 m.

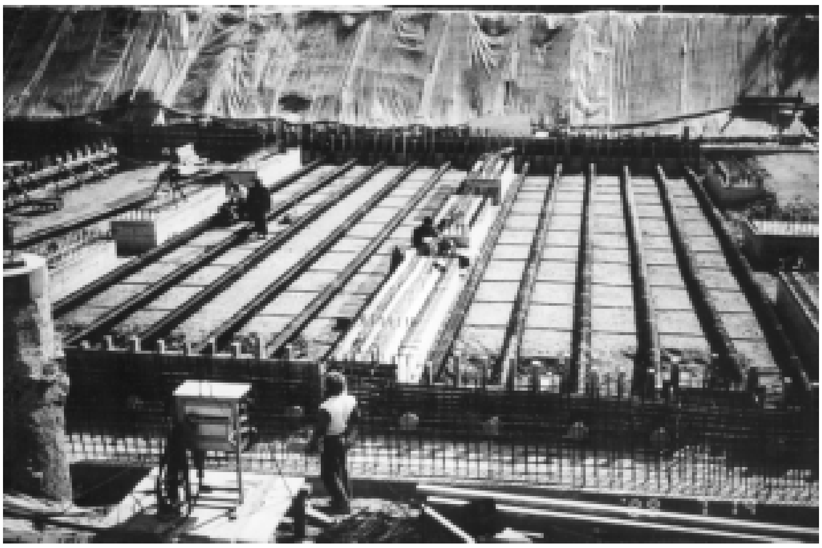

Figure 9: View of the ground coupled system during construction. At the front and rear of the picture, the accessible concrete ducts are seen under construction. At the right, the plastic pipes may be seen after covering with gravel.

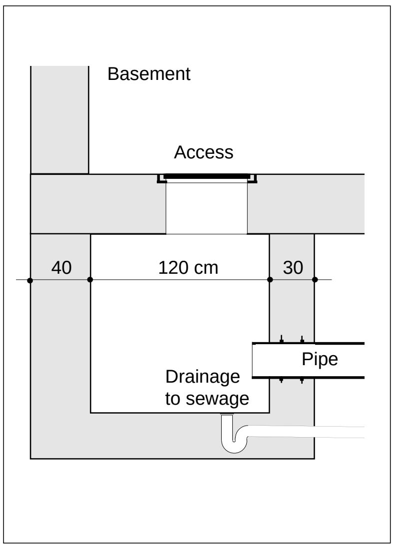

Figure 10: Detailed section of the watertight concrete duct of 30 cm wall thickness and the pipe seals

Performance Data

Overall Performance

The building has a heated floor area of approx. 8,000 m^2, which is equivalent to a heated volume of 27,000 m^3. It was designed as a low energy building with the overall objective of avoiding complex technology wherever possible.

The measured heating demand is 150 kW at -8 °C outdoor temperature, resulting in a specific heating demand below 0.7 W/m^{2}K. The heating demand is thus well below the 240 kW (30 W/m^2) calculated for a system without ground coupling. The ground coupling itself covers peak ventilation loads up to 60 kW (see Figure 12).

The measured heating energy consumption of 144 MJ/m^{2}a lies well below the target value of 240 MJ/m^2 specified in the current standard. The measured electricity consumption for the ventilation system of 23 MJ/m^2 is far lower than the 90 MJ/m^2 needed by a comparable office building having a standard ventilation and cooling system. Although the tenants' electricity consumption for lighting and equipment of 160 MJ/m^2 is higher than expected, it still lies within the usual range for contemporary buildings.

Cooling Performance

The cooling performance for a typical open-plan office room on the fourth floor was measured during one hot summer period in 1992. In Figure 11, measured room temperatures are shown in comparison to the standard comfort criteria. All temperatures are within the required limits, thus avoiding the need for an active cooling system.

The temperature in the ground below the building is influenced by the heat loss from the building,

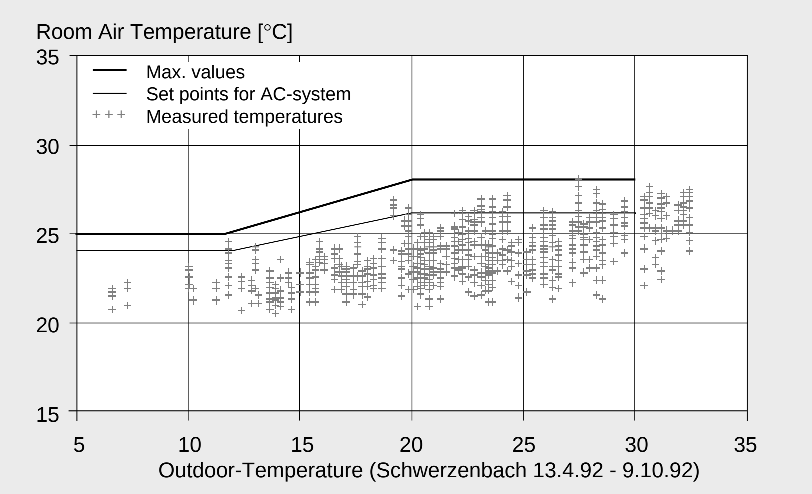

Figure 11: Measured air temperatures in a typical open-plan office during office hours (Monday - Friday). No excess temperatures were measured.

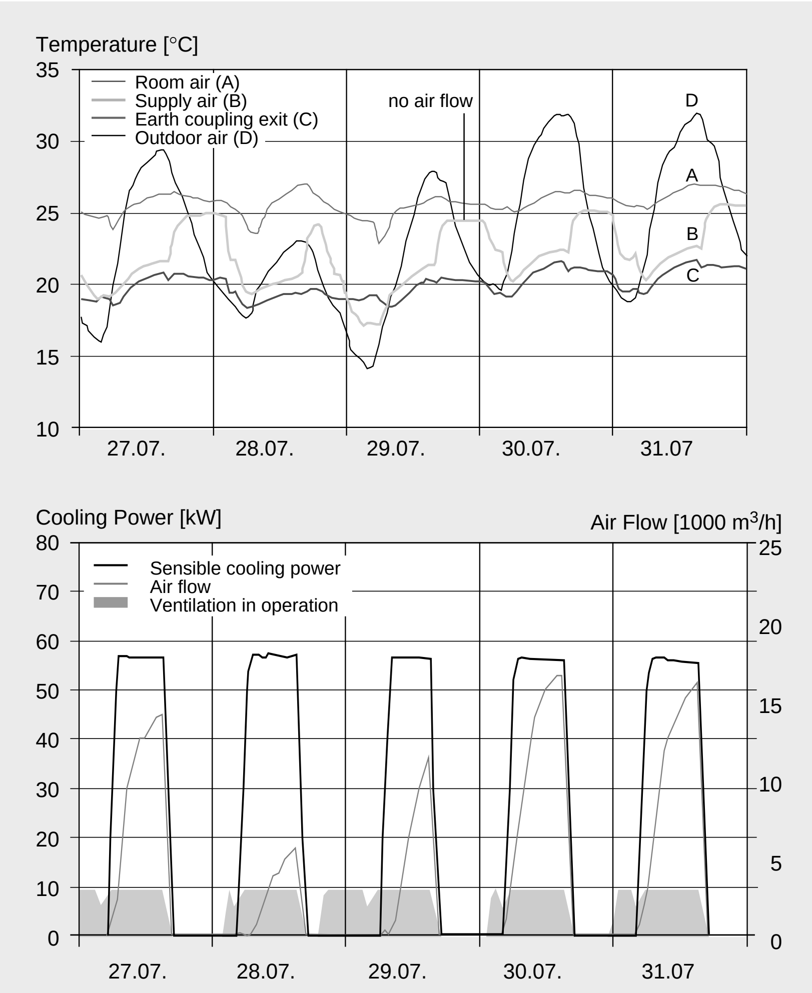

Figure 12: Outdoor temperatures and system temperatures, air flows and cooling rates during typical hot summer period

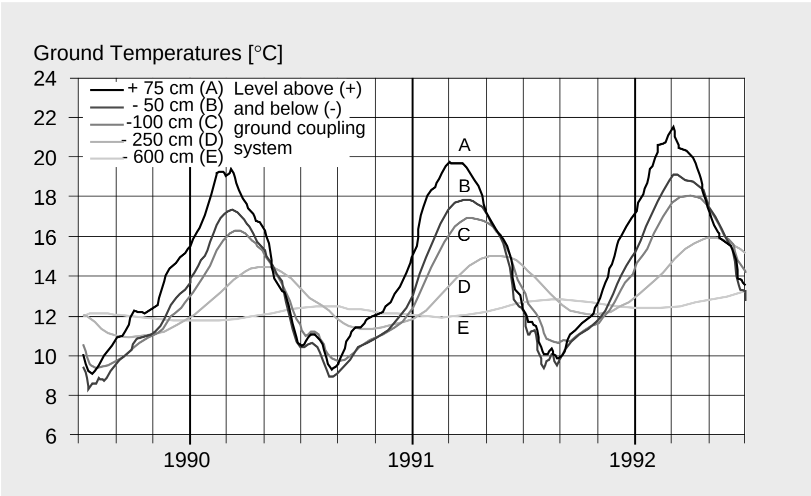

Figure 13: Ground temperatures at different depths above and below the ground coupled system over a three-year period

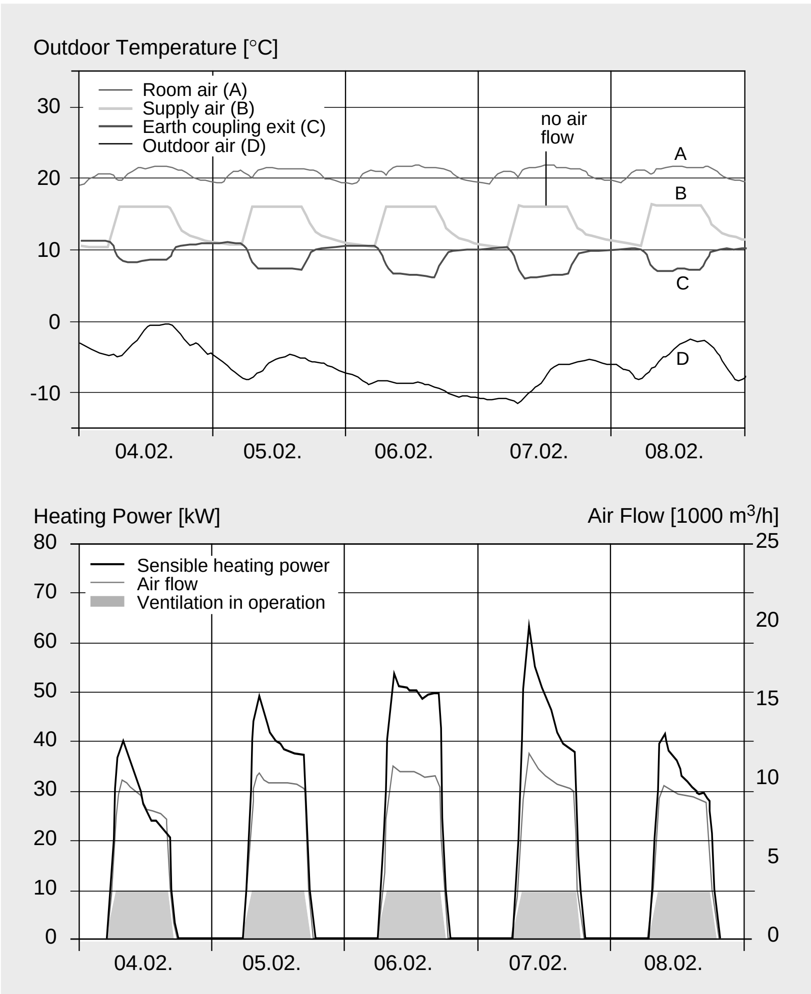

Figure 14: Outdoor temperatures and system temperatures, air volumes and cooling rate during typical cold winter period

and is a function of the insulation level and the room temperature above. Over the three-year period from 1990 to 1992, the average ground temperature at a depth of 6 m below the air ducts has increased by 1 K from 12 °C to 13 °C (Figure 13) but has then stabilized. An even more important factor influencing the ground temperatre is the ground water movement. With moving water the temperature becomes more stable.

The cooling rate and average air temperature in rooms adjacent to the ground are shown in Figure 12. Taking, for example, the 30th July 1992, the maximum cooling rate was 54 kW at an outdoor temperature of 32 °C. The supply air temperature was 23 °C and the room air temperature 26.5 °C at noon.

Heating Performance

The heating rate and the average temperature in rooms adjacent to the ground are shown in Figure 14 for a cold winter period. Taking the 7th February 1991, the air temperature at exit from the ground coupled system was 6 °C at an outdoor temperature of -11°C. This represents a sensible heating rate of 62 kW. The supply air temperature after heat recuperation is 16°C and the room temperature 20 °C.

Although the ground coupled system was designed principally for cooling, combination with preheat has several advantages:

- Freezing in the heat recuperation system is avoided
- Supply air preheating is not required
- Reduced heating capacity is needed (the reduction amounts to 70 kW in the present case)

Construction and Operating Costs

System costs are very dependent on the particular project. Figure 15 shows time-dependent costs for the Schwerzenbacherhof ground coupled system compared to a conventional cooling system. The costs for ground coupling include additional excavation, concrete ducts, piping system, special seals and the additional air inlet. The costs are higher than might be expected due to the hydrostatic pressure at a depth of 6 m below the groundwater table. The costs shown for the conventional cooling system include construction costs for the cooling plant room as well as equipment costs for the chiller, electrical control equipment and cooling tower.

There are no major operating and maintenance costs associated with ground coupled systems exept for an occasional cleaning of the system. The life span of the system is about equal to that of the buildings themselves.

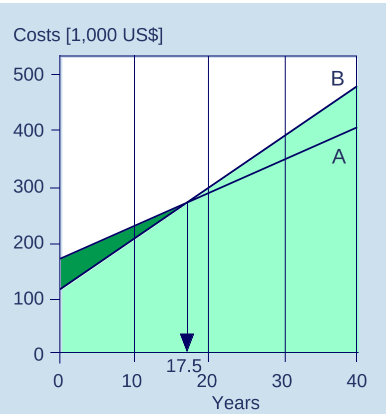

Figure 15: Sum of yearly costs of a ground coupled system (A) and a conventional cooling system (B). The calculation includes initial construction cost, amortisation over 20 and 80 years, and an assumed interest rate of 3 %. Inflation is not taken into account. Under these conditions, the additional costs of the ground coupled system have a pay-back time of 17.5 years.

The main advantage of the system is that it reduces peak demand for cooling and heating. This not only reduces energy costs, but also overall equipment and installation costs, since smaller dimensions may be used. On the basis of current Swiss energy charges, the above system was shown to have a pay-back time of between 15 and 20 years.

Used in dry ground, system performance is estimated to drop by about 50 %. Despite this, seasonal cold and heat storage in dry ground may well prove worthwhile under mild climatic conditions. Prerequisites are the avoidance of unnecessary cooling loads and the use of night cooling.

Practical Experience

Since ground coupled systems are installed below groundwater level, they require careful detail design and construction to ensure that the system remains watertight. Seasonal variations in temperature lead to shrinkage and expansion of the plastic tubes. This can result in leakage at the connections to the concrete ducts.

To ensure the tenants operate the natural ventilation, sun protection and artificial lighting devices correctly, comprehensive instruction is essential. Furthermore, to encourage them to adopt an understanding attitude towards the larger room temperature variations in summer, information on balanced ventilation and ground coupled systems should be provided.

Over one period of 14 days, failure of the night cooling system resulted in room air temperatures rising to 30 °C. This shows that even with efficient sun protection devices and ground coupling system, natural nighttime cooling is also needed to ensure adequate comfort.

Summary

Ground coupling could prove attractive for cooling and preheating ventilation air for many buildings in mild climatic regions.

The technology is already in successful use in several commercial, school and residential buildings. The potential for widespread introduction of the technology is greatest for new low-energy office buildings with moderate cooling loads, low ground temperatures, and large summer-to-winter and day-to-night temperature variations.

The system displays high peak load performance in both winter and summer. Owing to the fact that the supply air temperature is always slightly lower than room temperature, ground coupling is also applicable to displacement ventilation systems.

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The *SAS Frösundavik* Office Building Stockholm, Sweden

Aquifer Cooling and Heating

Architect: Niels Torp, Oslo
Energy design concept: AIB
Engineer: Arne Johnsson Ing. byrå
Reporter: Johnny Andersson

Date: August 1998

- Aquifer used for storing heat from the summer for use in the winter, and cold from the winter for use in the summer
- Same system used for cooling and heating
- Simple integration in ventilation system
- High peak-load performance
- Low operating and maintenance costs
- Environmental friendly system with reduced emission of green-house gases

Background

Aquifer heat storage has been applied in several Swedish experimental projects. Present-day building and building services system methods tend to increase the need for cooling of commercial premises during the summer, while significantly reducing the amount of heating required during the winter. This is due to the large amount of internal heat released from lighting and office equipment. Cooling requires a considerable energy input. It would seem feasible to store surplus heat produced during the cooling period for times of the year when heating is required. In other words, the heat store would be used as part of a combined cooling and heating system.

The Swedish Council for Building Research has formed an important part of the Energy Storage Program since the middle of the 1970s. However, the energy system for the SAS office at Solna is the first full scale installation of its kind in Sweden. The plant was put into operation in 1988 and has been extremely valuable as a reference installation.

Project Data

Location	Solna, Sweden
Altitude	30 m
Year of construction	1985/1988
Number of office rooms	1450
Degree days (20/12)	5,480 Kd
Cooling Degree days (18)	42 Kd
Heated floor area	64,000 m^2
Heated space	217,600 m^3
Glazed surface	37,000 m^2
Building corners	150
Inst. heating capacity	3,700 kW
Inst. cooling capacity	3,300 kW
Cost in MSEK(MUS$)	
• Energy system	15.6 (2.4)

What is an Aquifer?

An aquifer is a ground water reservoir, for which conditions are technically and financially favourable for the extraction of water. The word derives from the Latin, aqua, meaning water, and ferre, meaning to carry.

There are two main types of pore aquifer that are generally encountered in Sweden. The commonest type is found in eskers, which are gravel deposits left by the retreating ice from the Ice Age. Ground water in eskers has long been used as a source of water supplies for smaller and larger towns. The second type of aquifer is found in sandstone and limestone, which are encountered mainly in southern Sweden.

The material in an aquifer is highly permeable. The boundary envelope of an aquifer consists of surrounding, more impermeable materials such as clay, moraine or rock. Water continuously seeps down to the aquifer from precipitation reaching the ground. It flows through the aquifer and finally reaches lakes or the sea.

Figure 1: Location of the SAS building in Solna, a suburb to Stockholm

Figure 2: The "Interior Street" is ventilated by overflow air from the offices

Design Concept

The aquifer system is used for the SAS office at Solna outside Stockholm. The site is situated upon an esker containing a groundwater aquifer. During summer, cold groundwater at a temperature of +2 - 12 °C is pumped up from one of three cold wells and used to cool an intermediate heat exchange system. This system in turn cools incoming ventilation air in the building and also circulates cooling water which flows through baffles (vertical cooling elements) in the ceilings of the office areas.

The heated groundwater, now at a temperature of up to +15 °C, is returned through the warm wells 150 to 300 m from the cold wells. During the winter, heated groundwater is used to preheat incoming ventilation air and as a heat source for heat pumps for final heating of the ventilation air and supply domestic hot water.

Figure 4: The Frösundavik Aquifer with three cold wells in the center and the warm wells in the surrounding areas

Building

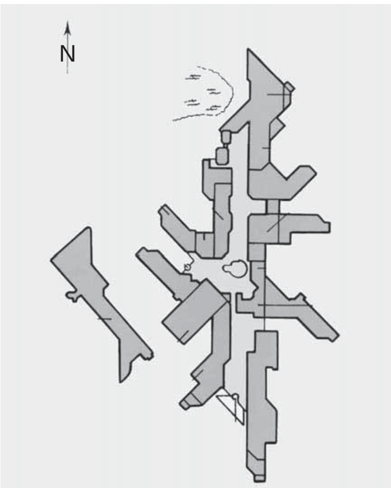

Figure 3: Plan of the building

The entire complex has been designed as a small self-contained community around a central street. This provides a natural way of creating human proportions in a complex as large as this. The concept of several buildings along a street results in an environment that is both comprehensible and varied, and to which it is easy to relate. Most of the complex is founded on sand and gravel. Structural elements below ground are cast in-situ, while the load-bearing structure above ground is of steel in combination with prefabricated concrete hollow deck beam structures.

Aquifer Heat Store at Frösundavik

Frösundavik is situated on the Stockholm Ridge, an ice-age esker. The volume of the aquifer at Frösundavik is about 1.5 million m^3. Design of the aquifer heat store was preceded by about 40 trial drillings and a test pumping, which together provided a good picture of the aquifer's extent and characteristics. Within the area investigated, the width of the ridge varies between about 100 m and 200 m. It is made up mainly of sand and gravel, with much of the ridge being below the ground water table level. The water-filled part of the ridge forms an excellent aquifer, in which conditions for ground water extraction are very favourable. The mean depth of the aquifer is about 15 m, with its greatest depth of about 30 m at the north end.

Normal temperature variations in the ground water have been monitored since 1985, when the preliminary investigations started. The mean temperature during the year varies between 7 °C and 8 °C. The aquifer now contains five wells that are used to circulate water in it. Two of them are used for warm water (at a temperature of 14 - 17 °C), while three are used for cold water (about 6 - 8 °C).

During the winter, warm water extracted from one of the two warm wells is used for preheating the ventilation air and as a heat source for heat pumps supplying heat to the building. The cooled water is then returned to the aquifer through the cold wells. During the summer, water is extracted from the cold wells and used to cool the building. This raises its temperature, and it is returned to the warm wells.

The wells have been drilled to depths of between 8 m and 28 m. The lower parts of the wells contain a filterscreen through which the water must pass when being extracted or infiltrated. The wells have been lined with stainless steel, and other pipes in the system are of polythene. The ground water pumps are installed in the plant room, which means that the equipment at the wellheads consists only of a pipe connection, an isolating valve and a vent valve.

Design Details

Aquifer System

Thermal energy is stored in an aquifer by infiltrating water at the required temperature. During the summer, warm water can be stored (heat storage) for use during the winter to supply heating. During the winter, the process is reversed with the storage of cold water (cold storage) for use during the summer for cooling. A heat store can be created, for example, by extracting ground water from a well (the cold well), raising its temperature (e.g. by using it for cooling a building) and then returning it to another well (the warm well) in the aquifer, as shown in the diagram, Figure 5.

The warmed water moves out from the warm well, gradually raising the temperature of the aquifer in the vicinity of the well. Heat is recovered when required by extracting water from the warm well, causing the warm ground water to flow back from the aquifer into the well. There is no net removal of water from the aquifer, as the system merely transfers it from one part of the aquifer to another. Aquifers often have a large volume, measurable in millions of m^3, and as they consist of about 25 % water they have a high heat storage capacity. As extraction and infiltration performances are good, high heating and cooling powers can be achieved.

Physical delineation of an aquifer for heat storage is not caused by any artificial means, but by the presence of impermeable natural formations such as underlying rock or clay beds. Local conditions: heat capacity, thermal conductivity, natural ground water flows, and differences in density between cold and warm water affects heat losses and efficiency more than the amount of energy.

If the temperature of the ground water changes, it can result in changes in the local water chemistry, which can lead to clogging of parts of the system, e.g. in wells.

Although the basic principle of energy storage in aquifers 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 and/or energy system.

Energy stores can be used when it is desired to even out the energy demand over the year, e.g. to store warmth from the summer for the provision of heating during the winter.

In order to avoid progressive heating or cooling of the ground it is important that the energy input to, and energy abstraction from, the store are approximately equal.

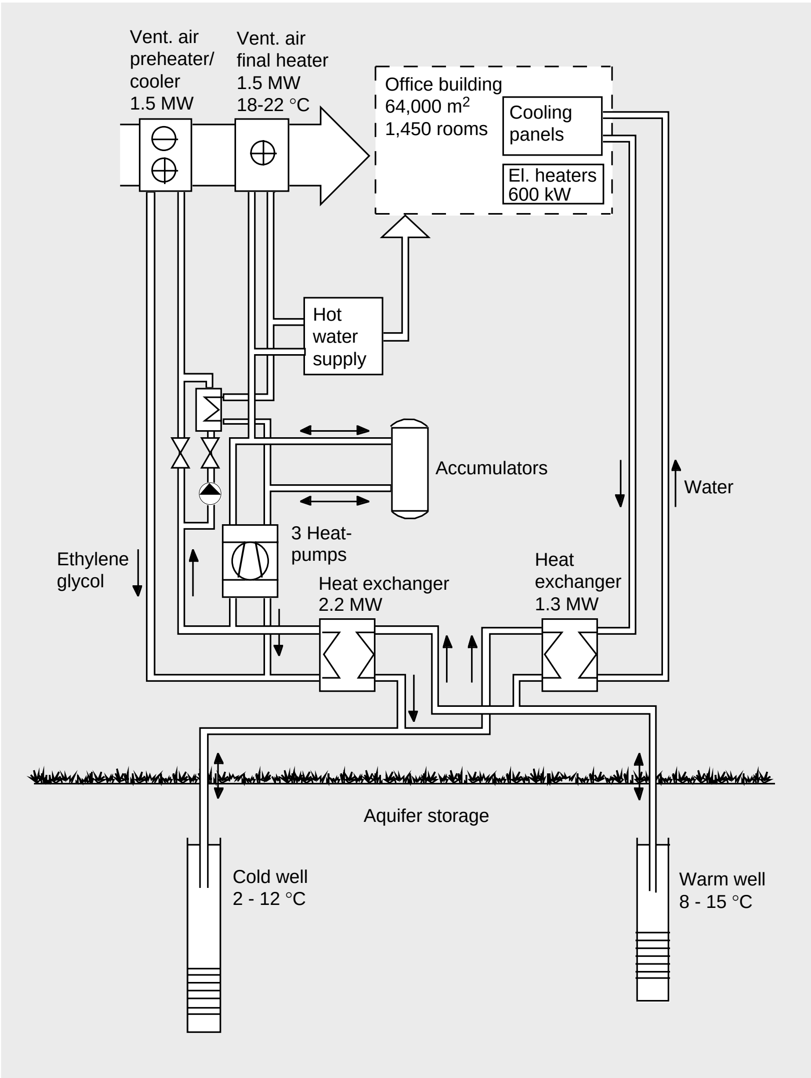

Figure 5: A simplified schematic diagram of the system. In order to facilitate operation of the plant, considerable work has been put into achieving as simple a design as possible.

System Components

The physical equipment consists of conventional standard components such as pumps, heat exchangers, heat pumps, electric boilers, water storage tanks, instrumentation equipment and circulation pumps.

Figure 6: The ground water pumps in the plant room

Heating and Cooling Requirements

The heating system has been designed to supply the building's needs in respect of pre-heating of ventilation air and the supply of domestic hot water. The total heat requirement amounts to about 3.7 MW. The system has been designed to be capable of meeting the entire cooling requirement, which at present amounts to about 1 - 1.5 MW. System cooling capacity, however, is greater: about 2 MW in the ceiling cooling convector circuit and about 1.3 MW for cooling ventilation air.

Indoor Climate System

Design of the ventilation system was preceded by careful development work, which included thorough interior climate investigations of full-scale office modules. Air quality measurements made by the Solna local authority showed that air quality was about the same close to the ground as higher up. Air intakes for the building could therefore be situated at ground level, in accordance with the architect's intentions to avoid "chimneys".

The system is based on the use of 100 % outdoor air in the ventilation system, as no re-circulated air is wanted. In order to reduce space requirements and costs of the ventilation ducts, the air flow rate has been restricted to 190,000 m^3/h.

Each office room has its own separate supply and exhaust air connections in order to meet hygiene ventilation requirements. Air is blown in and extracted at the inside wall of the room, which means that the ducts are connected to the short wall of each room bounding on the corridor. The temperature of the supply air can vary somewhat during the year. Air exhausted from the individual office rooms is discharged to the central 'street', thus heating it. Climate control of the office rooms is completely separate from the ventilation system, and can be regulated individually for each room.

During working hours, the rooms are heated by the office equipment (computers etc.). However, after office hours, and at times when the outdoor temperature is low, additional heat is required and is supplied by electric radiators. Cooling during the summer is provided by natural convection coolers, combined with the electric radiant heaters mounted above the windows. Cooled water circulates through them and creates a natural cooled down-draught. No fans or ventilation ducts are required, saving energy and space.

Ventilation

During the summer, it is necessary to cool the ventilating air. This is done by cooling the air in a heat exchanger with cold water from the aquifer through an interposing glycol circuit. This reduces the air temperature to about 18 °C and raises the ground water temperature to about 17 °C before it is returned to the aquifer via one of the warm wells. During the winter, the ventilation air is pre-heated by heat exchange with warm water from the aquifer via the interposing glycol circuit. The water flow direction is reversed relative to the summer, being pumped from a warm well. The temperature of the air is raised in the heat exchanger, while that of the water is cooled. The cooled water is then returned to the aquifer via one of the cold wells.

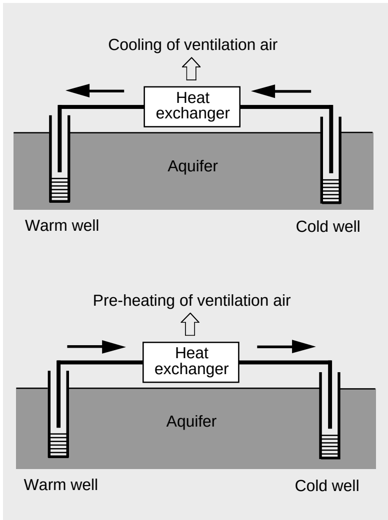

Figure 7: Cooling and preheating of ventilation air

Production of Cooling Services

Cooling can be produced either by cooling the ventilation air (pre-cooling) or via the ceiling-mounted cooling convectors. The pre-cooling is using ground water at a temperature of about 8 °C. Cooling is distributed within the building in a closed-circuit cooling system, the temperature of which is maintained at at 14 °C in order to avoid condensation on the pipes. No refrigerating machinery is required as would normally be the case in conventional office buildings. For cooling purposes, the cold ground water is extracted from the aquifer and used to cool the ceiling cooling convector circuit via a heat exchanger in the plant room. This raises the temperature of the ground water, which is then returned to the aquifer via one of the warm wells.The greatest cooling contribution is provided by the ceiling convectors. During summer, the amount of cooling required amounts to about 300 MWh/month and during winter to about 180 MWh/month, as shown in Figure 10. The mean total annual production has been approximately 2,900 MWh. This corresponds to an annual value of approx. 45 W/m^2. Pre-cooling requirements of the ventilation air vary during the year, with a load of about 30-70 MWh/month during summer.

Heating and Hot Water

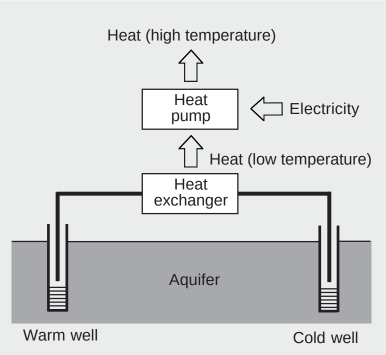

Figure 8: Production of heat at high temperature

Final heating of the ventilation air and heating of domestic hot water is done by three electrically-driven heat pumps having a combined thermal power output of 1,100 kW. The heat pumps use the warm water stored in the aquifer as their heat source, producing a domestic hot water output temperature of about 55 °C. After the water from the aquifer has been cooled in the heat pump, it is returned to the cold wells.

The maximum heat energy produced during one month was about 400 MWh. Stand-by capacity is provided by two electric boilers, having a total power rating of 400 kW.

Control System

The system is controlled and monitored by a computer. The computer records the outdoor temperature and energy requirements in the building, from which it calculates a suitable operating strategy on a daily basis.

Performance

Since starting up in 1987, the system has operated as intended, with no supply interruptions. Minor problems, of a normal nature, have of course occurred.

Extraction and storage of warmed and cooled ground water from and in the aquifer has operated well. However, one well (no. 34) suffered initially from problems with clogging during the summer of 1987. It was cleaned mechanically in October 1987 and chemically in June 1988, after which the wells have operated without problems. No clogging or performance deterioration has been noted in any of the other components of the system. It was not until 1991, however, that the heat pumps achieved their expected operational reliability. Several faults occurred during

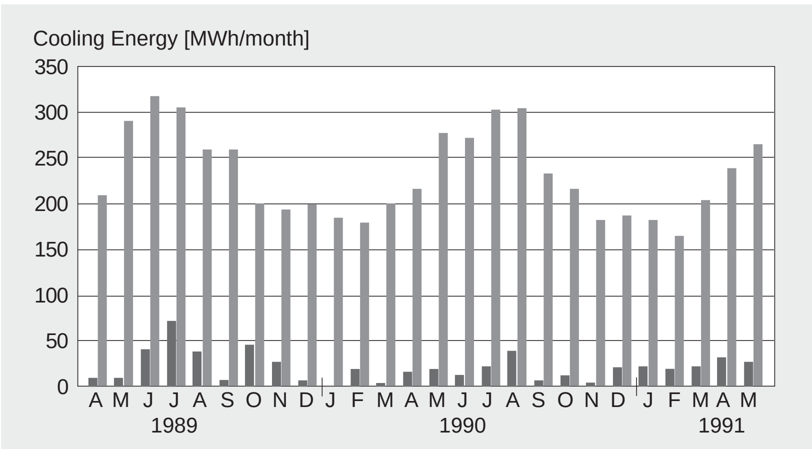

Figure 9: Monthly mean energy quantities for cooling
Dark = Pre-cooling Light = Ceiling-mounted convection coolers

the first years of operation, such as oil leaks and compressor failure. These problems were rectified by the supplier under guarantee. Between 1987 and 1990, the total downtime for the three heat pumps amounted to about one month per year. After that period the reliability of the heat pumps has been high.

Figure 10 shows that heat is stored in the aquifer between May and September, and is withdrawn from November to March. In April and October, the amount of energy interchanged is small, and can vary between heat and cold abstraction, depending on the ambient temperature. The monthly mean values shown do not include short-term storage quantities.

Figure 11 shows the performance of the aquifer system first as "system efficiency" that is defined here as the heating and cooling energy used in the building divided by the electricity used for operating the aquifer system. Figure 12 that covers the period up to and including 1995 also presents the COP-value for the heat pumps, and the relation between cooling and heating production during these seven years of operation.

The monthly system efficiency values during the first years of operation are presented in Figure 12. When the cooling production dominates, the system efficiency reaches its highest value, approx. 11. During winter when the main part of the heating energy is produced by the heat pumps, the system efficiency will come close to the heat factor (COP) of the heat pumps.

Based on measurements the annual system efficiency value should be between 4.5 and 5.0 for a normal year.

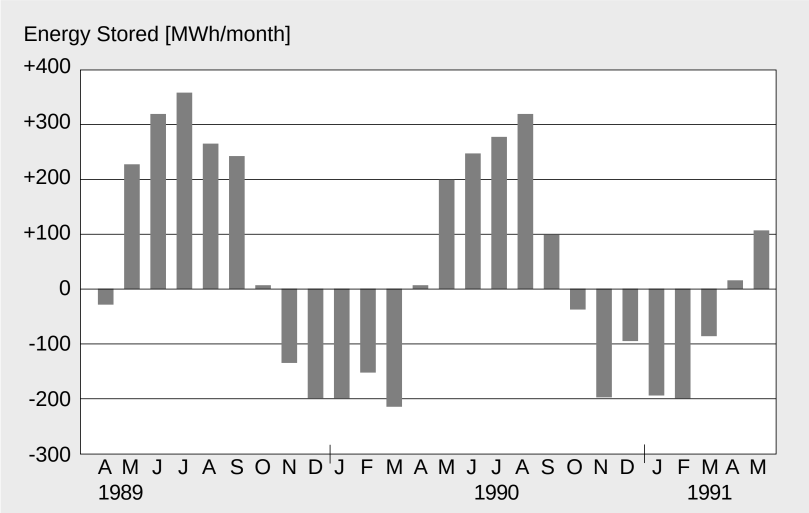

Figure 10: Energy quantities (monthly mean values) stored (+) in and withdrawn from the aquifer (-)

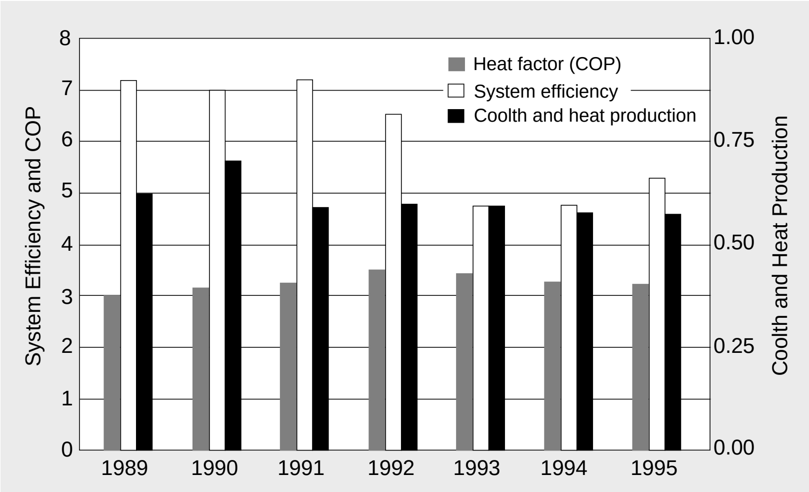

Figure 11: Aquifer system performance 1989 - 1995

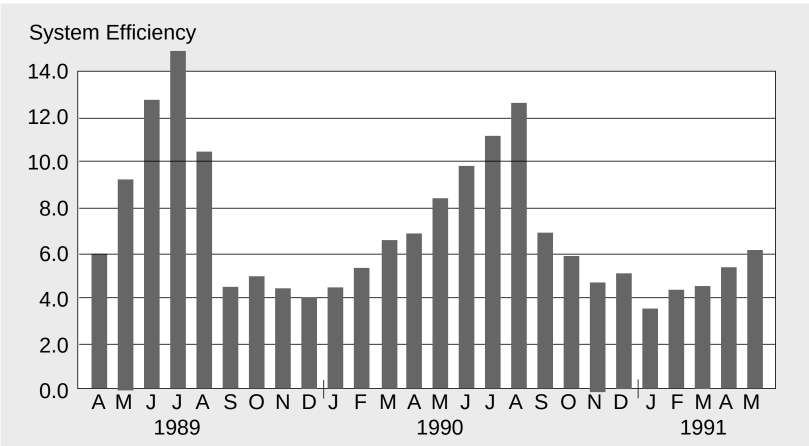

Figure 12: Monthly values of system efficiency, i.e. used energy for cooling and heating divided by the electricity energy used by the aquifer system

Summary

The energy system at SAS Frosundavik has shown that aquifers can be used for storage of energy, and that aquifer-based energy systems can be both reliable and economic. Several similar systems can therefore be expected in the future. However, it is important to remember that aquifer-based energy systems must be designed in such a way as not to conflict with local conditions. This rules out widespread application of the method, particularly on a smaller scale. On the other hand, if each installation is carefully designed, and matched to a suitable load, conditions are favourable for the construction of several financially viable aquifer-based energy systems.

The amount of purchased energy required can be reduced by about 65 % in comparison with that of a conventional system.

During 1989/90, the aquifer-based system replaced 2,750 MWh of district heating with 260 MWh of electricity. The Frosundavik energy system means that the amount of external energy supplied can be reduced by about 65 % in comparison with that needed by a conventional system.

This reduced requirement of external energy has a knock-on effect in reducing pollution elsewhere, including: reduced emission of acidifying gases, reduced emission of greenhouse gases, and reduced quantities of waste, e.g. from coal burning.

In comparison with a conventional energy system, the aquifer-based energy system results in approximately the following energy savings: 250 m^3 of fuel oil, or 330 tonnes of coal, or 1,000 tonnes of forest fuel, or 1,100 tonnes of peat.

Practical Experience

The SAS Frosundavik energy installation has produced valuable experience, both in terms of the system itself and for future projects. Experience from the installation an includes indication that:

- annual operating costs are about SEK 0.5 million less than they would be for a corresponding conventional system,
- the amount of purchased energy required can be reduced by about 65 % in comparison with a conventional system,
- the system has a high availability (100 %), despite the fact it is an experimental building installation.

Certain general conclusions can also be drawn in respect of future aquifer-based installations:

- with favourable geological conditions, aquifer-based energy systems are highly competitive,
- correct design and construction of aquifer-based energy systems requires a thorough knowledge of the performance of the entire system, together with special knowledge in key areas of aquifer storage technology, such as ground water hydraulics, water chemistry and the design of wells, together with the design of the building's energy system.

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The *Groene Hart Hospital* Gouda, The Netherlands

Consultant: Ir.J.J. Buitenhuis, DWA Consultants
Geological Consultant: IF Technology BV
Reporter: H.C. Roel

Date: August 1998

Aquifer Cooling and Heating

- Seasonal storage of coolth and heat in an aquifer
- One well for coolth and one for heat storage
- Same system for cooling and heating
- Simple integration into existing system
- Gas and electricity saving
- Reliable system

Background

Gouda is a provincial city in the west of The Netherlands. The *Groene Hart Hospital* is a medium-sized hospital with 450 beds. The hospital is 20 years old. At the beginning 1994 a merger between the Bleuland Hospital and the St. Jozef Hospital was undertaken. The new name for the two hospitals is *Groene Hart Hospital*.

Introduction

Five years ago, the *Groene Hart Hospital* in Gouda announced plans to make various extensions to the building complex. As a consequence of this, the cooling requirement would increase and the existing cooling installation would need to be extended. Moreover there were also proposals to equip a number of the existing air handling systems with cooling. Among others, this applied to the building with the nurseries, where there was no air cooling in the summer months. Cooling in the summer months would increase general comfort and benefit the quality of nursing care. An exploratory feasibility study showed that the seasonal storage of coolth in the soil would form an attractive alternative to a chiller. Based on the feasibility study, it was decided to go ahead with the project, with the aid of subvention from the European Community.

The objectives of the project are, to show that:

- the desired extension of the existing cooling capacity in the hospital, can be realised by the storage of *winter coolth* in a sandlayer (aquifer) in the soil, and that such a storage system can be integrated into the existing system,
- the technical and economical feasibility of combined coolth and heat storage in an aquifer for cooling and preheating of ventilation supply air,
- the benefits of the use of the aquifer for the short-term storage of coolth. This is done by night storage of coolth, generated by the existing chillers, for the creation of additional possibilities for energy control, and to compensate the risk of diminishing coolth storage due to climatic fluctuations

Project Data

Location	Gouda, NL
Altitude	2 m
Year of installation	1992
Number of beds	450
Degree days (20/15)	3,000 Kd/a
Heated floor area	5,200 m^2
Installed capacity	
• Cooling total	1,100 kW
• Cooling aquifer	500 kW
Heating consumption	900 MJ/m^2a
Cooling consumption	35 MJ/m^2a
Delivered by aquifer	23 MJ/m^2a
Costs in US$	
• Cooling incl. aquifer	480,000
• Reference system	350,000
Pay back period	4.5 years

Figure 1: Location of Gouda

Soil exploration
A soil exploration executed on the location in 1990, showed that the sandlayer (aquifer) suitable for energy storage is present at a depth of 75 to 90 meters under the surface. In Figure 2 a schematic presentation of the soil structure is given. It was concluded that combined coolth and low-temperature heat storage in the aquifer would be possible and it would yield attractive savings in electricity and gas consumption.

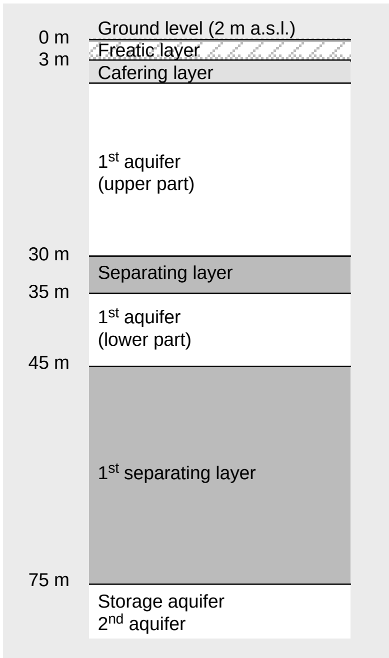

Figure 2: Soil structure

Design Concept

Description of the Installations

The cooling installation with subsoil coolth storage consists of two wells, the pressure tubes and the injection tubes and the connection pipe between the wells. The building circuit includes the separating heat exchanger, the chillers and the cooling coils in the air handling units of a groundwater circuit and a building circuit (Figure 4).

Groundwater Wells

The subsoil storage installation consists of two wells: one cold well and one warm well. The construction of the wells is shown in Figure 3. The wells are located close to the facade of the building, so that piping, accessories, cables, etc. can be installed inside the building. The distance between the wells is 150 meters, which is sufficient to avoid thermal short circuiting. Each of the wells can produce 60 m^3/h groundwater as a maximum. At partial charging, the flow can be reduced to 40 or 20 m^3/h.

Building Circuits

The cooling installation consists of two chilled-water circuits, indicated as circuit 1 and 2 in Figure 4. Circuit 1 is the original circuit, which is cooled by the chillers. The air handling units for the operating rooms are e.g. connected to this circuit. The chillers cool the water in circuit 1 down to 6 °C. The outlet temperature in the circuit varies from 6 to 12 °C, depending on the cooling load. Circuit 1 has not been connected to the storage system as the required water temperatures are too low. The design temperature for these air coolers ranges from 6 to 12 °C, whereas the temperature range is 10 to 20 °C for coolers in circuit 2 connected to the coolth storage.

Within the framework of an EC-project the chilled-water circuit 2 was installed. Eight air handling units have been connected to it (Table 1). The air handling units were not part of the EC-project with the exception of the required adaptations of the cooling elements.

Separating Heat Exchanger

In the central technical room at ground level, two water/water heat exchangers have been installed. Both operate as counter flow exchangers (HE).

The first heat exchanger, which is shown in Figure 4, functions as the separating heat exchanger between the building circuit and the groundwater circuit. By means of this heat exchanger, heat and coolth exchange with the subsoil storage takes place. In principle the groundwater could also be pumped directly through the building circuit. However in this project a separating heat exchanger is necessary for the following reasons:

- The groundwater is not a closed circuit. Pumping the groundwater directly to the more highly elevated air handling units would require a high pumping power. With the separating heat exchanger, the groundwater pumps only need to cope with a static pressure height of a few meters.

- The groundwater at this location is brackish (Chloride: 750 mg/l) and would corrode components in the building circuit, if it was pumped directly through the building circuit. The heat exchanger is made of stainless steel (AISI316) and is not expected to corrode. However an interesting aspect in this context is that there is no oxygen in the groundwater because it is taken from 90 meters depth from a layer without any oxygen. If the water is kept free of oxygen, it will be far less corrosive than in combination with oxygen. The groundwater circuit is mainly made of plastic (HDPE). Metal piping parts are made of stainless steel. As a part of the evaluation phase in the EC-project the separating heat exchanger was disassembled and inspected for corrosion.

- The methane content in the groundwater is moderate and could cause the forming of gas bubbles, if the pressure becomes to low. Gas bubbles would clog the injection well. Therefore the groundwater has to be kept at an over pressure. This is much easier if the building is separated from the groundwater by means of a heat exchanger.

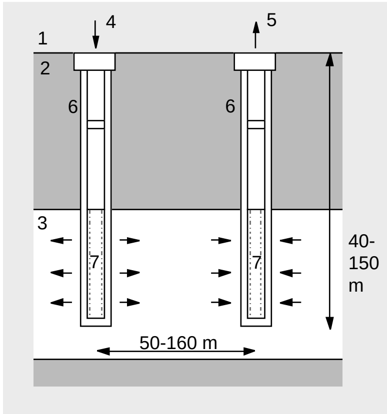

Figure 3: Structure of the wells in the soil
1 Ground level
2 Enclosing layer
3 Sand layer
4 Injection of cooled ground water
5 Withdrawal of ground water
6 Bore hole wall
7 Filter tube

To counter the danger of frost, a second water/water heat exchanger has been installed. It is connected to the heating installation at its primary side. Via this heat exchanger, heat can be supplied to circuit 2 in winter when the system is charging coolth into the aquifer. This may be necessary if the water outlet temperature from the coils becomes so low that danger of freezing occurs. During coolth charging, the water flow through the coil is controlled in such a way that the water outlet temperature is kept constant at 6 °C. At extremely low outdoor temperatures (< -5 °C) the water flow reaches its upper limit and from then the outlet temperature will drop below 6 °C. At that moment the control system will supply additional heat from the central heating system to increase the supply temperature in circuit 2. As a consequence the water outlet temperature of the coil will increase.

Chillers

The original cooling installation consisted of 2 chillers with air cooled condensers and a combined cooling capacity of 600 kW. These chillers supply all the coolth for circuit 1. They can also be used for additional cooling of circuit 2 if the coolth storage is unable to deliver the required capacity. This was the case during the first summer when no coolth had yet been charged into the aquifer.

Sizing of the Cooling Coils

The cooling coils in this system with long-term coolth storage have a double function. In summer they serve to cool the ventilation air. In winter they preheat the supply air and, simultaneously, charge coolth into the aquifer storage. The correct sizing of the coils is of great importance to get the storage balanced.

The coils have been designed for a relatively high water temperature rise, from 10 °C supply to 20 °C return water temperature. The supply air is cooled from 28 °C, 50 % r.h. (relative humidity) down to, for instance 14 °C, 98 % r.h. As a consequence of the smaller temperature difference between air and water, the cooling coils in the air handling units are almost twice as big as in a conventional installation connected to water chillers. Thanks to the higher water design temperature levels, the cold storage temperature can be kept at rather high temperature (8 °C). This is favourable for the storage efficiency. During winter, coolth can be stored at outdoor temperatures of 5 °C and lower. The average number of hours over which storage occurs is 3000 per annum.

Working of the System

Summer Mode

In the summer season, when cooling is needed in the building, groundwater is pumped up from the cold well. The groundwater passes heat exchanger HE1 and cools down the return water in circuit 2. With the 4 two-way valves MV1-4, the flow direction through heat exchanger HE1 is adapted to maintain a counterflow in both the summer and the winter mode. The three-way valve TWV1 controls the supply temperature at 10 °C and mixes in water at 6 °C from the chillers if the storage cannot deliver the whole cooling capacity.

Winter Mode

In winter, at outdoor temperatures of 5 °C and lower, coolth is stored in the cold well. The groundwater flows from the warm well through TSA1 and is cooled down to 7 to 8 °C. The required coolth is extracted from the ventilation air. In the air handling units of circuit 2 the ventilation supply air is preheated with heat from the warm well. Simultaneously, the water is cooled down to the desired temperature. The ability to preheat the ventilation supply air whilst charging coolth results in savings both on heating and cooling costs. Otherwise the outdoor air would need to be brought up to the desired supply temperature fully by the heating system (Virtually all air handling units were, formerly, without heat recovery systems).

Short Term Coolth Storage

During extremely warm periods or at the end of the summer season, when the cold well temperature is relatively high, a cold buffer can be formed in the aquifer at night which can than be used the next day. This is generated by the chillers running at low cost during the night. The cold water circuit 2 is short-circuited by closing motor valve MV5 and opening motor valve MV6. Pump P2 pumps the maxi-

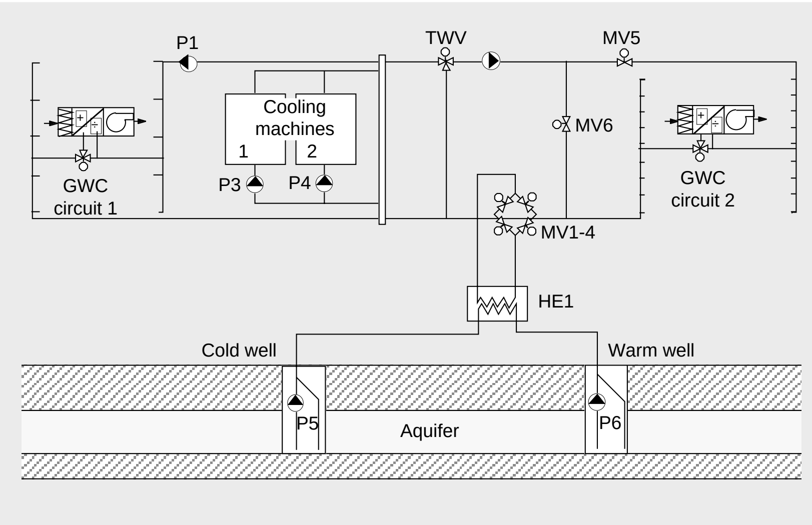

Figure 4: Installation diagram (GWC Ground Water Cooling; HE Heat Exchanger; MV Motor Valve, TWV Three Way Valve)

	Air flow [m^3/h]	Air discharge temperature [°C]	Cooling rate [kW]	Water flow [m^3/h]
Clinical laboratory	20,520	16	137	12.2
Polyclinic "N"	21,600	15	151	13.0
Outpatients therapy	22,320	17	97	8.3
Pharmacy	6,840	14	48	4.3
Nursing apartment A	34,560	17	44	12.2
Nursing apartment B	33,120	17	144	12.2
X-Ray Dept.	9,970	16	70	2.4
Kitchen*	4,500	16	100	3.4
Total	153,430			68.0

*Table 1: AC-units on circuit 2 (*after extension)*

mum water flow through the chillers through valve MV6 and heat exchanger HE1. The three-way valve TWV1 controls the mixing temperature at 6 °C. The coolth is stored in the coolth well at a temperature of approximately 8.5 °C. In the daytime this coolth is taken out again by switching over to the summer mode. As the losses are low during this short term loading the supply water temperature from the aquifer is rather low again (8.5 to 9.5 °C).

System Control

The application of aquifer heat and coolth storage puts some extra demands on the control strategy of the system.

In summer, the control system must make the right decision, when it has to choose between cooling with the coolth storage, with the chillers, or with both. The storage has first priority for coolth delivery, but only as long as the cold well water is used efficiently. The latter means that the cold well water has to be increased in temperature sufficiently before it is injected into the warm well. In the case of insufficient cooling capacity from the storage, the chillers will provide additional cooling capacity for after-cooling the cold-water circuit.

In winter, the system has to provide for enough coolth storage. The total amount of cooling energy to be stored must be known. This figure may result from an evaluation of the cooling energy, that may be still available in the store together with the nominal cooling demand per year. For proper control of the storage it is necessary to measure and register all energy flows in the storage system throughout the years.

The third control issue concerns frost protection. During coolth charging the coils in the air handling units cool down the water to the required temperature for coolth storage. At low outside air temperatures this process may become rather critical because of the danger that the water in the coil might freeze and damage the coil. Therefore, the water outlet temperature from the coil will be restricted to a minimum value (e.g. 3 °C). If the water outlet temperature becomes lower, heat will be supplied from the heating system by means of a central heat exchanger. The different options for frost protection have been studied in more detail. The effectiveness of the frost protection will get special attention during the test and evaluation phase of the project.

Performance Data

Measuring Programme

For monitoring the functioning of the coolth storage system, a measuring program has been carried out over a two year period. This program also provided the local authority with the measurement and registration data required in accordance with the Groundwater Act permit.

Measurements of Temperatures and Flows

The energy flows, extraction temperatures, injection temperatures and the wells water flows have been measured for both the sum-

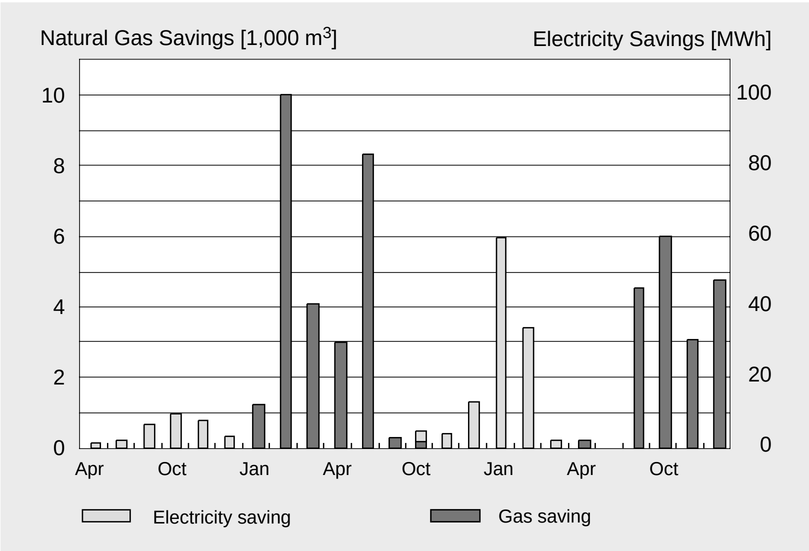

Figure 5: Gas and electricity savings by the seasonal storage (1993-1995)

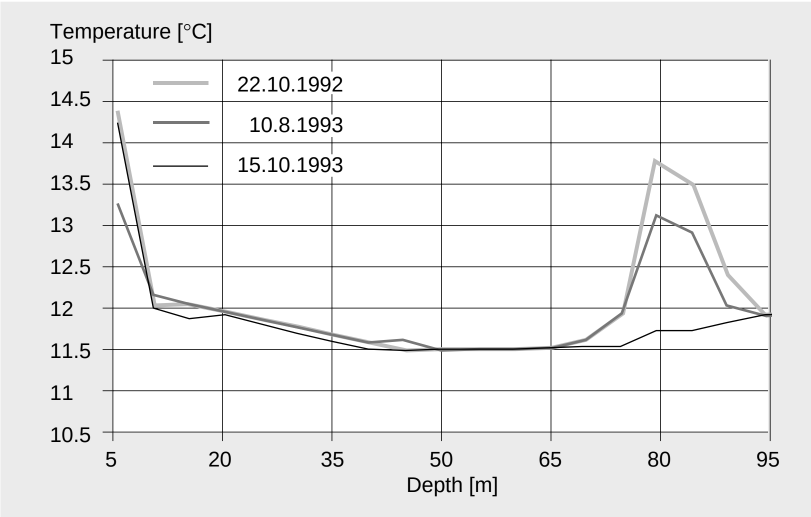

Figure 6: Temperature in the soil

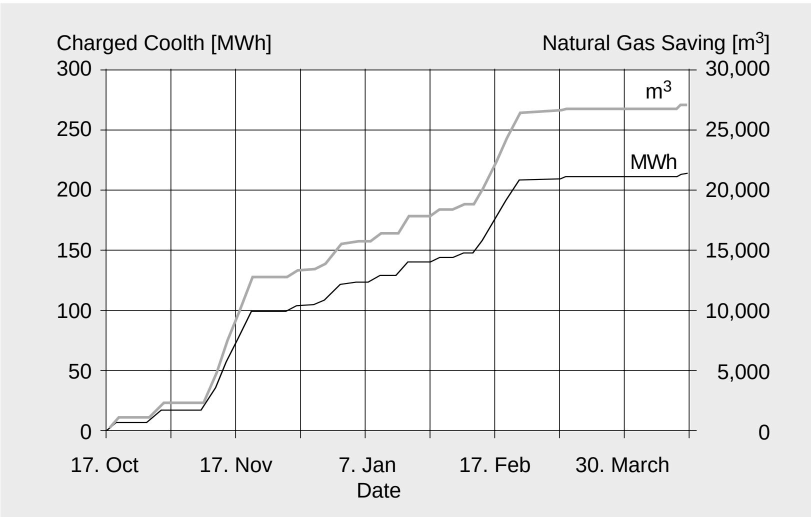

Figure 7: Coolth storage during winter '93/94

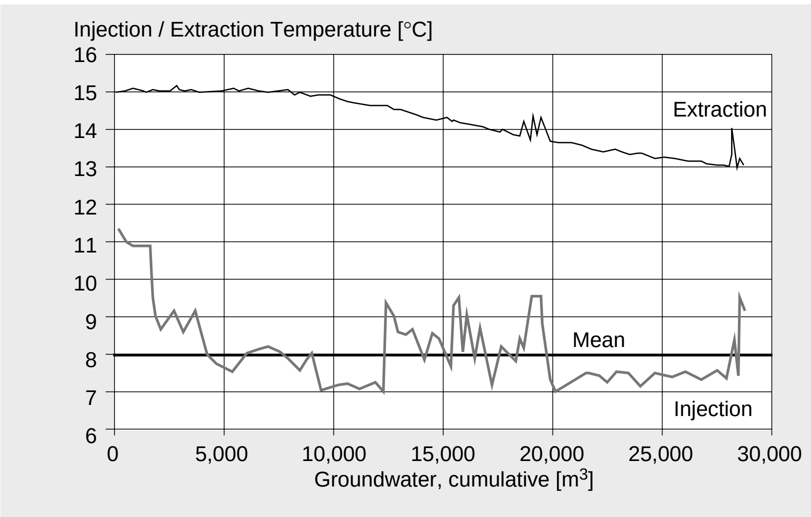

Figure 8: Injection and extraction temperatures in winter '93/94

mer and winter period. The supply and return temperature at HE1 and the water flow in the building circuit are also measured. An extra temperature gauge has been installed to measure the coolth delivery from the chillers. This temperature gauge measures the supply water temperature to the air handling units. With the return temperature (after HE1), the supply temperature to the air handling units and the flow in the building circuit, the contribution of the chillers can be determined in the summer period.

The measurements are registered with the aid of a Building Control System. The measuring values are read in and processed approximately every 4 seconds. Hourly average values are calculated and stored on disc for later processing.

Monitoring the Results

Soil Temperature

The soil temperature is shown in Figure 6. As shown, the ground temperature depths between 20 and 65 meters below ground level is very stable over the whole year. The ground surface temperature varies according to the ambient temperature. It also illustrates how the heat is stored around the aquifer.

Energy Results Winter 1993/1994

In Figure 7 the amount of stored coolth is presented. Totally about 29,000 m^3 of groundwater passed through the cold well during the winter of 1993/1994. This corresponds for this plant to 210 MWh of coolth. During charging, the ventilation air is preheated with groundwater from the warm well. By doing, this natural gas is saved. In Figure 7 the natural gas saving is also shown. This amounts to 27,000 m^3 in total.

Figure 8 shows the injection and extraction temperatures. As shown, the stored groundwater had a mean temperature of 8 °C. This is in accordance with the design temperature of 7.7 °C.

Energy Results Summer 1994

In Figure 9 the amount of extracted coolth is given. A total of about 57,000 m^3 groundwater was extracted during this summer. This corresponds to 350 MWh of coolth. By doing this electricity is saved, as shown in Figure 9. This amounts to almost 120,000 kWh$_e$. Figure 10 shows the injection and extraction temperatures. Both, the real and simulated extraction temperatures are given. The simulation temperature is calculated with PIA 12. From the data it appeared that the extracted groundwater had a mean temperature of 10.5 °C.

The following remarks can be made with respect to the coolth extraction during the summer of 1994:

- Figure 9 shows that at the beginning of the summer the amount of cooling supplied was small. But during July and August being extremely warm, with outside temperatures up to 35 °C a lot of coolth was extracted.
- Figure 10 shows a decline of the extraction temperature at 49,000 m^3 groundwater. This is the consequence of the application of short term coolth storage in the soil. At night (low electricity rate) coolth is produced with the chillers and stored in the cold well at 8.5 °C. In the daytime this coolth is extracted once again.

In Figure 11 the cumulative coolth storage of the soil is shown. When the value exceeds the zero-line, the average soil temperature for the energy storage is lower than the average groundwater temperature. When the value is under the zero-line, heat is stored in the soil.

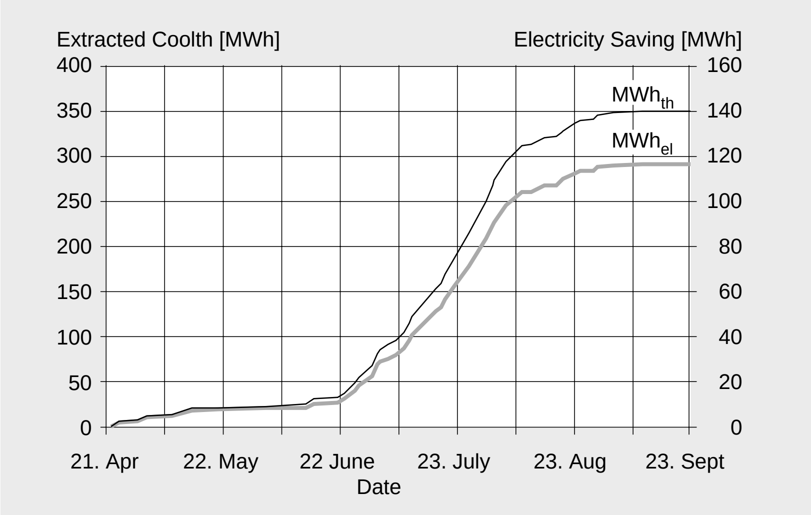

Figure 9: Extraction of coolth in Summer 1994

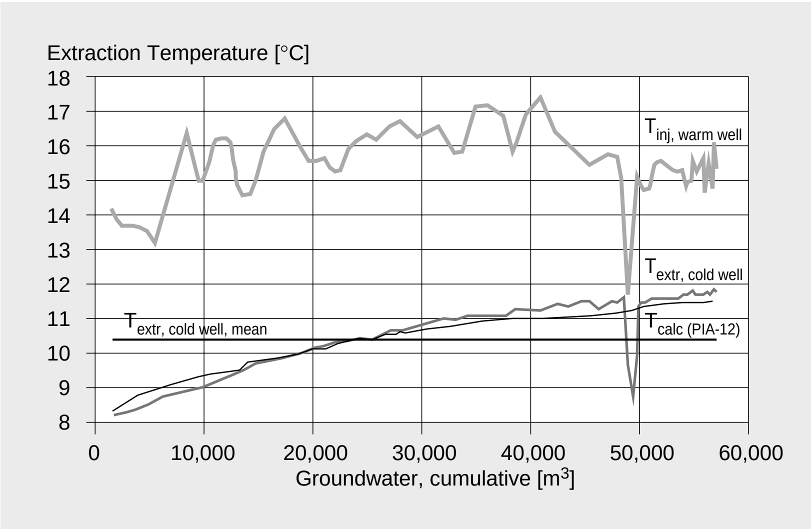

Figure 10: Extraction and injection temperatures in Summer 1994

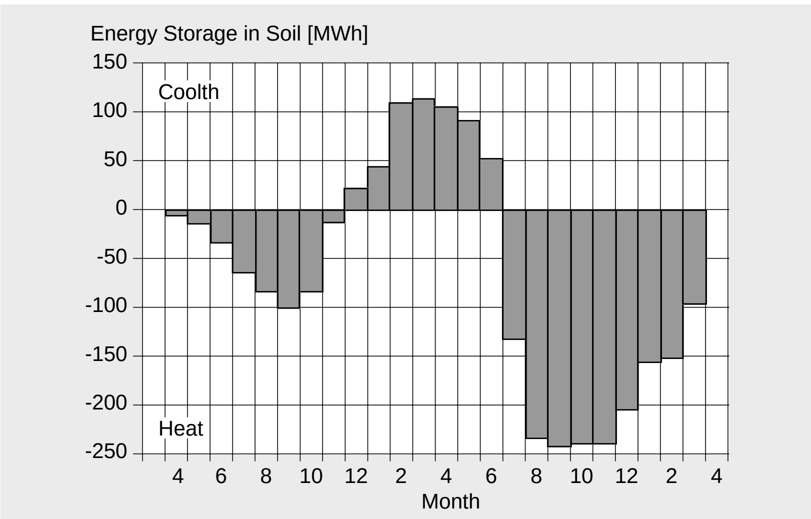

Figure 11: Cumulative energy storage in the soil, 1993-1995

Efficiency of the System

The energy efficiency of the coolth storage system can be determined by dividing the amount of coolth supplied by the subsequent electrical energy requirement, Analogous to the Coefficient Of Performance (COP) for chillers, a COP for coolth storage can also be defined:

$$COP = \frac{\text{Supplied coolth}}{\text{Electricity consumption}}$$

In addition, the Primary Energy Ratio (PER) is a useful parameter for assessing coolth storage, because it can also express the efficiency of coolth and heat supply:

$$PER = \frac{\text{Supplied coolth and /or heat}}{\text{Used primary energy}}$$

In Table 4 the supplied heating and cooling are shown for a winter and a summer season. For coolth storage, the above mentioned consumption of electricity is calculated. For comparison the calculated energy consumption for the reference-installation has been incorporated.

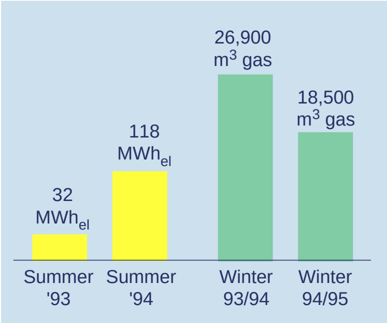

Figure 12: Natural gas and electricity savings during the measurement period

Environmental Influences

The whole project is based on energy storage in soil and groundwater. For the necessary groundwater pumping a permit from the local authority is required.

From measurements it appears that the quality of the groundwater, the groundwater level and the soil temperatures did not undergo any significant changes during the first two years of operation. It can therefore be concluded that the soil has not been damaged by the energy storage.

Practical Experience

After two years of operation, no serious defects or shortcomings have been found. The project functions very well. Because the extension to the hospital has yet not been finished, the full working of the system cannot be evaluated. In practical terms, we may say that this system has proved a success, and due, in part to this it will be applied frequently in the future. This is already evident.

From the calculations of the efficiency of the system, it is clear that the system is cost-effective. For bigger projects, with a cooling capacity of at least 300 kW and with at least 400 full-load hours a year, coolth storage is recommended. Soil exploration has to ensure that the requirements for an aquifer are fulfilled, e.g. that there is a suitable sandlayer in the soil.

Construction Costs

The pay-back period for the additional investment costs of US$ 305,000 is calculated to be 4.5 years.

Period	Supply	Installation with Coolth Storage Energy Consumption [kWh]		Reference-Installation[1] Energy Consumption [kWh]		
		Electricity	Primary Energy[2]	Electricity	Natural Gas	Primary Energy[2]
Winter 93/94	210 MWh_{th} warmth	9,515	23,788	-	262,500	262,500
Summer 94	352 MWh_{th} coolth	16,630	41,575	117,333	-	293,333
Total	562 MWh_{th}	26,145	65,362	117,333	262,500	555,833
"Overall" COP for cooling		352,000 / 26,145 = 13.5		352,000 / 117,333 = 3.0		
PER with only cooling involved		352,000 / 65,362 = 5.4		352,000 / 293,333 = 1.2		
PER with cooling & heating involved		562,000 / 65,362 = 8.6		562,000 / 555,833 = 1.0		
Electricity saving with coolth storage	117,333 - 26,145 = 91,188 kWh_e (~78 %)					
Gas saving with coolth storage	262,500 kWh = 26,870 m^3 gas					
Saving of primary energy	555,833 - 65,362 = 490,471 kWh = 50,200 m^3 natural gas equivalent (= 88 %)					

[1] A water chiller with reciprocating compressors and an air cooled condenser, a mean COP of 3
A heating installation with gas-fired boiler with a mean efficiency of 80 %
[2] Basic assumption: a mean efficiency of 40 % for electricity generation and transport

Table 2: Comparison of the energy efficiency for coolth storage and reference installation

The *Purdy's Wharf* Halifax, Canada

Sea Water Cooling

Architects: Shore Tilbe Henschel, Irwin Peters
Energy design concept: JSA Energy Analysts
Engineering: JSA Energy Analysts
Program Supervisor: Bill MacNeil
Reporters: S. Hosatte, H. Bui, CEDRL-CANMET

Date: August 1998

- Sea water provides cooling for about 10 months per year
- Reduction of operation and maintenance costs
- Reduction of ozone-damaging CFC's
- Annual savings: 177,000 CAD
- Simple payback of 2.3 years

Background

The current strong interest in environmental protection has placed limits on the use of various technologies in the modern air conditioning system. Refrigerants using chlorofluorocarbon compounds have been banned on the fact that they destroy the ozone layer, a stratospheric layer essential to humans. Meanwhile, energy conservation measures are being pursued for the benefits they bring towards reducing global warming gases, such as CO_2, and other harmful emissions. These environmental measures have spurred on the drive for innovative solutions, especially for "win-win" solutions where environmental benefits can be obtained at negative cost, i.e. for a profit. One such innovation can be found in the scheme of coastal cooling for buildings.

Introduction

On the Halifax waterfront, the *Purdy's Wharf* project has developed an air conditioning system that uses cold sea water from the harbour to provide cooling for nearby buildings. By drawing on the inexhaustible cold source from the sea, a continuous open-cycle system is created which can eliminate the need for a conventional, refrigerant-based closed-cycle system during most of the year and reduce power needs. This unusual design of sea water cooling can be shown to be technically and economically viable.

Figure 1: Location of Purdy's Wharf in Halifax, Canada

Buildings Description

The *Purdy's Wharf* complex, shown in Figure 2, comprises three buildings totalling more than 65,000 m^2 and a 1200-car parking garage. Originally, the eighteen-storey and 27,900 m^2 Tower 1 as well as the four-storey and 4,650 m^2 Commercial Building were constructed as part of the first phase of the project between 1983 and 1985. In the second phase, the twenty-two-storey and 34,000 m^2 Tower 2 was built between 1987 and 1989.

Project Data

Location	Halifax, Nova Scotia, Canada
Altitude	Sea level
Year of construction	1983 - 1989
Heat. degr. days (20/12)	4,254 Kd
Cooling degree days (18)	59 Kd
Cooled floor area	65,000 m^2
Cooled space	167,000 m^3
Office area	63,000 m^2
Commercial area	2,000 m^2
Number of storeys	
• Commercial Building	4
• Tower 1	18
• Tower 2	22
Installed cooling capacity	4.9 MW
Annual energy consumption	13,120 MWh
Fuel oil for furnace	750,000 litres per year

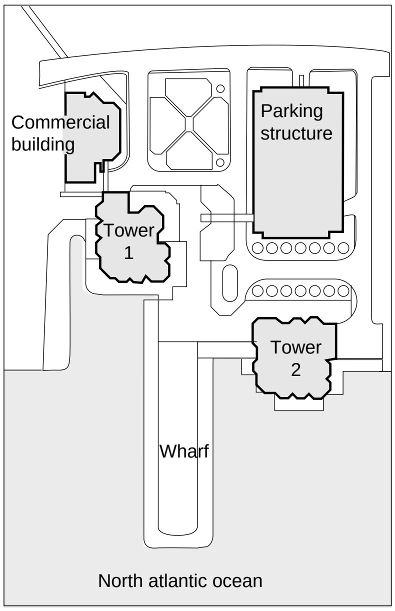

Figure 2: Building layout. Purdy's Wharf complex comprises two towers, a commercial building and a parking garage.

Design Concept

General Energy Concept

The concept of sea water cooling is simple. As shown in Figure 3, in each tower the sea water cooling system consists of one open piping loop containing two heat exchangers in series. Two centrifugal pumps (3) draw cold sea water (2) through the intake (1) located at the ocean depth of 18 m, drive it through the two titanium heat exchangers (4) in the mechanical room, and reject warmer sea water to the harbour (5). Both heat exchangers exchange heat from closed loop water circuits to the sea water. Chilled water from the first heat exchanger goes directly to the cooling coils (8) located in the building VAV system on each floor of the building. An air circulation fan (11) blows warm air (10) through the cooling coils which provide cool air. The water (9) having been warmed up by the air, returns to the heat exchangers for another sea water cooling cycle.

Chilled water from the second heat exchanger is used to cool the condensers of special purpose mechanical compression chillers installed by tenants for such applications as computer rooms, and/or to cool the condensers of mechanical compression chillers used to cool the building when the sea water temperature is to high to provide direct cooling.

Building Envelope

The building envelope consists of curtain walls made of aluminium and glass. The fenestration consists of high-performance double-glazing units using silver on clear glass, which is highly reflectant. The average U-values of the wall and of the glazing are respectively 0.34 W/m^2K and 2.44 W/m^2K.

Solar Gains and Overheating Protection

The massive glass structures found on the buildings enhance the indoor environment with natural light but do not create an overheating problem. The glazed units which comprise these structures have a solar energy transmittance of 8 % and reflectance of 25 %. Potential overheating can occur, though, through the internal heat gains generated by office equipment, such as computers. To prevent this, the rise in the inner core temperatures of buildings must be met by increased cooling. Even during the winter, cooling must be applied to this inner core while heating supplies the perimeters of the buildings.

Demonstrated Technologies

Corrosion Resistant Equipment

The salinity of the sea water requires durable, corrosion-resistant equipment. In the mechanical room, for instance, sea water is held in 20 cm diameter corrosion-resistant polyvinyl chloride pipes; the 30 cm diameter water supply pipe which extends from the mechanical room to the screened inlet, located approximately 230 m away at the bottom of the harbour, is made of polystyrene. The sea water pumps have 316 stainless steel housings, impellers and shafts. Each impeller eye, which includes the impeller face, collar, lock washer and lock cap screw assembly, is made of Hastelloy C276.

1. Sea water intake
2. Cold sea water
3. Sea water pump
4. Titanium heat exchanger
5. Warmed sea water outlet
6. Building circulating pump
7. Cooled fresh water
8. Cooling coil
9. Warmed fresh water
10. Warm air
11. Air circulation fan
12. Cool air

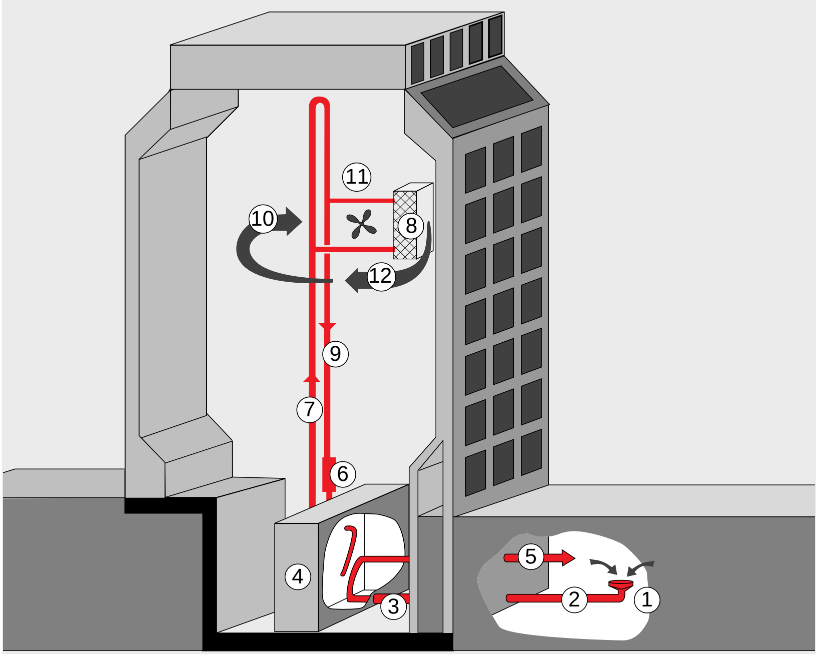

Figure 3: Schematic of the sea water cooling system

In the event of equipment failure, the sea water cooling system features bypass loops and valves which ensure that all parts can be repaired even during operation, if necessary.

Sea Environment
Marine growth in oceans poses a threat to the proper working of the cooling equipment. To prevent the entrance of foreign material into the sea water system, a screen is installed over the sea water intake, and the intake itself is located 3.7 m (12 ft) above the harbour floor. To discourage formation of marine biological growth on this intake screen, it must be protected with a coating of marine anti-fouling paint. To prevent blockage of the narrow passages between the heat exchanger plates, the sea water flows through strainers with 4.8 mm (3/16") perforations which are installed just ahead of the heat exchangers themselves. Initially, chlorine was added to the sea water to eliminate the development of organic compounds inside the system. But because chlorine is harmful to the environment and marine life, that system was recently replaced by cathodic protection.

Cathodic protection using copper and steel bars at the sea water intake impedes the proliferation and development of organic compounds, algaes, mussels, and other sea creatures in the piping and heat exchangers. This system, which has already been used in the marine industry, is based on an electrical method of preventing corrosion operating under the principal of electrolysis. The steel and copper bars are designated as electrodes or as cathode and sacrificial anode respectively, where the reduction and oxidation reactions occur. Both metal elements are connected to an external source of electricity and immersed in the sea water, which becomes the electrolyte. An implied electric potential of 12 Volts DC impels the copper bars to corrode while protecting the steel bar. Conduction of electricity occurs with the movement of ions in the electrolyte, resulting in a current of 1.8 Amps.

While cathodic protection impedes the development of organic compounds just as effectively as chlorine, operational costs are lower. Where the use of chlorine had costed 11,000 CAD per year, the replacement of copper bars costs only 3,750 CAD per year.

Heat Exchangers
Heat transfer between the two piping loops occurs in four heat exchangers, which are of standard configuration plate type. The warm and cool media, which are the fresh water closed loop and the sea water loop respectively, flow on each side of the plates. The plates of these heat exchangers, which are made of titanium, 0.6 mm thick and number in the hundreds, are unique and provide efficient heat transfer as well as corrosion resistance.
However, with the high cost of titanium, total construction cost of the four heat exchangers is 160,000 CAD. Treated aluminium, which has similar properties, but is cheaper, has been considered for future designs.

Design Details

Ventilation Strategy

Fresh air is drawn in at the top of each tower and on every floor of the Commercial building. Tower 1 uses a constant air volume (CAV) fresh air supply fan of 12 m^3/s fixed capacity, while Tower 2 uses a variable air volume (VAV) fresh air supply fan of 18 m^3/s maximum capacity. Each floor of the commercial building uses a VAV mixed air unit with air controls to ensure that the minimum 0.5 m^3/s fresh air required per floor is provided year round.

Air is distributed throughout the occupied areas of the buildings using one VAV compartment fan on each floor. In Tower 1, warm water returning from the cooling coils preheats incoming fresh air as necessary, during cold weather, before returning to the sea water heat exchangers. This heat recovery approach was not considered for the design of Tower 2, however, due to insufficient payback.

Indoor Air Quality
Fresh air supplies are regulated by monitoring CO_2 levels in the exhaust air stream and in the occupied spaces to ensure that the interior environment remains below 800 ppm. In summertime, a night cooling strategy is employed whereby air handling systems are brought on for one complete air change during the coldest time of night to decrease the cooling load and reduce CO_2 levels during the following day. During operating hours, the building is maintained at a slightly positive pressure to reduce drafts and prevent the entrance of unfiltered air. The fresh air supplied to each floor is regulated by varying the amount of washroom exhaust removed from each floor.

Performance Data

Cooling Control Strategy

A direct digital control (DDC) system is used to monitor and control air supply temperature and airflow based on the duct static pressure, the temperatures on each floor and the VAV vane position for an inferred airflow rate. The further open the VAV vanes are, the higher the fresh airflow rate is, and therefore, by inference, the higher the heat load would be on that floor during summer periods. To counter the warming effect, the temperature of the air supply is lowered, with 12 °C being the minimum.

During the winter, we know that the interior spaces of the buildings require cooling while spaces on the perimeter require varying degrees of heat. In order to satisfy the perimeter heating requirement, hot water convection heaters are placed around the perimeter and are controlled independently at each of 8 individual zones on each floor. Night and weekend perimeter heating is set at minimal, freeze protection levels. As programmed, the control system adjusts the inside temperature in coordination with scheduled occupancy.

Overall performance

To be effective in a cooling system, the sea water temperature must be below 10 °C. At *Purdy's Wharf*, with its 18 m deep intake, sea water can be used as a cooling medium for approximately ten and a half months of the year, providing a coefficient of performance (COP) of 40. Even during the summer months, when outdoor temperatures reach 32 °C, sea water temperatures at this intake level remain between 5 and 7 °C. The deeper layers of the ocean absorb solar energy slowly, as can be seen by the time lag.

In Figure 4, it is only after summer and during the months of September and October that temperatures rise above 10 °C and the cooling system cannot be used.

During September and October, chillers of 2.1 MW and of 2.8 MW, for Tower 1 and 2 respectively,

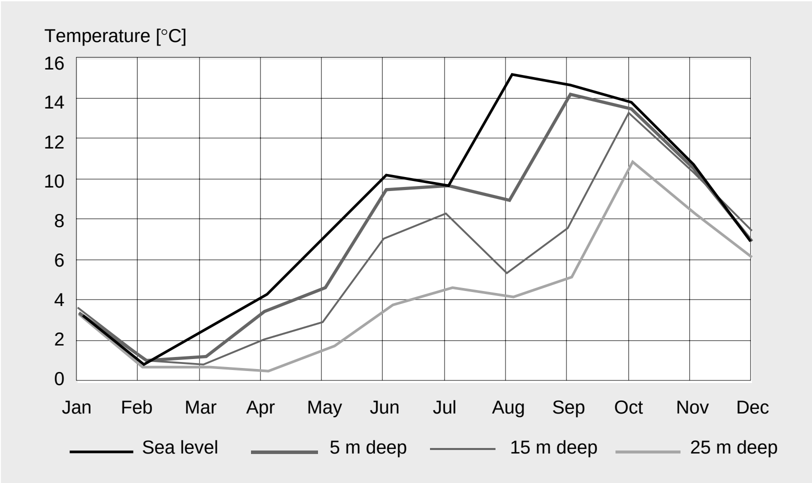

Figure 4: Sea water temperatures at different depths throughout the year. At Purdy's Wharf, sea water for cooling is pumped from a depth of 23 m.

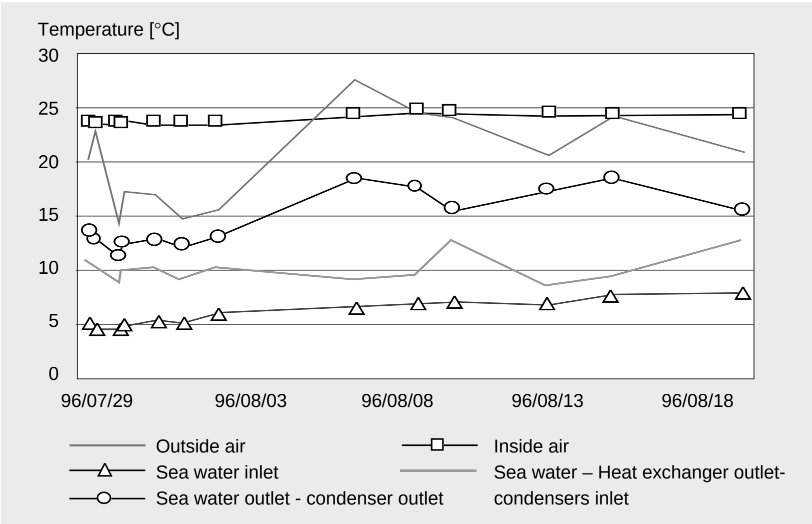

Figure 5: Outdoor, indoor and system temperatures of Tower 1

fulfil the cooling demand with a COP of 5. Sea water continues to be used to cool the chiller condensers, as sea water temperatures never get too high for this purpose. This sea water cooling system, also eliminates the need for cooling towers. If, for some reason, fouling or damage to the water intake pipe occurs, water for the cooling of the condensers can be pumped in through the culvert, which encloses the sea water outtake to the harbour.

During the month of August, even when intake sea water temperatures are less than 10 °C, the chillers provide additional cooling to the sea water system. As shown in Figure 6, when cooling requirements reach a threshold level, such as when the buildings are subject to increased outside air temperatures, the closed-cycle system is engaged because the sea water cooling system is already operating at maximum pumping capacity and cannot reject any further heat. This incremental cooling is above and beyond that provided by air-conditioning units installed locally by tenants. Figures 5 and 7 show outdoor, indoor and system temperatures of Tower 1 and Tower 2 during the month of August 1996. For the same period, Figure 6 shows the sea water cooling power delivered to the chilled water heat exchanger and to the condenser heat exchanger for Tower 1, while Figure 8 shows the total cooling power delivered to Tower 2.

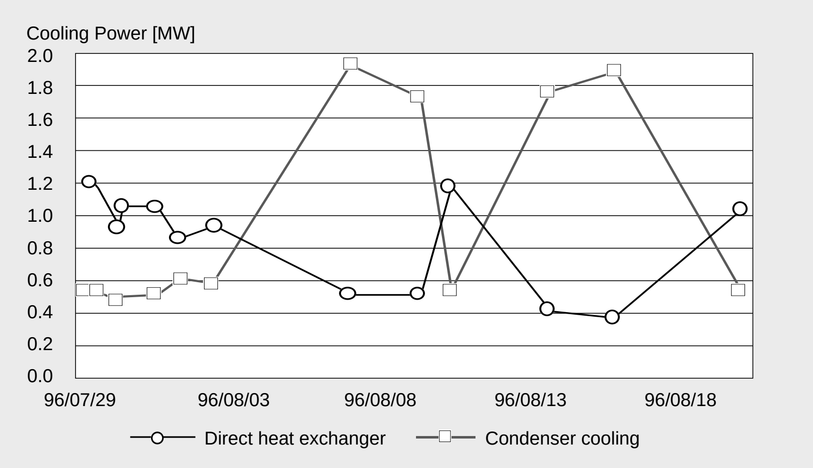

Figure 6: Sea water cooling power delivered to Tower 1

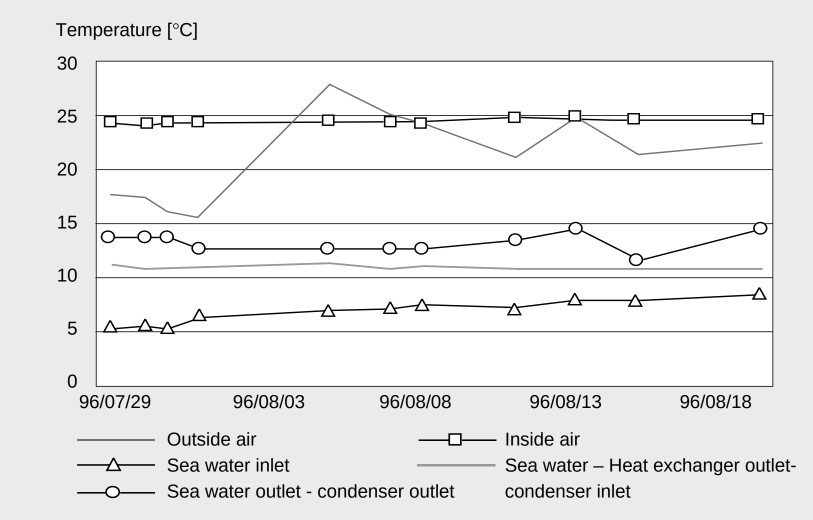

Figure 7: Outdoor, indoor and system temperatures of Tower 2

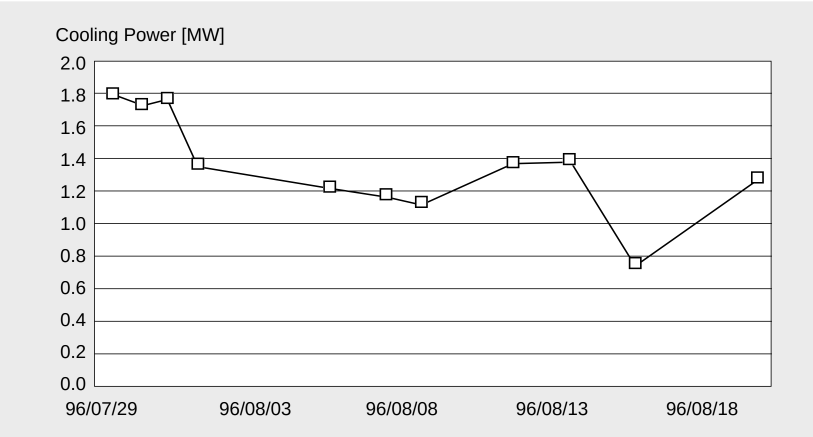

Figure 8: Total cooling power delivered to Tower 2

Construction and Operating Costs

The construction of the *Purdy's Wharf* sea water cooling system is estimated to have cost CAD 400,000 more than a conventional air conditioning system. This higher cost can be attributed mostly to the expensive titanium heat exchangers. Despite the free availability of the cold ocean source through most of the year, associated pumping costs are also significant. For *Purdy's Wharf*, these costs amount to CAD 30,000 per year.

Variable speed sea water pump drives currently under consideration at *Purdy's Wharf*, would reduce this amount to below CAD 20,000 per year. It should be noted that these pumping costs are approximately equivalent to what would be consumed in a conventional cooling tower, were the sea water systems not used. Other operational costs include the cathodic protection of the sea water intake, which were approximated at CAD 3,750 per year for the copper bars. On the savings side, though, sea water cooling provides annual savings of CAD 177,350 in reduced electricity load, as well as reduced building maintenance and operational costs.

	Savings	Cost
Electricity at CAD 0.075/kWh	127,000	
Maintenance staff	49,000	
Water consumption at CAD 0.57/m^3	5,100	
Copper bars		3,750
Average annual savings	177,350	

Table 1: Summary of operational costs and savings (CAD)

At an average power cost of CAD 0.075/kWh, sea water cooling saves around CAD 127,000 per year in avoided power and CAD 49,000 per year for the reduced maintenance staff.

In addition, the reduced water consumption due mostly to the elimination of cooling towers saves roughly CAD 5,100 at a cost of CAD 0.57/m^3. Overall, the implementation of sea water cooling yields a payback of approximately 2.3 years. The sea water temperature and the power rate are two factors that could affect the period of payback, however.

The simple payback of 2.3 years has been calculated by comparing the capital and operating of the sea water system against the capital and operating costs estimated for a mechanical compression system operating under equivalent conditions.

Summary

Coastal cooling reduces substantially the need for mechanical cooling. The *Purdy's Wharf* development project has proved that sea water can be used to provide more than ten months of cooling per year, thereby reducing power and other operational costs considerably. Future designs could focus on increasing performance, such as increasing the efficiency of the heat exchangers and pumps, so that the colder sea water available at greater depths can be exploited to provide free cooling year-round. Efforts could also be made in reducing capital costs, such as by developing lower cost heat exchangers using alternative materials.

The technology is relatively recent and many cities have already shown interest. The potential for widespread adoption of the technology is highest for buildings which are located near low temperature water sources. The construction of a canal to supply cold water to downtown buildings is one such potential application of the technology.

Practical Experience

Environmental
The proliferation of organic compounds can be controlled by adding chlorine to the sea water system, though it is detrimental to other marine life. An environmentally appropriate alternative is the cathodic protection system, which can provide the same results at much lower cost. Periodic cleaning and maintenance of the sea water equipment is still required under the cathodic protection system, however.

Energy Savings
Pumps and air circulation fans are the main electricity consuming devices in the sea water cooling system. A trade-off exists between electricity costs for pumping sea water from greater depths and the benefits of obtaining colder water for the sea water cooling system. Also, pumping costs are minimized when the buildings to be cooled are located next to the water intake area. The use of variable speed sea water pumps offers an interesting potential to reduce pumping cost.

Figure 9: Areal view of the Purdy's Wharf complex

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