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NIGHT COOLING CONTROL STRATEGIES

Final Report 11621/4

March 1996

A sponsored research project

Compiled by:

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BSRIA Quality Approved
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No. of pages: i-v preamble
34 of text

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ACKNOWLEDGEMENTS

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Department of the
Environment

BSRIA would like to thank the following for their contribution to the research project:

- The Department of the Environment via The Building Research Establishment
- Caradon Trend

Work in kind support was provided by:

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EXECUTIVE SUMMARY

Night cooling is an established technique allowing ventilation to take place at night with the intention of removing heat gains that have built up during the preceding day. By permitting the cool night air to flow through a building, heat is removed and a store of the cool air within the building fabric, furniture and fittings is achieved thus providing a cooling effect the following day.

In order to achieve the full benefit of this technique it is essential that appropriate night cooling control strategies are used thus achieving the maximum amount of cooling whilst avoiding overcooling and subsequent re-heating. In this way energy consumption relating to mechanical cooling and mechanical ventilation is minimised and consequently significant cost savings can be made.

The research carried out by BSRIA involved site monitoring of four night cooling control strategies, each of which was used in actual office buildings installation based upon a 'low energy' design. The performance of the control strategies was further verified through the use of thermal simulation software. This was used to model a basic representation of one of the case study buildings and the performance of a range of night cooling control strategies, including those applied in the case study buildings were tested against a selection of variables that could influence performance. The variables were designed to represent the range of conditions that could be experienced in actual buildings.

The work undertaken showed that all of the strategies are successful in helping to produce a satisfactory thermal environment as part of an overall low energy strategy. The research demonstrated that the application of complex control algorithms is not necessary in practice to achieve cost savings, although there may be benefits when trying to achieve energy savings. What is important is the careful selection of the control setpoints to initiate night cooling and in order to optimise the amount of night cooling taking place. The research showed that during the summer months all of the night cooling control strategies operated for the maximum amount of time. It was during the marginal summer months (May, June, September and October) where the different control strategies resulted in a wide variation regarding utilisation. Over-cooling of the space was generally not beneficial since it was only achieved under marginal conditions when the requirement for night cooling is reduced. (ie over cooling of the space under peak temperature conditions would lead to improved comfort conditions later in the day). A minimum zone setpoint should be specified to prevent overcooling. This should be related to the heating setpoint so that the situation where over-cooling followed by heating is avoided. The results showed that during peak conditions the external air temperature remained higher than the internal temperature until late into the evening. Therefore night cooling should only be permitted when the zone temperature exceeds the external temperature.

Night cooling by mechanical ventilation was typically no more successful than natural ventilation and also imposed a significant energy penalty. The use of mechanical ventilation should be restricted to bad weather conditions when natural ventilation is not feasible where the ventilation systems allow this. Where mechanical ventilation is utilised it was found that starting the plant at 21:00 hours rather than 18:00 hours resulted in a similar internal temperature being achieved at the end of the night cool period due to the lower external temperatures later in the evening.

The results of the monitoring and computer simulation has led to the provision of a recommended night cooling control strategy based upon the following rules:

- the night cooling should be initiated if any one or a combination of the following are satisfied:
  - Peak zone temperature (any zone) > 23°C
  - Average zone temperature (any zone) >22°C
  - Average afternoon outside air temperature >20°C

- night cooling should continue providing that all of these conditions are satisfied:
  - Zone temperature (any zone) > outside air temperature + 2K
  - Zone temperature (any zone) > heating setpoint
  - Outside air temperature >12°C

- night cooling should be carried out for all of these periods:
  - Days - 7 days per week
  - Time - entire non-occupied period
  - Lag - operate night cooling for an additional two nights following the control criteria no longer being satisfied. This only applies if night cooling operated for a minimum of the previous five consecutive nights.

PREFACE

Night cooling offers the potential to minimise or completely avoid the use of mechanical cooling and to improve the environmental conditions in naturally ventilated buildings. By allowing cool night time air to flow through the building the heat built up during the previous day is removed and storage of the cool air in the fabric, furniture and fittings is achieved, consequently providing a cooling effect the following day. However, in order to realise the full potential of night cooling systems adoption of the appropriate control strategies is essential.

A programme of research has been carried out by BSRIA to identify and verify the performance of control strategies for night cooling that can be used for both active, passive and mixed mode systems and to address the issues relating to their effective application. This report describes the research carried out.

CONTENTS

1. INTRODUCTION

1.1 BACKGROUND TO PROJECT

Night cooling is an established technique allowing ventilation to take place at night with the intention of removing heat gains that have built up during the preceding day. By permitting the cool night air to flow through a building, heat is removed and a store of the cool air within the building fabric, furniture and fittings is achieved thus providing a cooling effect the following day.

For the majority of buildings there is adequate 'free' cooling available during the day for approximately 90% of the year. This is directly from outside, either by opening windows or through the use of mechanical ventilation. It is during the periods of peak outside air temperatures that night cooling is particularly needed to provide additional cooling. Other buildings have higher internal heat gains and there is a requirement to provide cooling for a greater proportion of the year. These buildings can also benefit from the provision of night cooling strategies in order to reduce the need for mechanical cooling and/or mechanical ventilation and thus achieve energy and cost savings.

Typically, the use of an exposed ceiling slab in conjunction with an appropriate night cooling strategy will offset heat gains of approximately 20 W/m^2 and peak localised loads may even be higher. The use of solar shading, efficient and well controlled lighting systems and the removal of heat generating equipment from the general office spaces (or location adjacent to a ventilation extract) will provide additional heat gain reduction. The principle of night cooling can be applied to any building with heat gains over approximately 20 W/m^2 (below which daytime opening of windows and other vents should provide reasonable temperature conditions for most of the time) with a summer diurnal temperature range of 5 K or more.

In order to ensure that the full potential of night cooling systems are realised, whether passive or active, adoption of the appropriate control strategies is essential. Where mechanical ventilation is utilised a balance must be struck between the amount of night cooling taking place with the cost of running fans and the potential danger of over-cooling the space leading to a heating requirement prior to occupancy on the following day. It is essential that the net energy cost when operating a night cooling strategy is not greater than a system without night cooling.

This project concerns control strategies for night cooling that can be used for both active, passive and mixed mode systems. The research concentrates on strategies that may be implemented using existing control system technology and is intended to provide practical guidance regarding the application of control routines for night cooling.

1.2 PROJECT PROGRAMME

The research was undertaken in a number of steps and the principal ones are detailed below.

- A literature survey was conducted to review existing papers and articles concerned with night cooling, thermal mass and control algorithms. The literature review is detailed in report 11621/1 and the conclusions from the review are presented in chapter 3.

- Consultations were carried out with industry including consultants and control companies and the practical advice obtained is incorporated in this document.

- Monitoring of five buildings was undertaken, four of which utilised different control strategies for night cooling. The buildings were monitored between spring and autumn 1995 and the subsequent analysis of the data investigated the operation and effectiveness of each night cooling control strategy. Details of the site monitoring undertaken and the data analysis are provided in report 11621/2. A synopsis of the work is given in chapter 4.

- An assessment of control strategies using dynamic simulation software was conducted. APACHE thermal simulation software was used to model a basic representation of one of the case study buildings. A range of control strategies, including those applied in the case study buildings, were tested against a range of variables that could influence performance. The variables were selected to represent actual conditions that could be experienced in buildings. A résumé of the dynamic thermal simulation results is presented in chapter 5 and the full methodology, results and conclusions can be found in report 11621/3.

2. PRACTICAL ISSUES OF IMPLEMENTING NIGHT COOLING

2.1 OPTIMISING NIGHT COOLING

The key parameters in the performance of night cooling systems are:

- air supply rate
- ΔT between the air and the storage media (building fabric)
- thermal linking between the fabric and the air supply
- fabric storage performance (dependent on the fabric thermal properties - conductivity, heat capacity and density, together with the fabric thickness).

In order to optimise the performance of night cooling it is important to understand how these parameters vary. The air supply rate and the ΔT between the air and the storage media determines the amount of cooling introduced into the building. However, it is the thermal linking between the fabric and the air supply that is the critical factor affecting the storage effectiveness. This is dependent upon the heat transfer through the fabric surface and the fabric area (which can be increased by the use of coffered, waveform and vaulted ceiling slabs). It has been found that the storage performance of the ceiling slabs and variations in the thermal properties and thickness beyond approximately 75mm have little influence on the slab's performance [1]. However, where enhanced surface heat transfer occurs, perhaps due to particularly turbulent air flow, more heat will flow through the surface of the slab and so a greater thermal mass will be worthwhile.

The heat transfer into and out of the fabric surface is affected by the air supply rate passing over the thermal mass. For a mechanical ventilation system this is easy to quantify but the air supply in a naturally ventilated system will be variable depending upon the external weather conditions, the size and positioning of the inlet and outlet vents as well as the internal office temperature and layout. The air supply rate particularly affects the convective heat transfer into and out of the fabric. This has been found to vary widely and is difficult to determine. Convective heat transfer will depend upon whether the air movement is 'forced' (such as flowing through a duct or core with primarily turbulent flow) or driven by natural 'buoyancy' forces (such as within an occupied space). Reference [1] provides more information regarding heat transfer into and out of the fabric. As a rough guide, where air is being passed through a 300mm floor void an air velocity through the inlet damper around 1.5m/s should be sufficient to encourage good heat transfer. Fan power should not exceed 1 W/l/s for combined supply and extract [2].

2.2 MECHANICAL VENTILATION

Where mechanical ventilation is utilised for night cooling the operation of the system incurs an energy penalty in operating the fans. This should be weighed against the potential benefit to be obtained by night cooling in order that the net energy costs are not greater than that for a system with no night cooling. Variable air volume systems offer the benefit of being able to vary the air flow rate to optimise the amount of cooling introduced into the building, giving high air supply rates at peak loads but conserving fan energy by reducing the air flow at lower loads. This is important for a number of reasons:

- there is an optimum air velocity for heat transfer between the air and the fabric
- during the cooler months the air supply volume can be reduced due to a lower cooling load and the increased cooling temperature differential that is available
- the fan speed may be varied at night to make the optimum use of low tariff periods and/or the lowest external temperatures.

The fan energy consumed per unit of air delivered will increase with air supply rate, increasing the pressure drop through the ductwork. Where a variable speed drive is fitted to the mechanical ventilation fans there are significant energy savings to be made by running the fan at a reduced flow rate (figure 1). Thus, when the night cooling algorithm is likely to be satisfied before the end of the night cooling period it is more cost effective to supply a lower air flow rate continuously during the allotted period for night cooling. However, care should be taken to avoid running the fan below the 30% air flow rate since the power consumption increases dramatically (not shown in figure 1). An alternative approach may be to make use of two speed fans for night cooling as a compromise to the additional cost of variable speed drives.

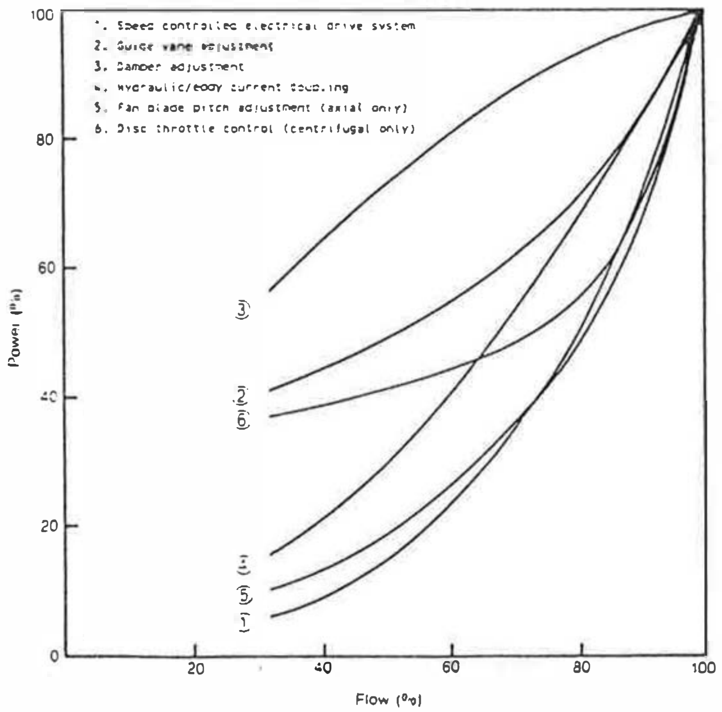

Figure 1 Fan power requirements with different control methods [3]

Where a supply fan rather than an extract fan is used to provide the night cooling the increase in energy consumption will manifest itself as an increase in fan pick-up, reducing the amount of free cooling available. Typical values for fan pick-up are between 1 and 2 K which can denigrate the benefit of night cooling, and indeed, render the fan operation for night cooling dubious. One way to minimise this is to locate the fan motor outside of the airstream so that the motor losses do not increase the supply air temperature.

Other sources of heat gain to the supply air may be due to:

- heating valves by-passing
- recirculation dampers by-passing
- air intakes being poorly positioned, for example taking air from above a dark roof exposed to the sun, or adjacent to extract vents.

A further possibility for improving the night cooling system efficiency relates to reducing the pressure drop through the air handling unit by making use of an arrangement to by-pass the filters and heating/cooling coils. This could allow the outside air to enter the supply fan chamber directly through a dedicated duct (with appropriate temperature interlocks) thus minimising the fan energy consumption per unit air volume supplied. One potential problem with this arrangement is an increase in the amount of dust and particulates entering the space which may result in increased cleaning costs.

The control principles are essentially the same for both mechanical ventilation and passive ventilation systems although mechanical ventilation systems may be configured only to run during low tariff periods. It is important when operating mechanical ventilation systems that the supply air setpoint is suitably adjusted to ensure that reheating of the cool night air does not take place.

2.3 PASSIVE VENTILATION

Where passive night cooling is undertaken consideration should be given to the appropriate inlet and outlet vent design, size and location as well as the shape of the building and the location and shape of adjacent buildings. Inlet and outlet vents should encourage air flow over the exposed ceiling surface yet should be secure from intruders and prevent the ingress of rain. Outlet vents may be configured such that the vents on the lee side of a building are opened to enhance air flow through the utilisation of the negative pressure area created. Other buildings make use of outlet vents that are designed to encourage the creation of negative pressure areas to enhance ventilation rates.

Stack effect is also used to improve ventilation rates. Stack effect has a greater influence at night than during the day since a larger temperature differential will exist between the internal and external temperature at night. However, it is likely that the wind speed will still be the dominant ventilation mechanism. A wind speed of 4 m/s, the average wind speed exceeded for 50% of the time in England at a height of 10m, produces a driving force through a ventilation opening of approximately 7 Pa with a surface pressure coefficient of 0.7. A stack effect of a similar magnitude will require a stack height of 10m and a temperature differential between inside and outside of approximately 18 K.

Automatic control of windows and other vents can easily be carried out since there are actuators available to open and close all types of windows, dampers, doors, rooflights etc. [4]. This offers the benefit of being able to carry out night cooling without any manual input. The control system should provide appropriate interlocks to prevent adverse influences on the building. These might include interlocks for high wind speed, rain, low external temperature, wind direction and low internal temperature. Weather monitoring sensors are normally provided as part of the automatic control system to monitor the external conditions. Reference [4] provides details regarding the selection and positioning of sensors suitable for the control of night cooling.

Some buildings are currently being designed with the intention of carrying out night cooling using manually openable windows (natural ventilation). As the external temperature increases in the peak summer months it is intended that more windows are opened. This is to be carried out on a daily basis by the security guards/occupants so that by the height of the summer all the windows are opened. As the external temperatures start to decrease (i.e. as autumn approaches) the security guards/occupants are expected to start closing windows. The practicality of this mode of operation has yet to be proven in practice.

2.4 MECHANICAL COOLING

Where buildings have particularly high thermal loads mechanical cooling can be used to cool the fabric to lower temperatures than would be possible with night cooling alone. This is achieved by cooling the air passing over or through the slab. The use of mechanical cooling offers the possibility of shifting the cooling load to a low tariff period thus providing cost savings, particularly where peak daytime cooling loads coincide with peak electricity tariffs. Additional savings may be available due to the improved cooling system performance at night due to more effective operation of the condenser with the cooler ambient air. Cooling system efficiency improvements may also occur due to operation at full load as opposed to possible part load operation during the day. However, where mechanical cooling is used a number of issues arise:

- the ventilation system should be run in recirculation mode to prevent energy wastage caused by loss of some the mechanically cooled air to atmosphere.
- the cost of the running the supply fan and chiller system for night cooling should be taken into account together with the efficiency of storage. It may be more cost effective to operate the chiller system solely at the time that cooling is required.
- the use of mechanical night cooling can reduce the requirement for additional chilling capacity where the chiller system is undersized.

- where mechanical cooling of a hollow core slab is carried out the cooling stored overnight will reduce the slab temperature below that with mechanical night ventilation alone. However, during the day, mechanically cooled air supplied via the hollow core slab will be warmed since the supply air into the slab will be below the slab temperature. This will affect the ability to rapidly cool the occupied space. A by-pass arrangement should be provided to overcome this thus maintaining the benefit of slab cooling for periods of peak electricity rates or lower cooling loads.

- there is a danger of over-cooling the slab and a condensation avoidance control strategy similar to that used for chilled ceilings is recommended. These are generally based upon monitoring the presence of moisture or the relative humidity and temperature close to the slab surface as an indicator of the risk of condensation.

2.5 CONDENSATION

The question of humidity control and risk of condensation is often posed in naturally ventilated buildings. Previous work by Barnard [1] has shown that the occurrence of high humidity (>70% RH) is rare for the temperature conditions analysed (>22°C). The provision of dehumidification is unlikely therefore to be necessary. With regard to condensation the dew point temperature of the ambient air will generally be below the minimum fabric temperature thus minimising the likelihood of condensation. However, a number of points should be remembered in the consideration of condensation:

- the risk of condensation will be increased at low air supply rates as there will be less removal of moisture.

- smaller sensible heat gains will reduce the fabric temperature achieved and so will increase the risk of condensation.

- the use of mechanical ventilation to cool the fabric temperatures below those which could be achieved by night cooling alone will also increase the risk of condensation.

3. CONCLUSIONS FROM THE LITERATURE SEARCH

As part of the research a literature review was conducted using the following keywords:

free cooling
ventilation/free cooling

fans/cooling
night cooling
pre-cooling

air conditioning/night cooling
air conditioning/free cooling

predictive control

The principle conclusions from the literature search are detailed below and full details of the review can be found in report 11621/1.

- The difference between the ground floor and the second floor internal temperature after night cooling is typically 2°C. This is due to the reduced stack effect available on the second floor, thus reducing the night (and daytime) ventilation rate. The ground floor slab is also likely to be cooler than the other floor slabs due to contact with the ground. This will further influence the ground floor temperature.

- When night cooling is utilised in a building with a comparatively heavyweight exposed structure, good solar shading, and internal heat gains below approximately $40W/m^2$, then the internal temperature can typically be held at 6-8°C below peak external summer time temperatures.

- In order to maximise the benefit of night cooling the vents should be shut during the daytime (except to provide the ventilation necessary for the occupants' health and comfort) to minimise heat gains from the ambient air, particularly in periods of high external temperature.

- On hot days when the internal temperature exceeds the upper level of comfort in still air, improvements in comfort may be obtained by increasing the indoor air speed with a fan (eg punkah fan), whilst minimising the ventilation with outside air.

- Passive night cooling saves the capital cost of air handling units and chilling plant etc. and hence incurs no energy expenditure on fan power or cooling costs. However this should be offset against the costs of additional solar shading, openable windows, vent actuators and other associated controls.

- Simple night cooling control routines have been suggested to offer the optimum cost savings whereas the more sophisticated control strategies resulted in the optimum energy savings. The cost savings achieved with the simple pre-cool strategies is due to the high utilisation factor which results in larger cooling savings and higher net cost savings (due to tariff differentials) whilst producing lower net energy savings due to pre-cool operation in longer (and consequently less favourable) periods. The conflict between the results demonstrates that the criteria for success (i.e. energy saving or cost saving) may determine whether simple or complex controls are more appropriate.

- Thermal mass alone can actually increase energy use if night cooling is not applied since the heat gains build up, increasing the average daytime temperature and thus requiring the greater use of mechanical cooling.

- A storage efficiency can be estimated based upon equating the cooling entering the space with the cooling transferring to the fabric:

- The penalty of having a thermally heavyweight building is that any mistakes in control can take significant time and energy to rectify.

- The use of phase change materials in the building fabric has the benefit of enhancing the cooling storage capacity of a building without an undue increase in the building mass.

- A number of predictive control techniques for night cooling/daytime temperature control have been developed using computer simulation. The predictive techniques generally incorporate some form of weather prediction modules based on a combination of meteorological institute forecasts, historical weather data, and consideration of today's weather to predict tomorrow's. Up-to-date weather monitoring is normally used to detect sudden changes in the weather that may affect the prediction. The weather predictions are generally used to predict the internal space temperature or comfort conditions based on the knowledge of the expected night cooling rate, the expected daytime external temperature and expected ventilation rates together with building thermal parameters and expected heat gains. However, none of the papers detail the results of any tests on real buildings.

4. RÉSUMÉ OF SITE MONITORING

4.1 INTRODUCTION

As part of the research four main night cooling control strategies were identified. Five buildings that utilise these strategies were monitored from spring to autumn 1995 using data collected by the building management system (BMS) installed on each site. The buildings monitored were ventilated using both mechanical and natural ventilation. These buildings were :

- buildings B and F at the Inland Revenue Building, Nottingham (utilising setpoint control initiated by the average afternoon external temperature)
- the Ionica Building, Cambridge (degree hours control)
- the PowerGen Headquarters Building, Coventry (setpoint control initiated by the average zone temperature and the minimum external temperature limits)
- the Inland Revenue Building, Durrington (slab temperature control).

The analysis investigated the operation and effectiveness of each cooling control system and the correlation between night cooling and the factors that could influence its operation. Full details regarding the site monitoring can be found in report 11621/2

4.2 DESCRIPTION OF BUILDINGS

4.2.1 Inland Revenue Building, Durrington

General building description

Durrington Bridge House is a 7500m^2, four storey office building constructed around a central atrium. The building has open plan office areas on the North and South sides and cellular offices provided on the East and West sides. The building benefits from an exposed concrete ceiling and external solar shading on the southern facade. Blinds are fitted internally to the windows. Internal light shelves are provided to improve natural light levels.

A mixed mode ventilation system is used supplying air either by a dedicated two speed mechanical ventilation system (1.5 or 4 air changes per hour), or by natural ventilation which provides air from automatically controlled casement vents fitted above manually openable centre pivot windows. Air is extracted via the atrium, either by the two speed extract fans or via the atrium rooflights which are under automatic control. There is no mechanical cooling available. Heating is provided via a thermal wheel and heater batteries in the supply air handling units. A perimeter heating system is also used.

Control strategy

The ventilation system for the open plan office areas is based upon controlling the two open plan office supply fans and the office/atrium casement vents during the occupied, non-occupied and night cooling periods. The supply fans operate to provide heating if the space temperature is below the space temperature setpoint. When the heating is on, the outer casement windows and atrium vents shut and the atrium casement windows open. If the average temperature exceeds the setpoint the heating switches off.

Perimeter heating is also available and is initiated if the outside air temperature is below the heating enable setpoint.

In the event that night cooling takes place, the perimeter heating is inhibited until the building is occupied. However, the perimeter heating is enabled according to an optimum start algorithm if night cooling occurs.

As the temperature of a zone increases above the cooling setpoint the automatic windows of that zone open. If the temperature of a zone falls below the cooling setpoint the outer windows of that zone shut.

When the average room temperature exceeds the cooling setpoint by 1K the supply fans operate at low speed and continue to operate until the average temperature falls 0.5K below the setpoint. If the average temperature rises 2K above the setpoint the supply fans switch to high speed and remain at high speed until the temperature falls to 1K above the setpoint when it reverts to low speed operation. The following illustrates the summer heating and cooling setpoints, with deadbands:

Temperature increasing ↑	T (°C)	Temperature falling ↓
High speed fans on	24 23.5	
Low speed fans on	23	High speed fans off
Cooling on (windows open)	22.5	
	22	
	21.5	Cooling off (windows shut/low speed fans off)
Heating off	21	
	20.5	
	20	Heating on.

Night cooling control strategy - slab temperature control

At the end of occupancy the cooling by natural ventilation is maintained, as required, for 1.5 hours. Following this, and provided the building is to be occupied within 24 hours i.e. not Friday night or Saturday night, night cooling is applied by opening the automatic windows and atrium vents for cooling by natural ventilation. This continues until the slab setpoint is achieved at which time the windows and vents are shut. If the slab setpoint is not achieved by the start of the low electricity tariff, the latest start time for mechanical night cooling to achieve the setpoint is calculated. The fans are only operated during the low tariff period. The windows remain open and the fans operate for the calculated period, or until the setpoint is achieved. The calculation of the time required to achieve the slab temperature setpoint includes the basic cooling rate, temperature differentials between the slab and outside air and a factor for high wind speeds.

Slab temperature setpoint

The slab temperature setpoint is calculated with the intention of equalising the slab temperature, the room temperature and the slab temperature setpoint at the end of the occupancy period on the following day. An adjustment factor is provided in order that a cooling effect is still available from the slab towards the end of the occupancy period (i.e. if the slab and the room are at the same temperature then there is no cooling available). The calculation is 'self learning' so that in the event that the slab temperature setpoint is not achieved then an additional factor is applied to the calculation in order that the setpoint might be achieved for the following night cooling period.

4.2.2 Inland Revenue Buildings B and F, Nottingham

General building description

Building B takes the form of a quadrangle and has a total floor area of approximately 8500 m^2, whereas building F is in the form of an L shape with a total floor area of about 5700 m^2. The buildings were completed in 1994 and are of similar construction with a 'waveform' exposed concrete ceiling.

The buildings are ventilated either via mechanical supply fans in the underfloor void (one per bay, manually controlled with four speeds) or by natural ventilation with air supplied via opening windows. In both cases the air is exhausted via 'extract' towers which are fitted with a roof arrangement that can be raised and lowered under BMS control to vary the air flow rate through the towers in order to maintain temperature control in the occupied space. There are four towers provided in building B and three towers in building F. Each tower is designed as a stairwell and is constructed partially of glass to aid the stack effect (solar tower).

The top floor of each building extracts air via manually controlled rooflights rather than the towers. This reduces the height required for the towers.

Heating is provided via finned tube heaters fitted as part of the underfloor fan system together with a perimeter heating system. There is no facility for mechanical cooling.

Solar shading is provided in the form of structural shading with the windows being recessed between deep load bearing piers. Light shelves are fitted externally and mid-pane automatic blinds are used which shut overnight to minimise solar gains from the sun rising. The blinds are also re-positioned at 45° twice each day.

Control strategy

The operation of the 'extract' towers is allowed providing the following conditions are satisfied:

- occupied period
- no security or fire alert
- wind speed < 8m/s
- temperature at top of tower (internal) > 27°C
- average corridor temperature > 25°C
- outside air temperature > 12°C
- rain intensity < intermediate.

If the above conditions are satisfied the tower roof is enabled and controlled between 0-100% depending on the tower temperature, outside air temperature, wind speed and direction and rain intensity. Wind speed and rain are combined in a 'lookup' table such that worsening rain at one wind speed or increasing wind speed at a particular rain intensity result in the opening being reduced. There is also a scaling factor applied depending on the wind direction and outside air temperature. If the wind is from the South West then the scaling factor is 1 i.e. the tower height was 100% of that determined by the combination of tower temperature, wind speed and rain. If the wind is from the North, South, West or South West the scaling factor is 0.95 and from the East, North East or North West 0.9. A scaling factor is also calculated according to outside air temperature. For example if the outside air temperature was 12 - 14°C the scaling factor was 0.85, 14 - 16°C 0.9, 16 - 20°C 0.95 and above 20°C 1.0. The lower scaling factor between wind direction and outside air temperature is multiplied by the value of the tower opening signal to provide the actual tower opening.

Night cooling control - setpoint control with average external temperature

Night cooling is enabled providing the average outside air temperature between 12.00-17.00 exceeds 18°C. The night cooling then operates if the following criteria are satisfied:

- night cool period
- outside air temperature >12°C
- inside air temperature > outside air temperature
- inside air temperature > 15.5°C with a 3K deadband centred on the setpoint.

The wind speed, rain, security and fire interlocks used for daytime control also apply.

If all of the above controls are satisfied the tower roofs open fully, the supply fans are enabled and the ridge vents open. The vents remain open until one of the above criteria is no longer satisfied.

4.2.3 Ionica Building, Cambridge

General building description

The Ionica building is a 4000 m^2 office building on three floors. The interior is designed around a 54m long atrium and is notionally divided into four main zones, North West, North East, South West and South East. The southern zones are open plan and have the option of being ventilated by natural ventilation or via a mechanical displacement ventilation system. This supplies air through a hollow core slab to the underfloor void where it enters the office space via floor grilles. The northern zones of the building are designed to be compartmented and consequently consists of cellular offices and meeting rooms. These rooms are ventilated via the mechanical displacement ventilation system. The building benefits from an exposed concrete ceiling throughout.

Manually openable windows are installed in all zones of the building although only the windows at high level on the southern facade are capable of being opened using automatic control. Low level manually operated windows are also provided.

The air is extracted from the building either via the mechanical extract fans or passively through the central atrium and out through purpose made wind towers, designed to operate under most conditions of wind and rain.

Heating is provided by the mechanical system which utilises a thermal wheel, heat pump and electric reheater to supply at a constant temperature of 18°C. Perimeter heating is also provided. Evaporative cooling on the mechanical extract is provided. This gives indirect cooling to the supply air via the thermal wheel. The heat pumps can also be used for cooling.

Control strategy

The control strategy operates to maintain the temperature conditions within the space. A number of control modes are specified according to the time of day and the internal and external temperature. In the main open plan area (SW zone) the control strategy enables either the natural or mechanical ventilation system to maintain the internal conditions. The natural ventilation system is enabled when the internal temperature is less than 26°C and the external temperature is above 14°C. If the internal temperature increases then the mechanical ventilation together with the mechanical cooling is initiated. Weather interlocks are provided to prevent the natural ventilation operating if it is too cold outside or if there is a danger of a back flow of air through the wind towers into the atrium due to the wind operating from a particular direction.

Night cooling control - degree hours control (south west zone)

The need for night cooling is determined by a degree hours calculation based on the slab temperature. The degree hours are calculated by assuming the slab is at a fixed temperature of 21°C and measuring the deviation of the zone temperature from this limit. If the net degree hours at the end of occupancy is positive it is assumed that this proportion of heat has been absorbed. The zone air temperature is also monitored during the day and only if it exceeds 24°C for more than 1 hour is night cooling permitted. The night cool period is 9pm to 6am and is operated until the heat extracted from the slab matches the heat absorbed by the slab during the day. The criteria to measure the night degree hours is different to the day. During the day the degree hours calculation includes both heat gain and heat loss from the slab, i.e. zone temperature above and below 21°C to determine night cooling target. At night only the heat loss is calculated i.e. zone temperature below 21°C and periods when the zone temperature exceeds 21°C are ignored. A self learning algorithm calculates the target proportion of heat to be extracted from the slab under night cooling. The rate of heat absorbed during the day to target heat loss is normally 1:1 but can be varied depending on the deviation of the average zone temperature from the zone setpoint.

4.2.4 PowerGen Building, Coventry

General building description

This is an open plan office building built around a central atrium. Three rows of windows are provided to the perimeter, two of which can be manually operated by the occupants. The third (top row) window is controlled by the BMS. The building is continuously ventilated via a mechanical displacement system (1.5 or 3 air changes per hour) which has the facility to mechanically cool the air, although this is not utilised. Air extract is via mechanical extract fans situated in the atrium roof or passively via two rows of windows under automatic control at the top of the atrium.

The building has an exposed concrete ceiling (vaulted) and external solar shading on the southern facade. Roller blinds are also provided for the windows.

Heating of the occupied space via electric heater batteries in the air handling units together with electric perimeter heating. Heat pumps are also used for both heating and cooling and the waste heat from operating the heat pumps in cooling mode is supplied to radiators in the atrium roof to assist ventilation via the stack effect.

Control strategy

The mechanical ventilation system operates continuously at low speed during the occupied period to ensure adequate ventilation of the cellular offices. When the zone temperature is greater than 23°C the natural ventilation system operates the automatically controlled windows together with the atrium windows on the opposite side to provide cross ventilation providing that the weather interlocks are satisfied. If the external temperature exceeds the internal temperature then the BMS controlled casement vents close in that zone.

Night cooling control - setpoint control with minimum external temperature and average zone temperature

The decision to night cool is made if the average office temperature at the end of the day is greater than 23°C and the maximum external temperature during the day exceeded 21°C. All the office and atrium windows are opened, subject to weather interlocks, and cooling takes place until a temperature of 18°C is sensed. At this point the windows relating to the zone where the 18°C temperature is sensed are closed. If, after closing the windows , the zone temperature rises to 20°C then the window are opened again to cool the zone. The weather interlocks for night ventilation are less stringent than for daytime ventilation, thus maximising the amount of ventilation that can take place at night. The daytime wind interlock closes all of the windows at a wind speed of 10m/s whereas this does not happen until a wind speed of 20m/s is sensed during night cooling.

4.3 CONCLUSIONS

The analysis of the site monitoring data led to a number of conclusions being made which are presented below. The full analysis of the results is provided in report 11621/2.

4.3.1 Inland Revenue, Durrington (Slab temperature setpoint control)

1) The slab setpoint was never attained during night cooling. The slab temperature only approached the setpoint as it reduced with the trend in average outside temperature. The minimum temperature difference was 1.2K and the maximum 7.8K during the August to October period.

2) The slab setpoint change was very limited (0.7K between August to October) considering the complex nature of the algorithms involved. The algorithms only permitted minimal change in the setpoint if it was not successful the previous night. The setpoint therefore changed very little.

3) The minimum permitted slab setpoint was unrealistically low. A regression analysis between the outside air and slab temperatures suggested the slab temperature would not fall below 18°C. Also the minimum slab setpoint would have caused a significant requirement for heating if it was ever achieved as the heating setpoints were 2 - 6.5K above the minimum slab setpoint.

4) The control strategy resulted in very high night cooling utilisation, even in the marginal months of September and October. It was only the bad weather mode, which inhibits the operation of passive night cooling but not mechanical night cooling (low tariff period only), that prevented further night cooling. Bad weather operated for 158 hours in September and October compared to only 109 hours for night cooling by natural ventilation.

5) There was not generally a significant difference in the cooling rates between night cooling with mechanical ventilation and natural ventilation.

6) The night cooling control, although successful in helping to maintain a satisfactory environment, was over utilised. In theory the night cooling technique was sound because it included two important parameters (slab and zone temperatures). However in practice the algorithms created unrealistic targets because the zone and slab temperatures were expected to achieve the cooling setpoint which was set too low eg 22°C in July. This compares, for example to Ionica where the zone temperature had to exceed 24°C for night cooling to take place. The peak zone temperatures are related to the peak outside air temperature and a low energy design (no mechanical cooling) can only expect to temper this by 3-4K. Therefore 22°C would be rarely achieved in peak summer. The slab temperature also followed trends in outside air temperature but was expected to be actually cooler than the cooling setpoint. The algorithms assumed the slab would demonstrate significant temperature changes but in practice this only occurred at the beginning or end of a hot spell of weather. One sensible precaution was the interlock that minimised setpoint change if night cooling did not succeed the previous night. This prevented even more unrealistic targets being set. The night control also included a minimum setpoint limit, which should have prevented it being set too low. However the actual limits were unrealistic and would have caused heating problems if ever achieved (see conclusion (3)).

4.3.2 Inland Revenue, Nottingham (minimum average afternoon outside air temperature control)

1) The minimum permitted night cooling zone temperature of 14°C was not approached during July to September. The minimum zone temperatures were 20.7°C in July, 19.8 °C in August and 18.2 °C in September. The night cooling technique in use at Nottingham allows the air temperature to cool to 14°C before the system switches off. The fabric is then expected to heat the air to 17°C when night cooling is again applied. The control strategy does not work in practice because an unrealistic temperature drop of 8-10K is required to cool the zone air temperature to 14°C.

2) The criteria that the average afternoon outside air temperature must exceed 18°C for night cooling to be permitted was satisfied throughout July and August. It was not a particularly extreme condition to satisfy.

3) The minimum outside temperature of 12 °C was a sensible precaution and would only have limited night cooling on 6 occasions between July and September.

4) The wind speed interlock setpoint (20m/s) was never exceeded and therefore did not operate to prevent night cooling.

4.3.4 PowerGen, Coventry (minimum outside air temperature and minimum average zone temperature control)

1) The 21 °C minimum outside air temperature limit for night cooling to apply was exceeded on 24 out of 29 days in July and August.

2) The 23 °C minimum average zone temperature limit for night cooling to apply was exceeded on 23 out of 29 days in July and August.

3) Although the actual hours of operation of the night cooling are not available, when night cooling was permitted it probably operated for the entire night period. The explanation for this is similar to conclusion 3) for Ionica above. The average daytime zone temperature must exceed 23 °C for night cooling to be permitted and if this were the case it is unlikely that the zone temperature would fall below the 18 °C minimum setpoint at night.

4) The PowerGen night cooling control was the most simple of the four strategies but was potentially the most successful. It did not include complex algorithms that had little practical benefit but it did include the most realistic control setpoints. The minimum average zone temperature interlock prevented night cooling unless it was necessary. Once that interlock had been satisfied maximum night cooling was permitted with a simple zone temperature minimum to prevent any risk of over-cooling.

4.3.5 General conclusions

1) There was generally a weak correlation (correlation coefficient r) between the peak zone temperature and the peak outside air temperature (0.724 at Inland Revenue, Durrington; 0.720 at Inland Revenue, Nottingham; 0.819 at PowerGen; 0.456 at Ionica).

2) There was a correlation between the ground floor peak temperature and the other floors. For all buildings, excluding Ionica, there was a temperature increase of approximately 2K between the ground and top floors.

3) There was no significant lag between the peak zone temperature and the peak outside temperature from day to day. If Durrington was used as an example the correlation between the peak temperatures was 0.849 with no lag, 0.806 with a one day lag and 0.710 with a two day lag. Only the Durrington control, based on slab temperature, accounted for this lag and continued to night cool. The Nottingham and PowerGen night cooling routine would not be enabled at the end of a hot spell because they both include minimum outside air temperature interlocks. The Ionica night cooling control is also likely to be off at the end of a hot spell because of the minimum zone temperature interlock.

4) The floor slab temperature demonstrated a significant correlation with the outside air temperature and followed its trends. For example at Durrington the weekly average slab temperature rose by 2.4K between June to August and then fell by 3.1K to October.

5) There was a significant lag between the peak daily slab temperature and peak daily outside temperature. At Durrington the correlation was 0.727 with no lag, 0.797 with a one day lag, 0.832 with a two day lag and 0.830 with a three day lag. This indicates that there was a lag of approximately two days between the outside air temperature and slab temperature.

6) Slab temperature changes were generally small but could be significant when ambient conditions suddenly altered, e.g. the start or end of a hot spell. For example the slab temperature at Durrington increased by 2K in a one week period.

7) Over-cooling was generally not beneficial. Night cooling in peak ambient conditions did not cool the zone to the heating setpoint. The zone temperature typically fell from, e.g. 26 °C to 22-24 °C. In marginal conditions, over-cooling is possible and the requirement for night cooling is also reduced. Consequently over-cooling is not beneficial and night cooling control should include a minimum zone temperature setpoint that is related to the heating setpoint.

8) Night cooling was applied at weekends at some of the sites and this is recommended particularly for peak ambient conditions. A minimum zone temperature setpoint should prevent over-cooling in marginal conditions.

9) Bad weather interlocks can potentially be very disruptive to the utilisation of night cooling. Their use needs to be carefully considered and not over specified.

10) There was no single overriding factor that influenced the success of night cooling (measured by zone temperature drop) over any other tested. This included wind speed, wind direction, night-time outside air temperature or the temperature difference between inside and outside.

11) Different facades may demonstrate different temperature patterns between floors. For example, at Durrington the northern facades showed a temperature increase from ground to top floor, but the southern did not. This indicated that different natural ventilation driving forces may have applied. Night cooling should, where possible, have individual control for zones with the building divided by floor and facade.

12) There was generally a significant temperature difference between inside and outside during night cooling. However, during peak conditions a positive differential may not occur until late evening, e g. Inland Revenue, Nottingham, was up to 21:45 hours. Therefore night cooling control should monitor the temperature differential between inside and outside and prevent operation if the outside temperature exceeds the inside. This practice, although commonly used, is not universal. Three of the four main buildings monitored incorporated it within the night cooling control strategy.

4.4 COMPARISON OF CONTROL STRATEGIES' HOURS OF UTILISATION

The conclusions from the site monitoring do not provide a direct comparison of the night cooling control strategies. However, if the analysis of the control strategies are carried out using the monitored data from one building a comparison of the results can be made. Consequently, the control strategies with their associated control setpoints and interlocks have been applied to the monitored data taken from the Inland Revenue building, Durrington. The conclusions (1) to (4) below compare the potential application of each strategy at Durrington during September and October. NB Analysis shows that there would have been full utilisation of all the night cooling strategies in the preceding summer months.

1) The zone temperature at Durrington did not exceed 24 °C and there would have been no night cooling if the Ionica control had applied.

2) The average afternoon outside air temperature exceeded 18 °C on 31 days out 47 at Durrington during September and October. Therefore the Inland Revenue, Nottingham control would have restricted night cooling by one third.

3) The average zone temperature exceeded 23 °C on only 12 days out of 47 at Durrington during September and October. The outside air temperature exceeded 21 °C on 20 days out of 47 at Durrington. The two limits combined were only satisfied on 7 days out of 47 at Durrington and this is the number of days that night cooling would have been applied with the PowerGen control.

4) The table below summarises the expected utilisation of the different night cooling control strategies if they had been installed on the BMS system at the Inland Revenue building , Durrington. As can be seen, the alternative control techniques would have resulted in a wide variation in utilisation.

Control type	September to October Utilisation (maximum = 47 days)
Slab setpoint (IR. Durrington)	47 days
Average afternoon OAT (IR. Nottingham)	31 days
Average zone temperature + peak OAT (PowerGen)	7 days
Peak zone temperature + degree hours (Ionica)	0 days

It is unlikely that the operation of the night cooling control strategies during September and October would really have been required for many of the 47 available days. The zone temperature never exceeded 24°C and only exceeded 23°C on 12 days. It would therefore seem appropriate that a night cooling control strategy that operated for a small number of nights or no nights at all would be most suitable. It should also be remembered that with the onset of the heating season there would be some benefit in maintaining as much heat as possible within the building fabric (but not to the detriment of comfort). This requirement obviously differs from that when using night cooling in the months preceding and during the summer when it is essential to limit the temperature rise of the building fabric.

4.5 NIGHT COOLING CONTROL STRATEGY RECOMMENDATIONS

The previous section detailed the conclusions from the site monitoring study. Each of the control strategies were successful in helping to produce a satisfactory thermal environment, as part of an overall low energy strategy. However as conclusions 4.3.1.(6), 4.3.2(5) and 4.3.4(3) show the use of complex algorithms may not be necessary in practice. These conclusions also show the daytime criteria to permit night cooling eg peak zone temperature often exclude the night criteria being satisfied. This was because the difference between day and night setpoints was too large. For example at Ionica the daytime zone temperature must exceed 24°C and a calculation of net degree hours is performed. However, the night cooling degree hours are unlikely to attain their target (match daytime heating degree hours) because the zone temperature must fall by at least 3K before the cooling degree hours are registered.

The different night cooling control strategies resulted in a wide variation in utilisation in the marginal summer months. It ranged from no night cooling with the Ionica control, to maximum night cooling with the Inland revenue, Durrington control (conclusion 4.4(4)). During peak summer periods each control would be applied for the maximum period. The results also show that, once initiated, each control would operate for the entire night cooling period since the control routines were unlikely to be fully satisfied. The reasons for this are as follows:

Inland Revenue, Durrington	- slab setpoint was never obtained
Inland Revenue, Nottingham	- zone temperature would not fall to 14 °C
Ionica, Cambridge	- night cooling degree hours unlikely to match daytime heating degree hours
PowerGen, Coventry	- zone temperature unlikely to fall to 18 °C if daytime average exceeded 23 °C

Each of the strategies was based on sound principles but, as the above shows, the daytime criteria to permit night cooling appears to exclude the possibility of less than maximum night cooling. Therefore the important difference between strategies was the specification of daytime conditions to permit night cooling.

Although some of the complex night cooling algorithms appear to be redundant in practice it is sensible to include simple controls to predict the need for night cooling. The most obvious indicators are the zone or outside air temperatures. A correlation was demonstrated between daytime peak zone and outside air temperatures (conclusion 4.3.5(1)). Therefore the use of either as a control limit should be applicable. If the zone temperature is used, either peak or average would be applicable because relatively small temperature changes are experienced. If the outside air temperature is used it should be an average to prevent temperature spikes, not representative of the day, influencing the results. The zone temperature limits applied at Ionica and PowerGen may be slightly too high in practice and prevent some beneficial night cooling. The outside air control at Inland Revenue, Nottingham, may conversely be slightly too low.

The slab temperature at the Inland Revenue, Durrington was weakly correlated to peak outside air temperature but demonstrated a lag of approximately two days (conclusions 4.3.5(3) and 4.3.5(5)). Therefore it may be applicable to operate night cooling for an additional two days after a prolonged hot period. This would not be necessary where night cooling was only utilised occasionally.

Over-cooling was generally not beneficial (conclusion 4.3.5(7)). A minimum zone temperature setpoint, related to the heating setpoint, should therefore be specified.

The peak zone temperatures were dependent upon the floor and facade (conclusions 4.3.5(11)). The building should be zoned between floors and facades with individual night cooling control in each zone.

The results demonstrated that during peak conditions the outside air temperature may exceed the zone temperature until late evening (conclusion 4.3.5(12)). Therefore night cooling should only be permitted provided the zone temperature (each zone) exceeds the outside air temperature. It is probably beneficial to include a small temperature difference, e.g. 2K, to account for sensor accuracy and location.

The addition of a minimum outside air temperature limit, e.g. 12 °C, should be included (conclusion 4.3.2(3)). This would reduce the possibility of condensation occurring. It should not affect the operation of night cooling during peak conditions because the outside air would be unlikely to fall below this level.

Night cooling by mechanical ventilation was typically no more successful than natural ventilation, (conclusion 4.3.1(5)), and also imposed a significant energy penalty. Fan energy was not measured but an indication of likely cost can be derived from the Inland Revenue, Durrington site. A simple calculation indicates that electrical power to the night cooling supply fans would have been approximately 144 kW. The cost of their operation from midnight to 7:00 am is £50 per night (5p/kWh). Therefore, its use should be restricted to bad weather conditions when natural ventilation was not feasible. Night cooling by natural ventilation should be applied from the end of occupancy, providing the interlocks, discussed above, are applied. Night cooling should also be applied at weekends (conclusion 4.3.5(8)) provided a minimum zone temperature setpoint has been specified.

The above discussion indicates the type of night cooling control that could be applied in practice. The following summarises those recommendations, but further reference should be made to the thermal simulation study (report 11621/3) summarised in chapter 5.

<u>Night cooling enable</u>

Days	-	7 days per week
Time	-	entire non-occupied period
Lag	-	operate night cooling for an additional two nights following the night cooling criteria no longer being satisfied. This only applies if night cooling operated for a minimum of the five previous consecutive nights.

Daytime activation requirement

Peak zone temperature (any zone) > 23 °C
Average zone temperature (any zone) > 22 °C
Average afternoon outside air temperature > 20 °C

Select any one of the above or a combination.

Night-time activation requirement

Zone temperature (any zone) > outside air temperature + 2K
Zone temperature (any zone) > heating setpoint
Outside air temperature > 12 °C

5. DYNAMIC THERMAL SIMULATION

5.1 INTRODUCTION

Thermal simulation was undertaken as part of the research in order to demonstrate the relative merits of each of the control strategies monitored in the case study buildings together with several other control strategies that have been identified. The strategies were tested against a range of variables that could influence performance that are typical of those experienced in actual buildings. One of the monitored buildings was selected to be modelled (Inland Revenue, Durrington) and the control strategies were tested using this design. A description of the building can be found in 4.2.1. Only one representative zone was modelled, south facing 1st/2nd floor and therefore the additional thermal influences in the top floor and ground floor areas were not included. The model was set up so that similar zones existed above and below. The south facing facade was selected because it had maximum heat gains and therefore maximum need for night cooling.

Further information regarding the Durrington model and the method of defining the control strategies in the APACHE software together with full details of the results are provided in report 11621/3.

5.2 NIGHT COOLING CONTROL STRATEGY DESCRIPTION

Seven night cooling control strategies were tested using the Durrington model and the following is a basic description of the different alternatives. The strategies described for named buildings are the same as applied in the actual buildings.

5.2.1 No night cooling

Night ventilation was not applied. This was included as a base case condition to compare the results of night cooling against. Each time a variable was changed e.g. slab construction, a base case simulation, with no night cooling, was performed.

5.2.2 Timeclock control

A simple timeclock controlled night cooling such that it was applied each evening prior to occupancy (not Friday or Saturday night). Natural ventilation was permitted from 21:00-07:00 and mechanical ventilation from 00:00-07:00. The control operated regardless of prevailing conditions or need and was the most simple form of night cooling that could be applied. In practice a manual decision would be taken to operate the system over the peak summer months.

5.2.3 Simple on/off based on zone temperature

This control permitted night cooling providing the following were satisfied:

zone air temperature > outside air temperature
zone air temperature > heating setpoint
outside air temperature > 12°C.

The first condition ensured that cooling and not heating would occur, the second condition prevented pre-heating being required prior to occupancy and the third condition minimised the risk of condensation. The control operated for the same period as the timeclock control.

5.2.4 Simple on/off based on slab temperature

This control was similar to the simple on/off based on zone temperature but night cooling was permitted if:

zone air temperature > outside air temperature
slab temperature > heating setpoint
outside air temperature > 12°C.

In practice a temperature sensor would be buried in the main fabric thermal storage element (ceiling slab) and the temperature of the slab instead of the zone used for control. The same night cool period as the timeclock control was applied.

5.2.5 Inland Revenue Building, Durrington

Night cooling was permitted providing the following was satisfied:

slab temperature > slab temperature setpoint.

The period that night cooling was available and the proportions of natural and mechanical ventilation were the same as the timeclock control.

Slab temperature setpoint calculation

The following rules were used to calculate the slab temperature setpoint in the actual building:

i) ΔT_1 = room setpoint - slab temperature at 17:00 - offset
ii) ΔT_2 = room setpoint - room temperature at 17:00
iii) Today's self learning value $\Delta T_3 = \Delta T_1 + \Delta T_2$
iv) ΔT_3 reduced if ΔT_4 was too high.
ΔT_4 = slab temperature at 07:00 - old slab temperature setpoint
v) Change in setpoint = $\Delta T = \frac{\Delta T_3 + \Delta T_3 \text{ old}}{2}$

ΔT_3 old = previous days adjustment

vi) Slab setpoint > minimum permitted slab setpoint.

5.2.6 Inland Revenue Building, Nottingham

Night cooling operated providing the following controls were satisfied:

i) Average outside air temperature (12:00-17:00) > 18°C

ii) Minimum zone temperature = 15.5°C with a 3K deadband centred in the setpoint

iii) Minimum outside air temperature = 12°C

iv) Inside air temperature > outside air temperature

The same time periods and ventilation system, as applied in the timeclock control were used.

5.2.7 Ionica Building

Under this control, night cooling was permitted if the following were satisfied:

i) Outside air temperature >7°C

ii) Zone air temperature > 14°C

iii) Peak zone air temperature during occupancy > 24°C

iv) Zone air temperature at beginning of night cool > 19°C

v) Zone air temperature > outside air temperature

vi) Night cooling continued until:
Daytime heating degree hours = target night cooling degree hours.

The target night cooling degree hours was increased if the average daytime zone temperature exceeded 21°C and reduced if the average daytime zone temperature was less than 21°C. The net daytime heating degree hours were calculated by combining the time and deviation of the zone temperature from 21°C. If the result was positive, night cooling was required. The night cooling degree hours were calculated by combining the time and deviation that the zone temperature was below 21°C.

5.3 TEST PROGRAMME

The test programme was divided into three sets of simulations, initial tests, special tests and main tests. The initial tests investigated the effect of night cooling period and ventilation rate and also the influence of construction and heat gains. A number of 'special' tests were also performed and these assessed the effect of the slab sensor depth on night cooling controls that used slab temperature in the strategy. The effect of no minimum zone or outside air temperatures limits during night cooling were also tested. The main series of tests compared different night cooling control strategies. A 'standard' model was defined as follows with only one parameter varied between tests:

Natural ventilation 1-8 ac/h dependent on temperature difference between inside and outside (0 - 6K).
Night ventilation rate - mechanical ventilation 4 ac/h
Night ventilation period - 18:00-07:00 natural ventilation, 00:00-07:00 mechanical ventilation.
Day ventilation rate - natural ventilation (see night ventilation rate), mechanical ventilation low speed 1.5 ac/h, high speed 4 ac/h.
Solar gains - low
Casual gains - low
Slab material - medium weight concrete
Slab covering - none (exposed)
Slab depth - 150 mm.

The seven night cooling control strategies (including no night cooling) were tested against a selection of variables with over 200 simulation runs being made. The variables were:

Weather data	- summer day (peak and typical), typical spring day - summer months (peak and typical)
Slab construction	- heavyweight, medium weight, lightweight concrete - 100 mm, 125 mm, 150 mm, 175 mm slab depth - exposed ceiling, false ceiling
Solar gains	- low, medium, high (high, medium and no shading)
Casual heat gains	- low, medium, high
Night mechanical ventilation rate	- 0, 2, 4, 6, 8, 10 ac/h
Night natural ventilation rate	- fixed 1, 2, 4, 6, 8 ac/h - variable 1-8 ac/h
Night ventilation periods	- 18:00-07:00, 18:00-05:00, 21:00-07:00, 21:00-05:00, 00:00-07:00, 00:00-05:00

Slab temperature sensor depth (applied to slab temperature and Durrington night cooling controls only) - 0 mm, 25 mm, 50 mm, 75 mm, 100 mm, 150 mm slab.

5.3 TEST PROGRAMME

The test programme was divided into three sets of simulations, initial tests, special tests and main tests. The initial tests investigated the effect of night cooling period and ventilation rate and also the influence of construction and heat gains. A number of 'special' tests were also performed and these assessed the effect of the slab sensor depth on night cooling controls that used slab temperature in the strategy. The effect of no minimum zone or outside air temperatures limits during night cooling were also tested. The main series of tests compared different night cooling control strategies. A 'standard' model was defined as follows with only one parameter varied between tests:

Natural ventilation 1-8 ac/h dependent on temperature difference between inside and outside (0 - 6K).
Night ventilation rate - mechanical ventilation 4 ac/h
Night ventilation period - 18:00-07:00 natural ventilation, 00:00-07:00 mechanical ventilation.
Day ventilation rate - natural ventilation (see night ventilation rate), mechanical ventilation low speed 1.5 ac/h, high speed 4 ac/h.
Solar gains - low
Casual gains - low
Slab material - medium weight concrete
Slab covering - none (exposed)
Slab depth - 150 mm.

The seven night cooling control strategies (including no night cooling) were tested against a selection of variables with over 200 simulation runs being made. The variables were:

Weather data	- summer day (peak and typical), typical spring day - summer months (peak and typical)
Slab construction	- heavyweight, medium weight, lightweight concrete - 100 mm, 125 mm, 150 mm, 175 mm slab depth - exposed ceiling, false ceiling
Solar gains	- low, medium, high (high, medium and no shading)
Casual heat gains	- low, medium, high
Night mechanical ventilation rate	- 0, 2, 4, 6, 8, 10 ac/h
Night natural ventilation rate	- fixed 1, 2, 4, 6, 8 ac/h - variable 1-8 ac/h
Night ventilation periods	- 18:00-07:00, 18:00-05:00, 21:00-07:00, 21:00-05:00, 00:00-07:00, 00:00-05:00

Slab temperature sensor depth (applied to slab temperature and Durrington night cooling controls only) - 0 mm, 25 mm, 50 mm, 75 mm, 100 mm, 150 mm slab.

5.4 TEST RESULTS AND CONCLUSIONS

The main conclusions from the tests carried out are detailed below.

5.4.1 Initial Test Conclusions

The initial tests set the boundary conditions that a night cooling control strategy could be applied to. The main set of simulations compared different night cooling control strategies and it was impractical to test every variable with each control strategy. Therefore, the initial tests assessed the influence of selected variables with the most simple, but extreme strategy (timeclock control).

(i) The night cool period for the main tests was 21:00-07:00 and the initial tests indicated that the effect of alternative night cool periods was small. The rate of cooling of the zone temperature was lower with the earlier start of 18:00 due to higher outside air temperatures. The later starts quickly attained a similar zone temperature to that of the earlier start, resulting in similar slab cooling for the majority of the night cool period.

(ii) The model tests were based on a mechanical ventilation air change rate for night cooling of 4 ac/h. This was the based on the fan sizing used at the Inland Revenue building, Durrington. The influence of higher or lower ventilation rates was found to be small with this model. At night, the Inland Revenue building, Durrington used the mechanical ventilation to supplement natural ventilation. When this was tested on the model it was found that this reduced the impact of increasing the mechanical ventilation rate.

(iii) The heat gains (both solar and casual) had a very significant effect on zone temperature. For example the use of an external overhang on the southern facade reduced the number of occupied hours above 22°C by 50%. The use of an internal blind and external overhang (as applied at the Inland Revenue, Durrington) reduced the hours above 22°C by 85%. The effect of solar shading produced a similar performance to no solar shading with night cooling. This was also shown with casual gain where halving the gains from 40 W/m^2 to 20 W/m^2 produced a similar performance to maximum night cooling (timeclock control) with a casual gain of 40 W/m^2. It demonstrates that preventative measures are at least as important as night cooling for controlling internal temperatures. In practice, heat gains are minimised in passive low energy designs. The site monitoring results demonstrated a significant difference between the peak zone temperature and peak outside air temperature and this was also shown in the low gain simulations. The high gain simulations imposed an additional load on the fabric resulting in the peak zone temperatures matching or exceeding the outside air. Therefore a model with low casual gains and a high degree of solar shading was used in the main tests. This model was more representative of actual passive low energy buildings than those with higher gains and reduced solar shading.

(iv) The choice of concrete for the slab only had a minimal effect on performance and a medium weight was selected for the main tests.

(v) The addition of a false ceiling adversely affected night cooling performance. It would not normally be fitted in passive low energy buildings and was also not included in the main test programme.

(vi) The slab depth only had a small effect on overall zone temperatures. The range of slabs tested varied between 100 mm to 175 mm. The slab depth at the Inland Revenue building, Durrington (150 mm) was applied to the main test simulations.

5.4.2 Special Tests Conclusions

The special tests assessed the influence of selected factors on specific control strategies. The effect of varying the slab temperature sensor depth was tested with the Durrington and slab control strategies. The standard zone control system was tested with the minimum zone temperature interlock disabled.

(i) There was not a significant advantage between slab sensors at different depths due to the thermal mass of the slab. There was a small temperature drop through the slab and a relatively small change in slab temperature during night cooling. Therefore night cooling was applied to a similar period regardless of sensor depth.

(ii) Night cooling controls should include a minimum zone temperature setpoint. The benefits of additional utilisation and cooling from not having this control were outweighed by the extra heating required.

5.4.3 Main Tests Conclusions

The main set of tests compared the performance of the model (occupied hours that the zone temperature exceeded fixed limits) with six different night cooling control strategies i.e. the no night cooling case was omitted. The main conclusions are as follows:

(i) The use of Kew 1964-65 and Kew 1967 weather data, together with low casual gains (20 W/m^2) and solar shading, resulted in generally acceptable zone temperatures even without night cooling. The weather data was statistically representative of what could be expected (excluding extreme summers such as 1995). However, when higher casual gains are present the benefits of night cooling become more apparent.

(ii) Ionica demonstrated the lowest night cooling utilisation due to a control condition which prevented it if the zone temperature was below 24°C. This temperature may have been too high and prevented some worthwhile night cooling. However, the inclusion of this zone temperature setpoint at a lower value or, alternatively, an outside air temperature setpoint, is still beneficial to prevent unnecessary night cooling.

6. OVERALL PROJECT CONCLUSIONS

The site monitoring work investigated the performance of four different night cooling strategies backed up by computer monitoring. The analysis resulted in a number of general conclusions as well as conclusions specific to individual strategies. This led to the definition of a recommended control strategy for natural ventilation night cooling as follows:

Night cool enable

Days - 7 days per week
Time - entire non-occupied period
Lag - operate night cooling for an additional two nights following the control criteria no longer being satisfied. This only applies if night cooling operated for a minimum of the previous five consecutive nights.

Daytime activation requirement

Peak zone temperature (any zone) > 23°C
Average zone temperature (any zone) >22°C
Average afternoon outside air temperature >20°C

Note: select any one of the above or a combination.

Night cooling activation requirement

Zone temperature (any zone) > outside air temperature + 2K
Zone temperature (any zone) > heating setpoint
Outside air temperature >12°C.

The above strategy was devised to include the optimum features of the alternative control strategies. The night cool period was set up to maximise utilisation of natural ventilation which does not incur an energy penalty or financial cost. However, this should only apply provided the other interlocks specified above are also included. The interlocks will limit night cooling to when it is beneficial and prevent over-cooling. The lag was included because the monitoring results showed that the slab temperature followed the trend in outside air temperature but peaks approximately two days after the outside air temperature peak.

Additional conclusions derived from the analysis of the site monitoring and computer modelling work are as follows:

- The monitoring study also demonstrated that the complex algorithms were no more beneficial than simpler systems. This was confirmed by the modelling where the most successful system was the zone temperature control which improved the peak zone temperatures but not at the expense of significant additional heating or fan energy.

- The monitoring demonstrated that although the complex algorithms were no more beneficial than other controls, some form of simple prediction of the need for night cooling was of benefit Therefore daytime criteria to permit night cooling is included in the recommended specification with the most relevant being the peak outside air or zone air temperatures. The monitoring results showed that if the daytime criteria, of the actual complex controls, were satisfied the night time criteria would never be satisfied with the night control operating all night. This conclusion was supported by the modelling work by demonstrating that when night cooling was permitted it operated for the entire night period.

- The recommended night cooling strategy only permits night cooling when it is beneficial and also prevents over-cooling. The site data showed that the maximum zone temperature drop was approximately 4K. This prevents over-cooling in peak ambient periods. Over-cooling will only occur in cooler periods when the need for night cooling is reduced and the lower ambient temperatures have a far more significant impact on the internal temperature.

- The site monitoring was supported by the modelling results. The modelling demonstrated that there was only a small benefit in peak zone temperatures between strategies with and without minimum zone setpoints. The simulations that included a minimum zone setpoint had reduced utilisation but this occurred in cooler ambient conditions when the requirement for night cooling was lower. Also, the energy penalty from additional heating in simulations without a minimum zone temperature, was significant.

- The monitoring study indicated that night cooling was, in general, no more effective with mechanical ventilation than natural ventilation. This led to the conclusion that night cooling by mechanical ventilation, although a useful backup, should be limited to selected conditions eg bad weather preventing the use of natural ventilation. The modelling results indicated that if the average natural ventilation rate was 4 ac/h or above the benefit of supplementary mechanical ventilation would be marginal.

- One additional conclusion from the modelling work was the importance of reducing heat gains. This showed that solar shading and minimal casual gains are as effective in controlling zone temperatures as maximum night cooling. If the two techniques are combined then significant reduction in heat gains can be obtained.