BSRIA

NIGHT COOLING CONTROL STRATEGIES

DYNAMIC THERMAL SIMULATION RESULTS

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A sp[illegible] project

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1. INTRODUCTION

This report is the third in a series produced for project 11621 "Night Cooling Control Strategies". The first report was a literature review of night cooling techniques, the second report detailed the results from case study buildings that were monitored in 1995 and this report includes the results of dynamic thermal simulation. APACHE thermal simulation software was used to model a basic representation of one of the case study buildings. 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 selected to represent the range of conditions that could be experienced in actual buildings.

2. MODEL DESCRIPTION

2.1 APACHE SOFTWARE

APACHE uses a nodal system that connects individual HVAC plant items and building zones[1]. The program begins with the outside air condition and works its way through the system calculating the air temperature, moisture content and mass flow rate at each node. An iterative process is then applied to determine the air and mean surface temperatures in each zone. The heat flow into and through opaque building elements is calculated using a finite difference technique. The amount of heat required to raise a body from T_1 to T_2 can be calculated as follows:

$$Q = m\ Cp\ (T_2 - T_1)$$

Where: m = Mass
Cp = Specific heat capacity.

It is not sufficiently accurate to assume a single temperature for each element and APACHE divides construction elements into a series of sub-elements. The number of sub elements selected involves a trade off between computer calculation time and required accuracy. The number of sub elements (slices) is limited by calculation of the Fourier number, which incorporates time step and slice thickness. The slice thickness that produces a Fourier number approaching 0.5 is selected by the software. The minimum number of slices in any element is three.

$$Fo = \frac{kt_s}{pcx2}$$

Where:

F_o	=	Fourier number
k	=	Thermal conductivity of material (W/mK)
t_s	=	Time step (s)
ρ	=	Material density (kg/m^3)
c	=	Material heat capacity (J/kgK)
x	=	Thickness of slice (mm).

2.1.1 APACHE HVAC controls

Two types of control are available from the software, on/off and proportional and the following is a description of the alternatives.

On/off control

The on/off controls include an operation time period (daily, weekly, monthly) and a sensed variable that specifies the type of control.

Alternative sensed variables include air temperature, air flow rate, relative humidity, wet bulb temperature, dew point temperature, enthalpy and solar radiation. If a sensed variable is not specified the control acts as a simple timeclock. The setpoints can be constant or time varying in which case the profile (day to day variation) is also included. Logic AND/OR functions can also be specified to link controller(s) such that plant is on only if all controls are on (AND) or plant is on if any control is on (OR). However, these only worked if the time period is the same eg an OR control could not be specified for a fan to operate with one control during the day OR a separate control overnight. Other factors that must be specified include:

- dead band
- whether a control is on or off if the setpoint is exceeded
- radiant fraction of temperature sensors.

Proportional control

Proportional controllers are specified with an associated on/off controller and the same sensed variables as the on/off controls are available. The control includes a simple proportional band and PI or PID controls can not be specified.

Night cooling control techniques from three of the case study buildings were modelled using APACHE. Each technique used daytime conditions eg zone temperature, outside air temperature, to determine the need for night cooling. The above demonstrates that the standard APACHE controls were not sophisticated enough to simulate the actual night cooling controls directly. For example the standard APACHE controls can only register instantaneous conditions and therefore a control that permits night cooling if the daytime zone temperature exceeds a fixed limit can not be simulated. An alternative method of simulating the actual controls was devised that could log daytime conditions and this is described in section 2.3.

2.2 BUILDING MODEL

2.2.1 Construction

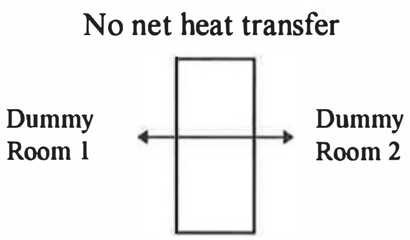
One of the monitored buildings (Inland Revenue, Durrington) was selected to be modelled and the night cooling strategies were tested using this design. The building has four storeys and a square plan with a central atrium. Only one representative zone was modelled, south facing 1st/2nd floor and therefore 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. Appendix A1 provides details of the layout and construction of the test zone.

2.2.2 HVAC system

The HVAC system was also set up to simulate that used at the Inland Revenue Building in Durrington and as such did not include mechanical cooling. The ventilation system was a combination of natural ventilation and mechanical ventilation with a two speed fan. Natural ventilation was modelled by including additional connections in the HVAC system but not specifying any plant i.e. fans. The control setpoints were those used in the actual building. Heating was provided by a heater battery and thermal wheel. Appendix A1 details the components, connections and controls of the HVAC system.

2.3 METHOD OF DEFINING COMPLEX NIGHT COOLING CONTROL STRATEGIES

APACHE software can only model simple on/off and proportional controls (see 2.1.1) and not more complex adaptive controls. The work required night cooling controls to be modelled that permitted night cooling if certain daytime conditions were satisfied. To achieve this a system was devised that entailed modelling dummy rooms with no thermal links to the main building or HVAC system. These rooms were set up such that there was no net heat transfer outside the room by specifying two adjacent dummy rooms with identical internal conditions and a single wall construction dividing them. There were no casual or solar heat gains to the dummy rooms and the air temperature was controlled by room heater and room cooler units. These units were powered by a special fuel type which did not contribute to the energy consumption of the main building or HVAC system.



As there was no net heat transfer, the air temperature in the dummy room remained constant unless the heater or cooler units operated. The heater or cooler units were set up to operate only when a particular condition was satisfied. If for example, night cooling is only permitted when the daytime outside air temperature exceeded 22°C it can not be modelled directly by APACHE. The APACHE controls only register the conditions at that time and cannot log data from the previous afternoon. However, a dummy room can be set up with an on/off heater such that if the outside air temperature exceeds 22°C the heater operates. As the outside air temperature falls below 22°C the heater switches off but the temperature in the dummy room remains at the elevated level because there was zero heat transfer with the external environment and between the dummy rooms. The temperature in the dummy room acts as a record that the outside air temperature had exceeded 22°C duiing the day. Therefore, the night cooling on/off control can be set up to only operate if the temperature in the dummy room exceeds the 22°C. At the end of the night cool period the temperature in the dummy room is be reset (using the cooler unit) ready for the next day.

It was necessary to use the dummy room method to define the night cooling controls used at the Inland Revenue buildings at Durrington and Nottingham and the Ionica building.

2.4 NIGHT COOLING CONTROL STRATEGY DESCRIPTION

Seven night cooling control strategies were tested and the following is a basic description of the different alternatives.

2.4.1 No night cooling

No nightime ventilation was 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, casual heat gains a base case simulation, with no night cooling, was performed.

2.4.2 Timeclock control

A simple timeclock controlled night cooling such that it was applied each evening prior to occupancy (not Friday night 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 practise a manual decision would be taken to operate the system over the peak summer months.

2.4.3 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.

2.4.4 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 practise 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.

2.4.5 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. The above control was specified with the standard APACHE controls but it was necessary to use the dummy room method to calculate the slab temperature setpoint, which was variable.

Slab temperature setpoint calculation

The following procedure was 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) Todays 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.

Only control (vi) could be specified using standard APACHE controls. For controls (i)-(v) it was necessary to use the dummy rooms technique (see 2.3) to indirectly model the controls.

Control (i)

A dummy room was set up and between 17.00-18.00 the temperature was heated or cooled to match the slab temperature. A temperature profile was generated that matched the monthly variation in room setpoint (including the offset). The setpoint and offset were those used on site and are specified in report 11621/2. Between 18.00-19.00 a second dummy room, used to calculate the slab temperature setpoint, was heated or cooled at a rate dependent on the temperature difference between the original dummy room and the room setpoint (including offset). The heating or cooling was on a 1K for 1K basis i.e. a 1K difference between slab and setpoint would result in a 1K change in the second dummy room temperature. The 1K for 1K was also dependant on control (iv) and was reduced if control (iv) was not fully satisfied.

Control (ii)

Control (ii) was similar to control (i). A profile was generated that matched the monthly variation in room setpoint. A third dummy room was heated or cooled between 17.00-18.00 to match the zone temperature level. The slab setpoint dummy room, which was also used for control (i), was heated or cooled between 18.00-19.00 depending on the temperature difference between third dummy room and the room setpoint. Heating or cooling was on a 1K for 1K basis, similar to control (i), providing control (iv) was satisfied.

Control (iii)

The combination of controls (i) and (ii) was achieved by heating or cooling the slab setpoint dummy room simultaneously.

Control (iv)

Controls (i) and (ii) calculated the rate of heating or cooling of the slab setpoint dummy room e.g. ΔT of 5K would result in the maximum heat output/change. Control (iv) determined the size of the maximum heat output. A fourth dummy room was heated or cooled between 07.00-08.00 to match the slab temperature and a fifth dummy room was heated or cooled to match the old slab setpoint. When controls (i) and (ii) were active a comparison was made of the temperatures in the fourth and fifth dummy rooms. If the temperature difference was within 1K, the setpoint had been achieved the previous night and therefore the full effect of controls (i) and (ii) was permitted (1K for 1K increase or decrease). However, if the temperature difference was greater than 1K the heating/cooling of the slab setpoint dummy room was reduced in the following manner:-

ΔT (Old slab setpoint - Slab temperature at 07.00)	Heat output (% of maximum)
0-0.9	100 (this resulted in a 1K for 1K change)
1.0 - 1.9	20
2.0 - 2.9	5.9
3.0 - 3.9	2.7
4.0 - 4.9	1.5
>5.0	1

Therefore, although between successive days, controls (i) and (ii) may have called for the same change in slab setpoint the actual change was dependent on the success of previous night cooling.

Control (v)

After controls (i)-(iv) had been completed, control (v) was activated between 19.00-20.00. This control re-adjusted the slab setpoint dummy room according to a combination of that days adjustment and the previous days adjustment and therefore it was necessary to record the setpoint from the day before last. This was achieved with a sixth and seventh dummy rooms, one recorded the setpoint temperature on Monday, Wednesday and Friday and the other on Tuesday and Thursday. A further (eighth) dummy room was set up and heated or cooled to match the most recent changes in the setpoint. A comparison was made between the most recent slab setpoint and the old slab setpoint. The temperature in the slab setpoint dummy room was readjusted such that the final setpoint temperature was between the most recent change and the old setpoint.

Control (vi)

After controls (i)-(v) had been completed the slab setpoint was increased, if necessary, to the minimum permitted. This was calculated from the monthly profile used on site (see report 11621/2).

Figure 1 and Figure 2 demonstrate the variation of zone and slab temperature and the slab setpoint over a 21 day period when the same weather data was repeated. The model started with each node at the same temperature and the zone air and slab temperatures achieved steady cyclic condition after about 7 days. Figure 1 illustrates results with the typical summer day weather data and shows that on the first few days the slab temperature attained or approached the setpoint as it achieved a steady cyclic condition. The effect of this was to permit the maximum change in setpoint that the night cooling controls called for. The changes in setpoint became progressively smaller towards the end of the simulation period because the setpoint was not attained and therefore the permitted change was minimal. The setpoint did, however, continue to reduce because the zone and slab temperatures exceeded the target temperatures at the end of occupancy. Figure 2 shows results with the peak summer day weather data repeated for 21 days. In this case a big change in setpoint was permitted on the first day because the slab temperature was the same as the setpoint. However from this point the high slab temperature resulted in the setpoint not being achieved again and therefore the permitted changes in the setpoint were minimal.

Model inaccuracy

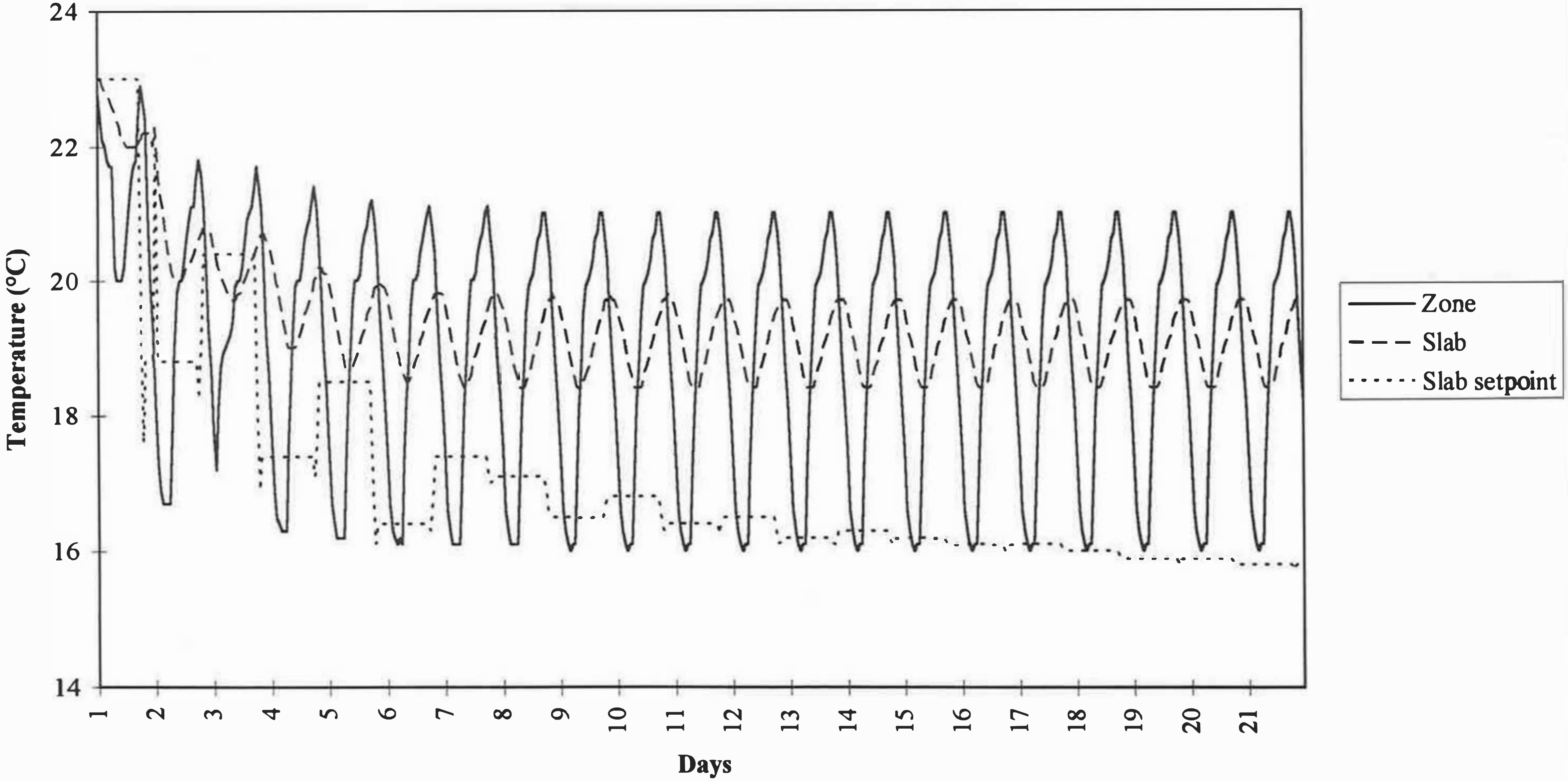
The slab temperature setpoint was adjusted on a 1K for 1K basis. However this introduced a potential inaccuracy because as the temperature of dummy room SP changed, the specific heat at constant pressure (Cp) of the air also changed. Therefore the actual effect of the heater output in changing the temperature in room SP was dependent upon the start temperature. The table below demonstrates the effect at it most extreme.

Dummy room temperature (°C)	Cp (KJ/m^3K)	Dummy room ΔT with the same heat input
-25	1.416	4.18
0	1.289	4.59
25	1.183	5.00

The output of the heater was based on a Cp (1.2095KJ/m^3K)) that applied to an air temperature of approximately 20°C. The overall effect of this inaccuracy was minimal because the controls generally prevented large changes in the setpoint temperature.

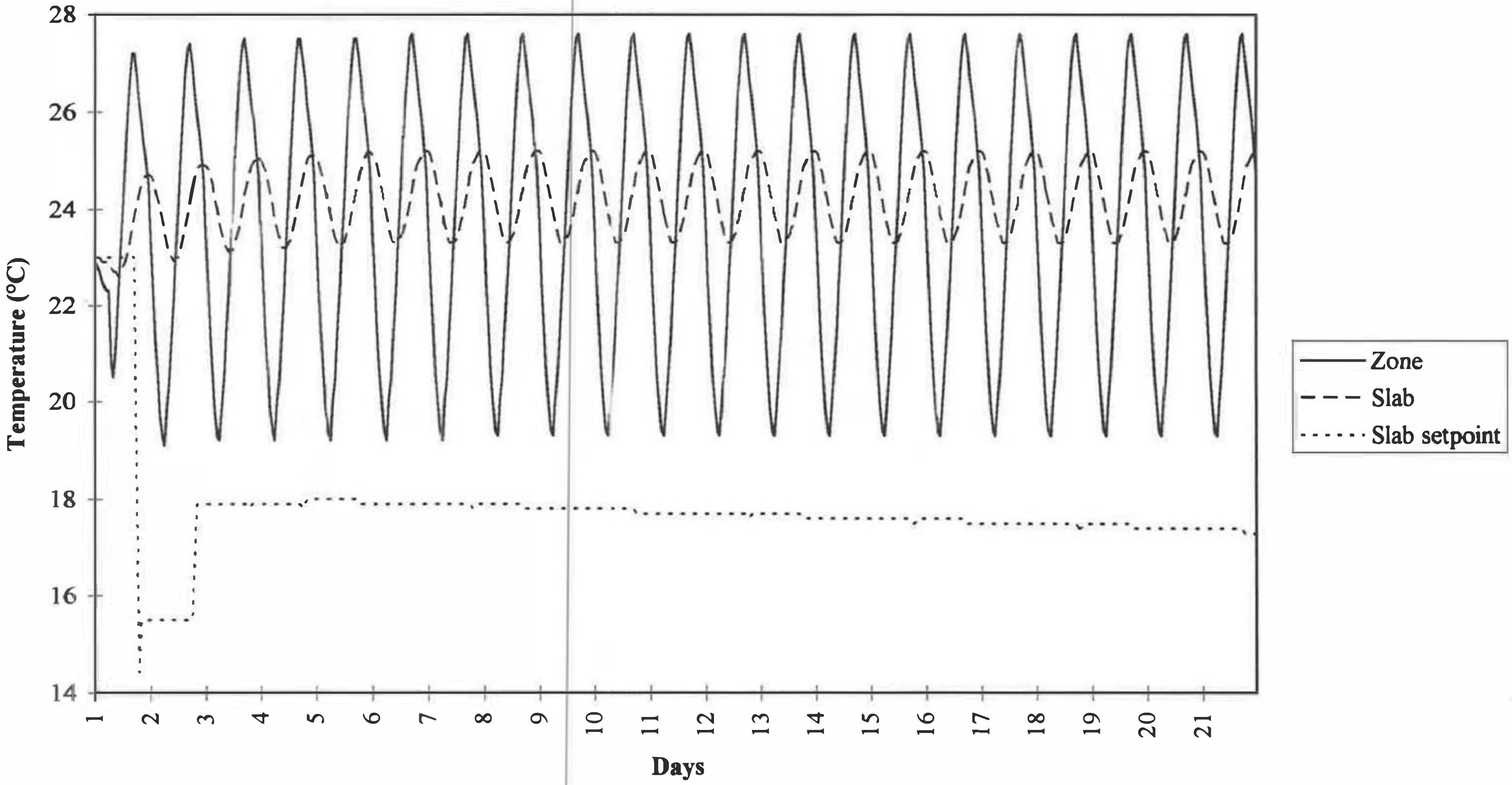
VARIATION OF SLAB SETPOINT- TYPICAL DAY

Figure 1



VARIATION OF SLAB SETPOINT- PEAK DAY

Figure 2



2.4.6 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

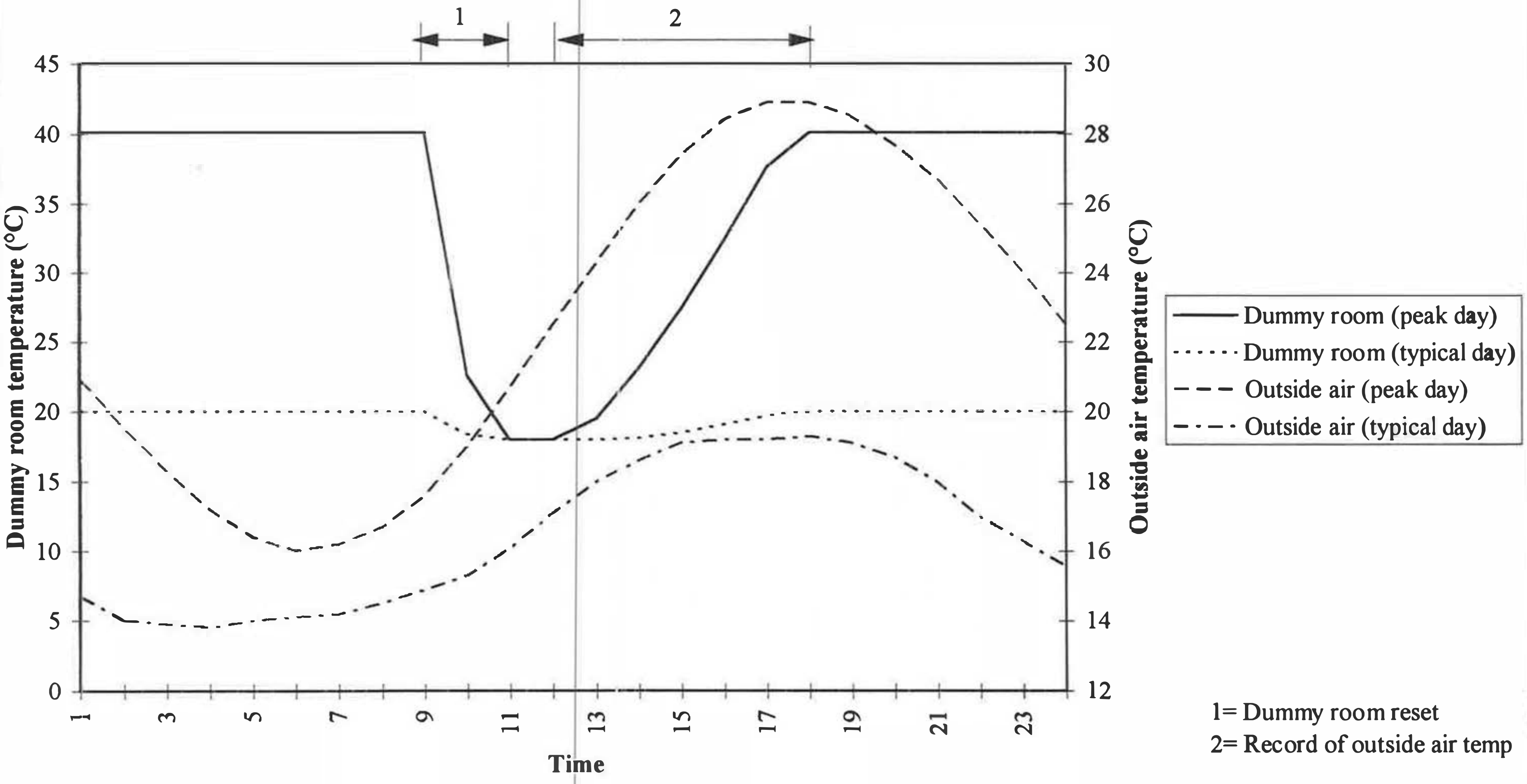
The same time periods and ventilation system, as applied in the timeclock control were used.

Controls (ii)-(iv) were specified using standard APACHE controls. Control (i) was specified using a dummy room. Between 12.00-17.00 the temperature of the dummy room was heated if the outside air temperature exceeded 18°C and cooled if the outside air temperature was below 18°C. The heating/cooling was proportional to the deviation from 18°C. Therefore the temperature in the dummy room at 17.00 was an indication of whether the average outside air temperature was above or below 18°C and if above 18°C night cooling was permitted. The temperature in the dummy room was reset to 18°C at the end of night cooling.

The operation of control (i) is illustrated in Figure 3 which shows the outside air temperature and dummy room temperature for the typical and peak days. On the typical day the outside air temperature was initially below 18°C, resulting in the dummy room being cooled. It then rose above 18°C and the final dummy room temperature was above 18°C, permitting night cooling. The peak day was constantly above 18°C and therefore the dummy room was only heated. During the night cool period the dummy room temperature remained constant and this was used as the night cooling reference i.e. night cooling was permitted if the dummy room temperature was above 18°C. At the end of the night cool period the dummy room temperature was reset to 18°C.

Figure 3

APACHE MODELLING RESULTS- RECORD OF AVERAGE OUTSIDE AIR TEMPERATURE



1= Dummy room reset
2= Record of outside air temp

2.4.7 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 hrs = 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.

Controls (i), (ii) and (v) were specified using the standard APACHE controls. To simulate controls (iii), (iv) and (vi) it was necessary to apply the dummy room method.

Control (iii)

A dummy room was heated if the zone temperature exceeded 24°C during occupancy. Night cooling was permitted if the temperature of the dummy room exceeded 24°C.

Control (iv)

A second dummy room was heated if the zone temperature exceeded 19°C between 18.00-19.00. Night cooling was permitted if the temperature of the second dummy room was greater than 19°C.

Control (vi)

A third dummy room was heated if the zone temperature exceeded 21°C during occupancy and cooled if it was below 21°C. The heat output was proportional to the deviation from 21°C. At night the same dummy room was cooled if the zone temperature was below 21°C. The output of the cooler unit was proportional to the deviation of zone temperature from 21°C. Night cooling was permitted until degree hours heating matched cooling i.e. the dummy room temperature was returned to its original value (21°C).

A self learning algorithm altered the target proportion of nightime cooling degree hours to daytime heating degree hours. This was dependent on the deviation of the average zone temperature from the zone setpoint. The change was 2.5% per K deviation up to a maximum of 20% as follows:

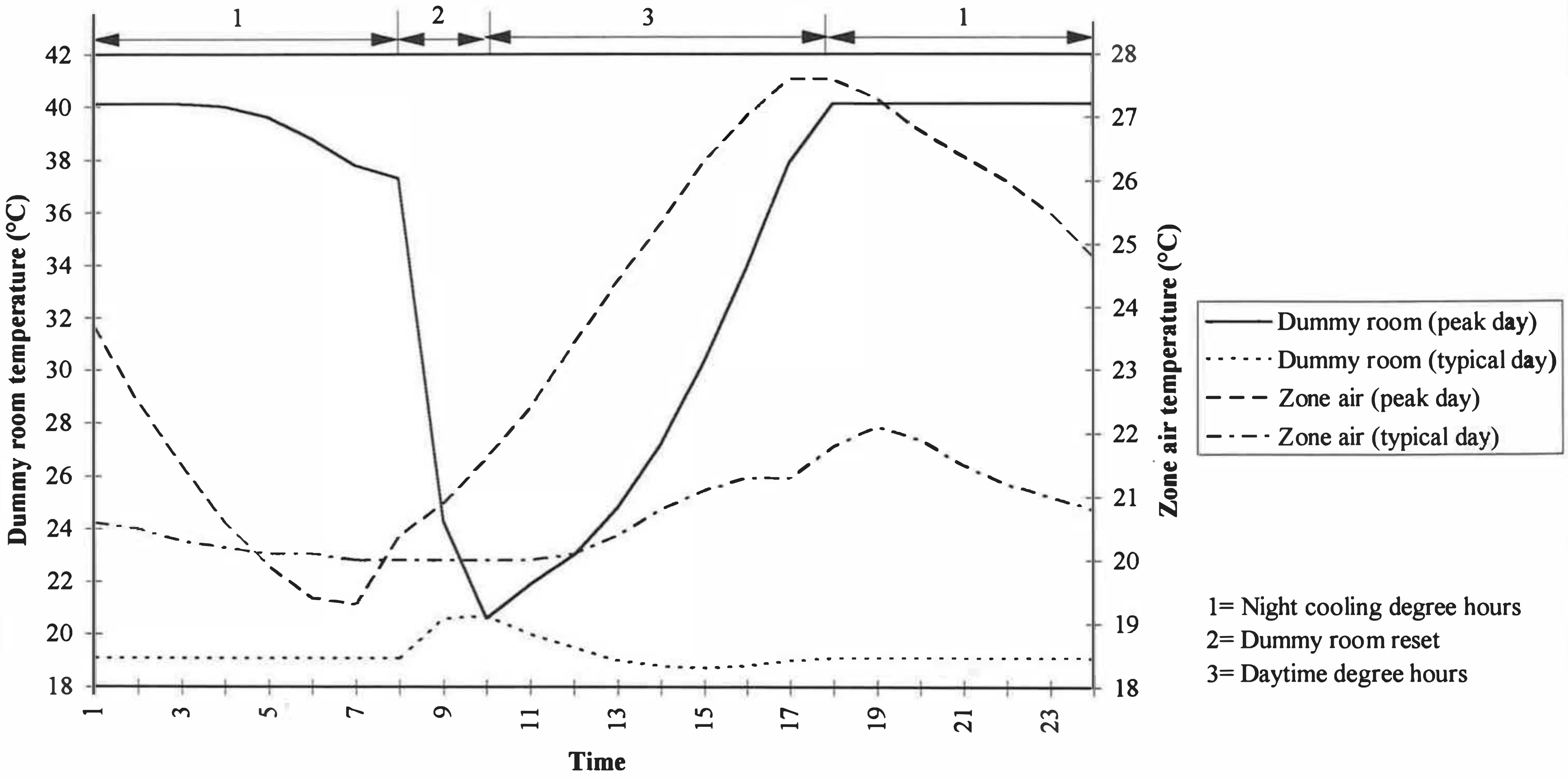
Zone ave - zone setpoint (K)	Degree hours ratio (day heating : night cooling)
-8	1:0.8
-4	1:0.9
0	1:1
+4	1:1.1
+8	1:1.2

Therefore at night, the degree hours dummy room could be cooled at a different rate dependent on whether the average zone temperature during occupancy was above or below 21°C. The average zone temperature was measured by a fourth dummy room which was heated during the day if the zone temperature was above 21°C and cooled if below 21°C. The heat output from the heater and cooler was proportional to the deviation from 21°C. If the temperature in the fourth dummy room exceeded 21°C, the degree hours dummy room was cooled at a lower rate at night to allow longer night cooling. If the temperature in room fourth dummy room was lower than 21°C then the degree hours dummy room cooled at a higher rate at night and allowed a shorter night cooling period.

Figure 4 shows how the Ionica control model worked in practise. The dummy room was used to calculate degree hours of heating and cooling. During the day the temperature of the dummy room was heated if the zone temperature exceeded 21°C and cooled if it was below 21°C with the rate of heating/cooling proportional to the deviation from 21°C. The zone temperature for the typical summer day was below 21°C for most of the occupied period and therefore the resultant dummy room was below 21°C and night cooling not applied. The peak day zone temperature was constantly above 21°C and therefore the dummy room was heated. During night cooling, the dummy room temperature remained constant until the zone temperature fell below 21°C. It was then cooled at a rate proportional to the deviation of zone temperature below 21°C. This would have continued until the dummy room temperature was cooled to 21°C when night cooling would have stopped (daytime degree hours of slab heating matching night cooling). However, the end of the night cooling period occurred first and the dummy room temperature was reset to 21°C ready to record the degree hours during the next occupied period.

Figure 4

APACHE MODELLING RESULTS- COMPARISON OF DAY AND NIGHT DEGREE HOURS



3. TEST PROGRAMME

The test programme was divided into three parts, initial tests, special tests and the main tests. The initial tests investigated the effect of variables that were not actual controls but could influence the performance of the controls e.g. ventilation rate. The special tests investigated factors unique to particular controls and secondary effects of night cooling e.g. optimum slab sensor depth. The main tests compared the performance of different control strategies under a range of conditions. A "standard" model was defined as follows with only one parameter varied between tests:

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

3.1 TEST VARIABLES

Seven night cooling control strategies (including no night cooling) were tested. The following is a simple description of each control and a more detailed description is contained in Section 2.

(i) No night cooling

(ii) Timeclock

(iii) Simple on/off based on zone temperature
- zone air > outside air
- zone air > heating setpoint
- outside air > 12°C

(iv) Simple on/off based on slab temperature
- zone air > outside air
- slab air > heating setpoint
- outside air > 12°C

(v) Inland Revenue, Durrington

(vi) Inland Revenue, Nottingham

(vii) Ionica, Cambridge

The above controls were tested against a selection of variables:

(i) Weather data - summer day (peak and typical), typical spring day
- summer months (peak and typical)

(ii) Slab construction - heavyweight, medium weight, lightweight concrete
- 100mm, 125mm, 150mm, 175mm slab depth
- exposed ceiling, false ceiling

(iii) Solar gains - low, medium, high (high shading, medium shading, no shading)

(iv) Casual heat gains - low, medium, high

(v) Night mechanical ventilation rate - 0, 2, 4, 6, 8, 10ac/h

(vi) Night natural ventilation rate - fixed 1, 2, 4, 6, 8 ac/h
- variable 1-8 ac/h

(vii) Night ventilation period - 18.00-07.00, 18.00-05.00, 21.00-07.00, 21.00-05.00, 00.00-07.00, 00.00-05.00

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

3.2 TEST DESCRIPTION

3.2.1 Initial tests

(i) Night cool period - one selected control strategy was tested with each weather file (5) and each night cool period (6). Number of tests = 30. The effect of night cooling on a Monday morning after a weekend off was also tested with selected weather data [spring, typical summer and peak summer days](3). Number of tests = 3. Total number of tests = 33.

(ii) Night cool rate - one selected control strategy was tested with selected weather data [hot summer and typical summer] (2) and each night cool ventilation rate (5). Total number of tests = 10.

(iii) Solar gains - one selected control strategy and no night cooling (2) were tested with selected weather data [hot summer and typical summer] (2) and each solar gain intensity (3). Total number of tests = 12.

(iv) Casual gains - one selected control strategy and no night cooling (2) were tested with selected weather data [hot summer and typical summer] (2) and each casual gain intensity (3). Total number of tests = 12.

(v) Slab material - one selected control strategy and no night cooling (2) were tested with selected weather data [hot summer and typical summer] (2) and different slab materials (3). Total number of tests = 12.

(vi) Slab covering - one selected control strategy and no night cooling (2) were tested with selected weather data [hot summer and typical summer] (2) and slab covering i.e. false ceiling (2). Total number of tests = 8.

(vii) Slab depth - one selected control strategy and no night cooling (2) were tested with selected weather data [hot summer and typical summer] (2) and each slab depth (4). Total number of tests = 16.

3.2.2 Special tests

(i) Slab sensor depth - control strategies 4 and 5 (2) were tested with selected weather data [hot summer and typical summer] (2) and each slab sensor depth (5). Total number of tests = 20.

(ii) Condensation - control strategy 3 was tested with and without the minimum outside air > 12°C specification (2) and with selected weather data [spring day] (1). Total number of tests = 2.

(iii) Heating - control strategy 3 was tested with and without the minimum zone air > 18°C specification (2) and with selected weather data [spring day and typical summer (2). Total number of tests = 4.

3.2.3 Main tests

(i) Control comparison - each control strategy (7) was tested with each weather file (5) and selected night ventilation rates (2). Total number of tests = 70.

4. TEST RESULTS

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. The results are provided in Appendix A2. A few "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 results of the special tests are provided in Appendix A3. The main series of tests compared different night cooling control strategies and the results from these tests are provided in Appendix A4. The zone temperatures illustrated in the figures of each appendix were dry resultant temperatures.

4.1 INITIAL TESTS

The night cooling control for the initial tests was a simple timeclock unless stated. This was because the initial tests were intended to investigate the effect of secondary influences, not sophisticated night cooling strategies.

4.1.1 Night Cooling Period

Figures A2.1 to A2.5 show the effect of the night cool period for each set of weather data (spring day, typical summer day, peak summer day, typical summer and peak summer). The summer simulations (Figures A2.1 and A2.2) were illustrated in terms of occupied hours above fixed temperature limits, compared to the outside air, for April to October. The typical summer (Figure 2. 1) shows that the outside air temperature peaked at 26.5°C and only exceeded 24°C on approximately 5 hours out of 1540. Even the peak summer was relatively cool when compared to the actual conditions in 1995. It peaked at 28°C with approximately 25 hours above 24°C. Therefore the zone temperatures were also low. The difference between night cooling for 5 hours or 13 hours was relatively small in terms of limiting daytime temperatures however the benefits of night cooling to no night cooling were clearly demonstrated. One major influence on the difference between five and 13 hours night cooling was the ventilation rate. The control system was set up as it was at the Inland Revenue Building in Durrington (see Appendix A1 of this report and report 11621/2). Night cooling by natural ventilation was available from 18.00-05.00 or 07.00 and by mechanical ventilation from 00.00-05.00 or 07.00. The five hour period had the combined effects of mechanical and natural ventilation but the 13 hour period had six hours of natural ventilation only. A further explanation is discussed in the following paragraph (see figures A2.3-A2.5). For the typical summer the zone temperature with night cooling peaked at 23-23.5°C compared to 25.5°C for no night cooling and 26.5°C outside air. The peak summer also demonstrated a 2.5K difference between the peak outside air temperature and peak zone temperature with night cooling applied. The 22°C limit was exceeded by the no night cooling simulation on 160 hours compared to only 80 hours with 5 hours night cooling and 50 hours with 13 hours night cooling. At higher temperature limits the difference between the alternative night cooling periods reduced significantly.

Figures A2.3 to A2.5 illustrate the effect of different night cool periods for spring, typical summer and peak summer days respectively. The spring day demonstrated the limitations of simple timeclock control and even the no night cooling simulation required some pre-heating. The use of night cooling caused significant temperature problems with heating being required throughout the day. The points at which night cooling were applied, 18.00, 21.00 or midnight could be clearly seen by the deviation from the natural temperature cycle. It should be noted that the Spring day simulation was included to demonstrate the effect of night cooling in cool ambient conditions. As later results show (see 4.3), controlled night cooling prevented its use in April because conditions were too cool. Figure A2.4 shows a typical summer day where the outside air temperature peaked at 19°C. It again demonstrated the limitations of simple timeclock control because even under these average summer conditions over cooling resulted and pre-heating was required. As with the spring day the different times at which night cooling were applied could be seen (deviation from the natural temperature cycle). This figure gives an indication of why the effect of increasing the night cooling period from five to 13 hours was lower than expected. Night cooling was tested with a start time of 18.00, 21.00 and midnight. At 18.00 the zone cooled at a low rate because the outside air temperature was still high. The simulations that started night cooling at 21.00 or midnight demonstrated increased initial cooling such that the zone temperatures rapidly approached that of the simulation where night cooling was started at 18.00. Therefore for the majority of the night cooling period the simulations with the later start were cooling at the same rate as the earlier start. The overall result was that although the night cooling period was increased by a factor of 2.6 (5 to 13 hours) the effect on daytime temperatures was considerably less.

Figure A2.5 demonstrates a different limitation of simple timeclock control. At 18.00 the outside air temperature was hotter than the zone air and resulted in marginal heating of the zone when night cooling was applied. Even at 21.00 the temperatures were similar and the benefit of night cooling was marginal. This conclusion was also shown in the monitoring results where the outside air temperature exceeded the zone temperature up to 21.45 on hot days. The difference in the start time for night cooling had very limited impact on zone temperature because of the low rate of cooling of the earlier start. The influence of the fabric was also shown in the simulations where night cooling stopped at 5.00. The zone temperature increased by 1K between 5.00-7.00 however the effect of this early stop on the daytime zone temperature was marginal.

4.1.2 Night Cooling Ventilation Rate

Figures A2.6 and A2.7 show the effect of varying the rate of mechanical ventilation at night. Night cooling by natural ventilation was applied from the end of occupancy (18.00) to the daytime plant start up (7.00). The ventilation rate was scheduled on the difference between inside and outside air temperature as follows:

ΔT(K)	Natural ventilation airflow (ac/h)
0	1
6	8

It was necessary to define a simple schedule because the standard APACHE software could not calculate natural ventilation rates. Mechanical ventilation was applied during the low tariff period only (midnight to 7.00). The effect of increasing the mechanical cooling rate did not produce a significant benefit in terms of reduced daytime temperatures. The reason for this may be that the natural ventilation rate was already significant. Also night cooling had already been applied for 6 hours prior to the mechanical ventilation and therefore this would have reduced the impact of whether natural ventilation plus 2ac/h mechanical ventilation or natural ventilation plus 10 ac/h mechanical ventilation was used.

Figure A2.8 shows the results with a fixed night cooling ventilation rate. This was included because the standard model had a variable natural ventilation schedule applied from 18.00-07.00 combined with fixed mechanical ventilation from 00.00-07.00 (as used at Inland Revenue, Durrington). Therefore the total ventilation rate was variable and could not be quantified. Testing with a fixed night cooling ventilation rate removed this uncertainty. Figure A2.8 demonstrates a wide variation in daytime zone temperature between simulations with alternative night cool ventilation rates. The increase in rate from 1ac/h to 8ac/h resulted in a reduction in the occupied hours over 22°C by over 40%. The 6ac/h and 8ac/h simulations produced similar performance curves which shows a diminishing return from elevated ventilation rates. The low heat gains resulted in little difference between exceedance hours at higher temperature limits. For example the 24°C limit was exceeded by the no night cooling simulation on only 18 hours and this reduced to 12 hours with 1ac/h night cooling and 5 hours with 8ac/h. There was a 0.5K difference between the peak temperature with no night cooling and that with 1 or 2ac/h night cooling rate and a 1K difference for higher ventilation rates.

Figure A2.8 also provides an indication of when mechanical ventilation may be required for night cooling. The monitoring results demonstrated there was not a significant difference between night cooling with mechanical ventilation or natural ventilation. Figure A2.8 shows building performance with selected night cooling fixed ventilation rates. There was only a marginal difference between the number of hours that the zone temperature exceeded 23°C for night cooling rates of 4 to 8 ac/h. This indicates that if the average natural ventilation rate was 4 ac/h, supplementary mechanical ventilation would not significantly improve peak daytime zone temperatures. If the average natural ventilation rate was 1-2 ac/h it may be beneficial to supplement it with mechanical ventilation in low tariff periods. The results are obviously dependent on a wide range of variables. However, the simulation was typical of low energy design with low heat gains and exposed ceiling and the Kew 1967 weather data does represent a hot summer. Therefore the simulation could be considered reasonably represenative.

4.1.3 Solar gains

Figures A2.9 and A2.10 show the effect of solar gains on the zone temperatures (the zone was south facing). Most simulations included the type solar shading used at the Durrington building i.e. external overhang and internal blinds. The effect of removing some or all of the solar shading was tested The low gains simulation had an external overhang and internal blinds whilst the medium only had the overhang. The high gains simulation had no solar protection. The additional benefit from blinds and the overhang was relatively small on the overhang would have prevented much of the direct solar gain during the peak summer period. However, the benefit of solar shading as part of an overall low energy strategy could be clearly seen and also the need for night cooling. If the peak summer (Figure A2.10) was used as an example, the use of solar shading reduced the number of hours above 22°C by half and the combination of solar shading and night cooling reduced the hours by 85%. There was also a significant improvement in the peak zone temperature.

4.1.4 Casual heat gains

Casual heat gains are another factor that could affect the performance of a building and the influence of night cooling. Tests were carried out with casual gains of $20W/m^2$, $30W/m^2$, and $40W/m^2$ using the typical and peak summer weather data. The results are illustrated in figures A2.11 and A2.12. The main set of simulations used the low gain case because low energy designs tend to minimise casual heat gains e.g. low energy lighting. The peak zone temperature was 29°C with $40W/m^2$ casual gains and no night cooling compared to 25°C for the $20W/m^2$ with night cooling simulation.

4.1.5 Floor slab construction

The effect of the slab material was investigated with three types of cast concrete, lightweight, medium weight and heavyweight (APACHE database materials were used). The thermal properties of the different concrete types are outlined in Appendix A1 and figures A2.13 and A2.14 show the results for the typical summer and peak summer respectively. The results show that the influence of different floor slab concrete types, of the same thickness, was small where night cooling was not applied. The tests where night cooling was applied show a greater effect but overall it was still small compared to night cooling against no night cooling.

An exposed concrete ceiling is an important element in a low energy design. The services eg cabling are typically routed through hollow cores in the slab or raised floor voids. A test was performed to demonstrate how a false ceiling could effect the performance of night cooling. Figures A2.15 and A2.16 show results for the typical summer and peak summer respectively. There was a significant difference between the no night cooling simulations with and without a false ceiling. This demonstrated the beneficial effect on the dry resultant temperature (comfort temperature) of exposing the high mass ceiling soffit even when night cooling was not applied. However, the effect was even greater between the night cooling simulations with and without the false ceiling. The false ceiling acted as a barrier between the cooled zone air and the ceiling slab.

The thickness of a floor slab can vary from 100mm up to 250mm or more. The thickness is typically 100mm-175mm. Tests were carried out to assess the influence or varying the thickness on the performance of night cooling. Figures A2.17 and A2.18 illustrate results from the typical summer and peak summer respectively. These figures show that variation in slab depth of 100-175mm only produced a small reduction in zone temperatures.

Table A2.1 shows the requirements for heating from the initial tests. The pre-heat was permitted from 7.00-9.00 to ensure an acceptable zone temperature at occupancy. It can be seen that even the no night cooling simulations required significant heating during the early and late summer months of the simulation period (April-October). The uncontrolled (timeclock) application of night cooling resulted in a large increase in heating needs.

4.1.6 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 also 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 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 night cooling mechanical rate for the main tests was 4ac/h which was used at Inland Revenue building at Durrington. The influence of higher or lower ventilation rates was found to be small with this model. At night, mechanical ventilation was used to supplement natural ventilation and 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 overhand (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 $40W/m^2$ to $20W/m^2$ produced a similar performance to maximum night cooling (timeclock control) with a casual gain of $40W/m^2$. It demonstrates that preventative measures are at least as important as night cooling for controlling internal temperatures. In practise, heat gains are minimised in 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 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 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 100mm to 175mm. The slab depth at the Inland Revenue building, Durrington (150mm) was applied to the main test simulations.

4.2 SPECIAL TESTS

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 slab depth was 150mm and the temperature sensor was tested at depths from the surface to 100mm. The resultant zone temperature hours above fixed limits are shown in figures A3.1 to A3.4. These figures indicated that the depth of the slab sensor had only a small influence on performance (zone temperature hours above fixed temperature limits). Night cooling operated for similar periods with the different slab sensor depths and resulted in similar performance. The explanation for the small variation in night cooling operation was the thermal mass of the slab. The high thermal mass of the slab and being an internal floor i.e. subjected to similar influences from above and below results in a small temperature change through the slab. The mass of the slab also results in relatively small temperature changes during night cooling compared to the zone air. Figures A3.3 and A3.4 illustrate the same tests with the slab control system. The slab temperature with this system was only limited by a minimum value to prevent over-cooling and reduce the need for additional heating. These figures show similar results to the variable slab setpoint (Durrington) control with little difference between performance curves for slab sensors at different depths. The results were confirmed by Table A3.1 which shows the energy consumption and night cooling hours from the different simulations. If the peak summer simulations with the slab control system are used as examples, the number of hours that night cooling operated only increased from 730 for a temperature sensor on the slab surface to 770 with a sensor at a depth of 100mm.

Figure A3.5 shows the effects of not having a minimum zone temperature setpoint with the night cooling control. The standard zone control system permitted night cooling provided the outside air was greater than 12°C, the zone air was greater than the heating setpoint and the zone air was greater than the outside air. The figure shows that the removal of the minimum zone temperature interlock had a significant influence on the building temperatures. The peak zone temperature was reduced by 1K and the number of hours above 22°C reduced by nearly half. The number of night cooling hours increased from 276 to 693. However there was a considerable energy penalty and the heating consumption increased by a quarter and the fan energy doubled. Although allowing the zone to cool below the heating setpoint does have a beneficial effect on zone temperatures, it is not sufficient to outweigh the disadvantages. In hot conditions the zone temperature will not fall to a level where heating is required. In cooler conditions the minimum setpoint may prevent some night cooling but its need is also reduced. The only situation where it could be an advantage to over cool is where a few cool days follow a prolonged hot spell. However, even in this case it was unlikely that specification of a minimum setpoint will have a significant detrimental effect. The elevated fabric temperature will limit the zone temperature drop.

4.2.1 Conclusions

(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.

4.3 MAIN TESTS

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:

Timeclock	-	simple timeclock
Zone	-	minimum zone temperature > heating setpoint
Slab	-	minimum slab temperature > heating setpoint
Durrington	-	variable slab setpoint
Ionica	-	daytime zone temperature > 24°C, degree hours slab heating = degree hours slab cooling
Nottingham	-	average afternoon outside air temperature > 18°C.

The above outlines the main requirement of each night cooling strategy (details are in section 2.4).

Figures A4.1 and A4.2 illustrate the performance of each strategy for the typical summer and peak summer respectively. The results demonstrate a wide divergence and a significant difference between the typical summer and the peak summer. In both cases the Ionica control closely matched the no night cooling simulation, indicating little utilisation. This was because a control interlock prevented night cooling if the zone temperature the previous day was below 24°C. The weather data for Kew 1964-65 (typical year) and Kew 1967 (hot year) were statistically representative of what could be expected in England. Although recent summers have been hot with monitored temperatures in 1995 up to 37°C these conditions are, at present, not thought to be typical. Low energy design with minimal casual and solar heat gains indicate that need for night cooling under normal conditions may be reduced. The inclusion of a maximum zone or outside air temperature interlock would therefore appear to be necessary to prevent night cooling when it is not needed. Although the Ionica control did not operate for a prolonged period it did operate under extreme conditions resulting in the same peak temperature (26°C) as the alternative controls.

The typical summer simulation produced a spread of results between the other control strategies, although all demonstrated a significant improvement from the no night cooling test. The Durrington and zone controls were least utilised (excluding Ionica). This was because the cool summer (relative to 1995) resulted in cooler space temperatures which would in turn affect the Durrington slab setpoint. The slab control and Nottingham control demonstrated longer utilisation. The limit on the slab control was that the minimum slab temperature exceeded the zone heating setpoint and this permitted lower zone temperatures. Similarly, the Nottingham control specified a minimum average afternoon outside air temperature of 18°C for night cooling to be permitted. However at night the zone was allowed to fall to 14°C. In both systems the additional utilisation occurred in marginal seasons when night cooling was probably not required. This is confirmed in Figure A4.2 which showed results from the peak summer. In this case all control strategies with the exception of Ionica, produced similar performance curves. It indicated that there was a lower incidence of cooler conditions than the typical summer weather data and that controls were more fully utilised. Even the timeclock control, with no interlocks to prevent operation, followed a similar performance curve.

Figures A4.3 and A4.4 show a comparison of the energy consumption for the model when operated with the different control strategies. The results were obviously dependent upon many factors including the fan efficiency curve, heating system type and efficiency and heating system control. However these factors were consistent between simulations and it did present an indication of the energy penalty from night cooling. The simple timeclock control produced a large increase in both the heating and fan energy relative to no night cooling (see Table A4.1). The strategies with no interlocks to limit heating i.e. slab control, Nottingham control and Durrington control demonstrated the most significant increase in energy consumption (30-50%) from the no night cooling simulation. The increase applied to both the heating and fan energy and the fan energy was due to additional utilisation in cooler periods. The zone control and Ionica control resulted in only small increases in overall energy consumption. This was particularly relevant to the zone control because, as Figures A4.1 and A4.2 show this system produced a similar building performance to the other controls.

Figures A4.5 and A4.6 show the month by month utilisation of night cooling, including both mechanical and natural ventilation. The timeclock control represents the maximum utilisation against which the other controls could be compared. Although the simulations ran from April to October the other controls demonstrated no utilisation in April and very limited use in May. The typical summer figure (A4.5) showed that the zone control limited utilisation to approximately one third of the potential due to the cooler zone temperatures. This was also the case with the Nottingham control where only half the days achieved the required conditions. The Durrington and slab controls demonstrated a high degree of utilisation in the peak summer months. All controls resulted in reduced night cooling in September and virtually none in October. The Durrington and slab controls still maintained a significant proportion of night cooling in early September compared to the other controls which had reduced to a minimum. This was probably because the controls, based on slab temperature, were slower to react the trend of cooler ambient conditions at the end of the summer. The additional night cooling in the marginal months resulted in extra heating and fan energy. A similar pattern was demonstrated with the peak summer. The results indicated that in the early months (April to June) the ambient temperatures were similar to the typical year with hotter conditions only occurring in July and August. In this simulation the Durrington control was also slow to react to the changing ambient conditions at the start of the summer. Figures A4.7 and A4.8 show the variation of slab temperature and slab temperature setpoint for the peak summer. In the early months the low zone and slab temperatures resulted in a slab setpoint above the slab temperature. It was not until the increasing ambient conditions gradually increased the slab temperature that the setpoint was exceeded and permitted to change significantly. In the peak summer months the slab temperature was above the setpoint resulting in maximum night cooling. Once again it was not until the cooler ambient conditions in late August/early September cooled the slab enough to allow the setpoint to be significantly changed and night cooling limited.

Figures A4.9 and A4.10 show the change in zone temperature, resulting from different control strategies, for the typical summer and peak summer days respectively. The three control strategies studied in the site monitoring work (Durrington, Nottingham and Ionica) were included. The typical summer day did not satisfy the Ionica control (minimum zone temperature 24°C) and therefore night cooling did not operate. The Durrington and Nottingham controls permitted night cooling but did not attain their respective setpoints and therefore full utilisation occurred. Night cooling also resulted in the need for heating prior to occupancy. There was a 1K advantage between the peak temperature of night cooling and no night cooling simulations but as the temperature peaked at only 22°C, night cooling was not necessary. The maximum outside temperature of the peak summer day weather data was 30°C and under these conditions the criteria for each strategy were satisfied. When night cooling was permitted, similarly to the typical summer day, it operated for the full period because the setpoints were not attained. There was a 1.5K reduction in peak temperature between the night cool and no night cool simulations. Therefore the peak and typical day simulations did not demonstrate any advantage between the strategies. It did however indicate that when conditions permitted night cooling it was unlikely that the respective setpoints would be attained and that maximum utilisation was probable.

4.3.1 Conclusions

(i) The use of Kew 1964-65 and Kew 1967 weather data, together with low casual gains and solar shading, resulted in generally acceptable zone temperatures even without night cooling. The weather data was representative of what could be expected (excluding extreme summers such as 1995) as was the casual gains and solar shading used in low energy design. This, therefore, indicate that the need for night cooling is reduced for a typical summer.

(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 a maximum zone or outside air temperature would be beneficial to prevent unnecessary night cooling.

(iii) The Durrington control and zone control demonstrated significant utilisation but lower than the slab control or Nottingham controls. The zone control only permitted night cooling if the zone temperature exceeded the heating setpoint. The reduction in utilisation was in cooler ambient conditions.

(iv) The slab control permitted night cooling until the slab temperature fell to the heating setpoint. This allowed the zone air temperature was to be cooler than a similar control based on zone temperature (zone control). The result was longer utilisation but this was concentrated in cooler ambient conditions when the need for night cooling was reduced.

(v) The Nottingham control permitted night cooling if the average outside air temperature exceeded 18°C. This condition was regularly attained, even with the relatively cool weather data (relative to 1995) used, and indicates that it may have been set too low. The zone temperature under night cooling was permitted to fall to 14°C. However this was never achieved because, if the outside air temperature criteria was satisfied, the zone temperature was high and would not cool by more than 3-4K. Therefore the Nottingham control demonstrated a high utilisation.

(vi) The Durrington, slab and Nottingham controls demonstrated significant increases in heating requirements.

(vii) The use of the zone and Ionica controls resulted in only a small increase in heating. This was particularly relevant to the zone control which produced a similar performance to the other controls.

(viii) The month by month utilisation showed little application in April, May, September and October, with night cooling concentrated in June, July and August.

(ix) The Durrington and slab controls demonstrated significant night cooling in September (unlike the other controls). The reason was that being based on slab instead of air temperatures there was a lag in response to changing ambient conditions.

(x) The Durrington control was slow to react to changing ambient conditions at the start of summer. Low zone and slab temperatures produced a setpoint above the slab temperature. It was not until the increase in ambient temperature resulted in an increase in slab temperature that the setpoint was exceeded and permitted to change. During the peak summer period, the slab setpoint was constantly above the slab temperature and therefore maximum utilisation occurred.

(xi) Each control showed that when the daytime conditions for night cooling were satisfied, e.g. minimum zone temperature 24°C, the night setpoints were not attained. Therefore, for each night it was permitted, maximum utilisation occurred.

5. COMPARISON OF SITE MONITORING AND THERMAL SIMULATION

The site monitoring work (Report 11621/2) investigated the performance of four different night cooling strategies. 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:

<u>Night cool enable</u>

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.

<u>Daytime activation requirement</u>

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.

<u>Nightime activation requirement</u>

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 because natural ventilation 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 overcooling. 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. 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 nightime 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 nightime recommendations only permit night cooling when it is beneficial and also prevent over cooling. The site data showed that the maximum zone temperature drop was approximately 4K. This prevented over cooling in peak ambient periods. Over cooling could only occur in cooler periods when the need for night cooling was reduced. 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 4ac/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. Also if heat gains are already minimised the need for night cooling is relatively small.

REFERENCES

1. QUICK J.P. and IRVING S.J. Computer Simulations for Predicting Building Energy Use.

APPENDIX A1

MODEL DEFINITION

No. of pages: 7

APACHE Data Files

The APACHE software was divided into 12 different modules:

(i) Weather - weather data

(ii) Profiles - daily profiles, e.g. occupation, plant operation

(iii) Profile groups - weekly and monthly variation of daily profiles

(iv) Materials - definition of materials not in database

(v) 3-D solids - fabric elements in three dimensions, e.g. used for edge effects

(vi) Detailed fabric elements - sandwich of fabric materials, e.g. wall, roof

(vii) Rooms - layout and construction of building using detailed fabric elements

(viii) HVAC components - definition of plant efficiency curves and outputs, e.g. boilers, chillers, fans, heater batteries

(ix) HVAC system connections - HVAC system connections between plant and rooms

(x) HVAC controllers - definition of on/off and proportional controllers

(xi) Control connections - definition of plant outputs and air flows controlled by HVAC controllers

(xii) Output options - days that simulation will run and type of results output

Each job file comprised of one file from each of the modules. Where more than one file could be specified per module, there is a brief description of the alternatives.

(i) Weather (*.WEA)

KEW.WEA - Kew 1964-65 (typical summer)
KEW 67.WEA - Kew 1967 (peak summer)
PRETEST.WEA - Single days repeated for one month (typical spring day [April], peak summer day [July], typical summer day [August], typical autumn day [October].

(ii) Profiles (*.PDB)

NITECOOL.PDB

(iii) Profile groups (*.PRO)

NITECOOL.PRO

(iv) Materials (*.MAT)

CL.MAT	floor slab of lightweight concrete	(Conductivity 0.38 W/mK Thermal capacity 1000 3/KgK Density 1200 Kg/m^3)
NITECOOL.MAT	floor slab of medium weight concrete	(Conductivity 1.13 W/mK Thermal capacity 1000 J/KgK Density 2000 Kg/m^3)
CCD.MAT	floor slab of heavyweight concrete	(Conductivity 1.40 W/mK Thermal capacity 840 J/KgK Density 2100 Kg/m^3)

(v) 3-D Solids (*.3DS)

Not used because the floor slab was a simple construction.

(vi) Detailed fabric elements (*.DFA)

NITECOOL.DFA - standard element constructions [150mm depth, sensor depth 75mm, exposed ceiling, solar shading]
SD100.DFA - slab depth 100mm
SD125.DFA - slab depth 125mm
SD175.DFA - slab depth 175mm
SSD0.DFA - slab sensor depth 0mm
SSD25.DFA - slab sensor depth 25mm
SSD50.DFA - slab sensor depth 50mm
SSD100.DFA - slab sensor depth 100mm
SGM.DFA - solar gains medium (no blinds)
SGH.DFA - solar gains high (no blinds, no overhang)
FC.DFA - false ceiling

(vii) Rooms (*.DER)

NITECOOL.DER - People 16.7m²/p, Lights 6.6W/m², Equipment 5W/m² = 20W/m²
CGM.DER - People 16.7m²/p, Lights 10W/m², Equipment 8.4W/m² = 30W/m²
CGM.DER - People 16.7m²/p, Lights 10W/m², Equipment 18.4W/m² = 40W/m²

(viiii) HVAC components (*.SDB)

NITECOOL.SDB

(ix) HVAC system connections (*.SYS)

NITECOOL.SYS

(x) HVAC controllers (*.CON)

NITECOOL.CON - standard controllers file
NOHEAT.CON - night cooling minimum zone air temperature of heating setpoint not included
COND.CON - night cooling minimum outside air temperature of 12°C not included

(xi) Control connections (*.CCN)

NNC.CCN - no night cool
T187.CCN - Timeclock control 18.00-07.00
T217.CCN - Timeclock control 21.00-07.00
T007.CCN - Timeclock control 00.00-07.00
T185.CCN - Timeclock control 18.00-07.00
T215.CCN - Timeclock control 21.00-07.00
T005.CCN - Timeclock control 00.00-07.00
T1872AC.CCN - Timeclock control 18.00-07.00
natural ventilation 1-8ac/h (18.00-07.00)
mechanical ventilation 2ac/h (00.00-07.00)
T1874AC.CCN - Timeclock control 18.00-07.00
natural ventilation 1-8ac/h (18.00-07.00)
mechanical ventilation 4ac/h (00.00-07.00)
T1876AC.CCN - Timeclock control 18.00-07.00
natural ventilation 1-8ac/h (18.00-07.00)
mechanical ventilation 6ac/h (00.00-07.00)
T1878AC.CCN - Timeclock control 18.00-07.00
natural ventilation 1-8ac/h (18.00-07.00)
mechanical ventilation 8ac/h (00.00-07.00)
T18710AC.CCN - Timeclock 18.00-07.00
natural ventilation 1-8ac/h (18.00-07.00)
mechanical ventilation 10ac/h (00.00-07.00)
SLAB.CCN - slab temperature control
ZONE.CCN - Zone temperature control
DURR.CCN - Durrington control
NOTT.CCN - Nottingham control
ION.CCN - Ionica control
DURR1OAC.CCN - Durrington control with nightime mechanical ventilation of 10ac/h
NOTT1OAC.CCN - Nottingham control with nightime mechanical ventilation of 10ac/h
ION1OAC.CCN - Ionica control with nightime mechanical ventilation of 10ac/h
SLAB1OAC.CCN - Slab temperature control with nightime mechanical ventilation of 10ac/h
ZONE1OAC.CCN - Zone temperature control with nightime mechanical ventilation of 10ac/h

(xii) Output options (*.OPT)

SPRINGDAY.OPT	- Typical spring day
PRSUMDAY.OPT	- Peak summer day
TYSUMDAY.OPT	- Typical summer day
SUMMER.OPT	- Summer period

Weather Data Module

Three weather files were created for the single day simulations and the following illustrates the dry bulb temperature for each file. Each file represented typical conditions for Kew.

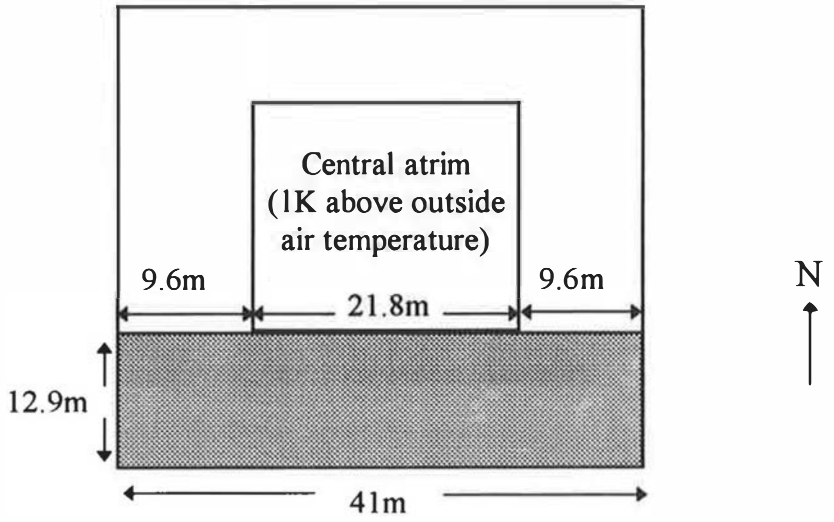
The example days were repeated for an entire months weather data to allow simulations to be operated over multiple days to achieve steady cyclic conditions.

Time	Typical spring day (April)	Peak summer day (July)	Typical summer day (August)
1	7.8	18.9	13.9
2	7.3	17.7	13.9
3	7.0	16.8	13.8
4	6.8	16.1	14.2
5	6.7	16.0	14.1
6	6.8	16.3	14.3
7	7.3	17.0	14.7
8	7.9	18.2	15.0
9	8.7	19.8	15.6
10	9.5	21.6	16.6
11	10.3	23.4	17.6
12	11.1	25.2	18.3
13	11.7	26.8	18.9
14	12.2	28.0	19.2
15	12.3	28.7	19.2
16	12.2	29.0	19.2
17	12.0	28.9	19.4
18	11.7	28.2	18.8
19	11.2	27.3	18.6
20	10.7	26.1	17.4
21	10.1	24.8	16.7
22	9.5	23.3	15.9
23	8.9	21.7	15.4
24	8.3	20.2	14.1

The summer simulations used actual weather data with the typical summer data originating from Kew for October 1964 to September 1965 weather file and the peak data from Kew January to December 1967 weather file.

Building Construction

(i) Layout



Floor area = 529m²
Room volume = 1,586.7m³
South facing window area = 32.4m²
North facing (internal) window area = 22.5m²
East/West window area = 10.2m²

(ii) Construction elements (m)

External wall	Internal wall	Floor/ceiling [1]	External window [2]	Internal window
Brick 0.105	Plaster 0.013	Cast concrete 0.15	Glazing 0.006	Glazing 0.006
Cavity 0.05	Wallboard 0.01	Carpet underlay 0.005	Air gap	
Insulation 0.05	Plaster 0.013	Carpet 0.005	Glazing 0.006	
Block 0.100				
Plaster 0.012				

(1) The floor/ceiling construction included options for lightweight, medium weight and heavy weight concrete and a variation in concrete slab depth (100mm, 125mm, 150mm, 175mm). There was also the option for a false ceiling.

(2) The external glazing element included three options to vary the amount of solar gain. The low gain option included an overhang above the window and internal blinds, the medium gain option only included the overhang and the high gain option had no solar protection.

Figure A1.1

Control Setpoints

(i) Heating (heater battery + low speed fan)

Period	Setpoint (°C)
Oct - May	19 ± 0.5
June - Sept	18 ± 0.5

(ii) Cooling (daytime)

Period	Natural ventilation zone setpoint (SP) (°C)	Low speed fan zone setpoint (°C)	High speed fan zone setpoint (°C)
Nov & Mar	22.0	23.0	24.0
Apr	21.5	22.5	23.5
May & Oct	21.0	22.0	23.0
June & Sept	20.5	21.5	22.5
Jul & Aug	20.0	21.0	22.0

	Open/on	Shut/off
Natural ventilation	SP +0.5K	SP -0.5K
Low speed fan	SP +1K	SP -0.5K
High speed fan	SP +2K	SP +1K (reverted to low speed)

Note: the daytime HVAC controls applied to all simulations.

Ventilation

(i) Daytime

Natural ventilation:

Natural ventilation rate was proportional to the temperature difference between inside and outside with a 6K band.

ΔT	Air flow (ac/h)
0	1
6	8

Mechanical ventilation:

The fans operated at two speeds depending the zone temperature (see setpoints).

High speed = 4 ac/h
Low speed = 1.5 ac/h

(ii) Nightime

At night the natural ventilation operated under the same basis as the day but the mechanical ventilation only operated at high speed.

Note: the daytime and nightime ventilation rates applied to all simulations and the only difference was the criteria for night cooling to operate.

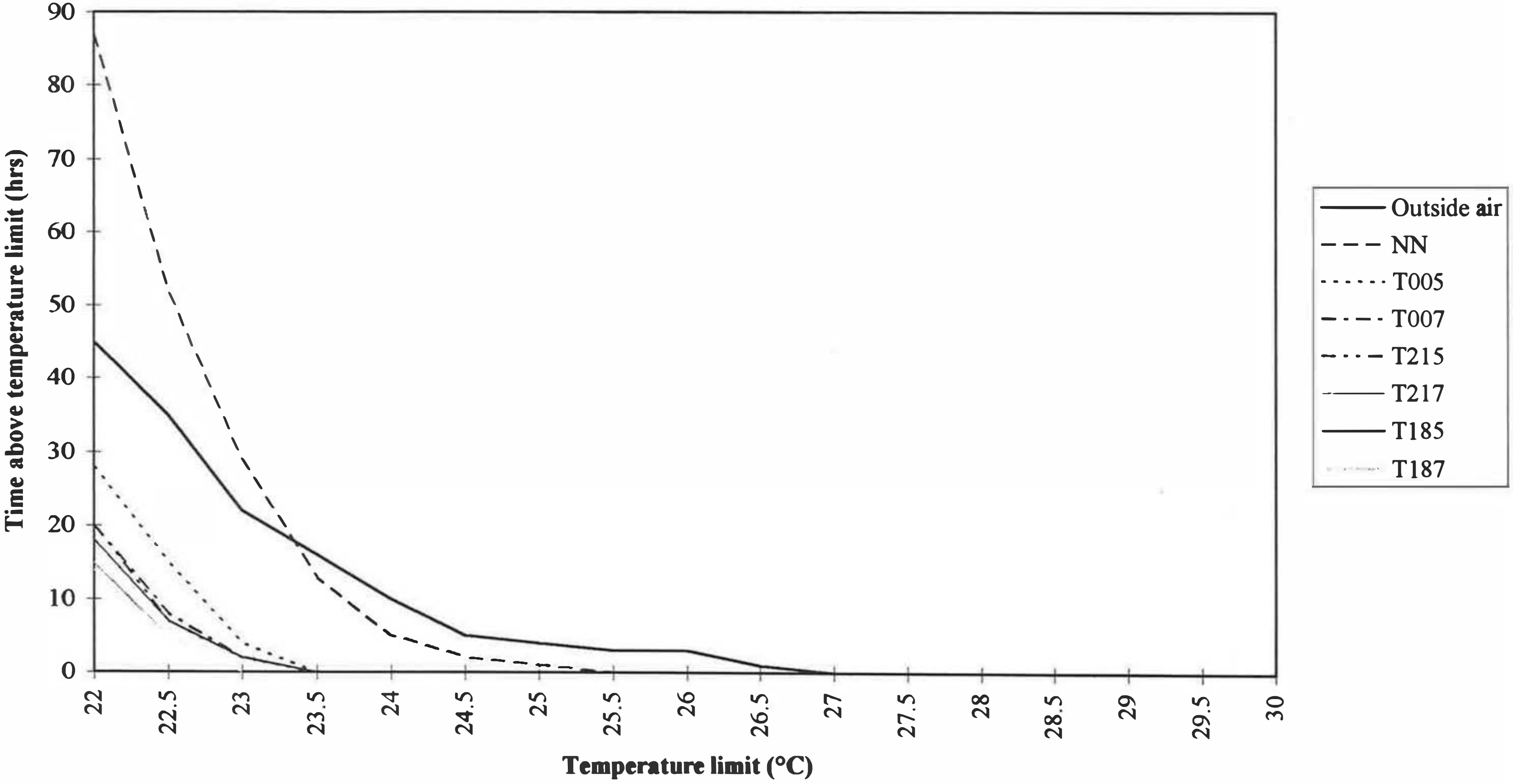
APPENDIX A2

RESULTS OF INITIAL TESTS

No. of pages: 21

NIGHT COOL PERIOD TEST- TYPICAL SUMMER

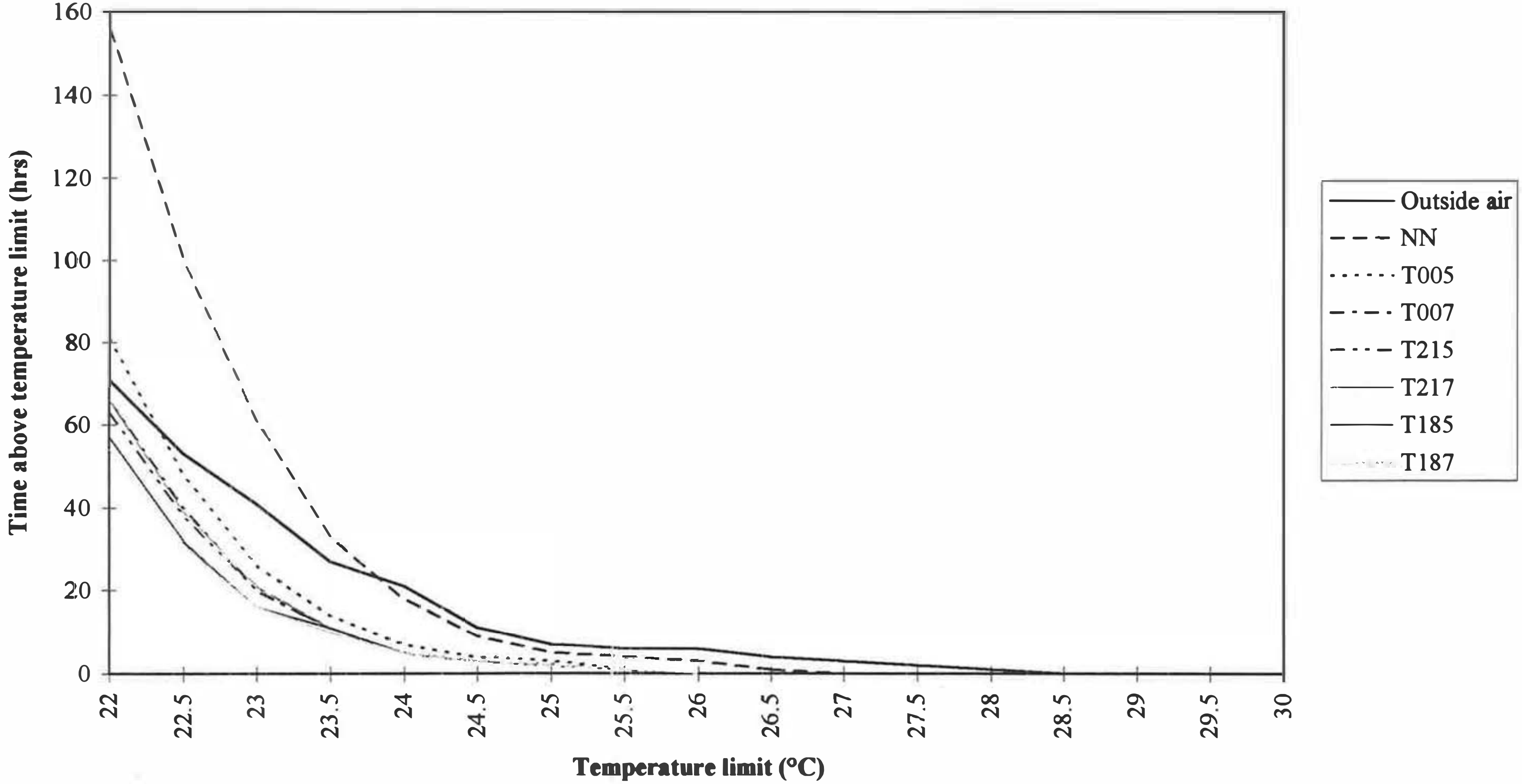
Figure A2.1



Legend details
NN= No night cooling, T005= Timeclock control (00.00-05.00), T007= Timeclock control (00.00-07.00), T215= Timeclock control (21.00-05.00), T217= Timeclock control (21.00-07.00), T185= Timeclock control (18.00-05.00), T187= Timeclock control (18.00-07.00)

NIGHT COOL PERIOD TEST- PEAK SUMMER

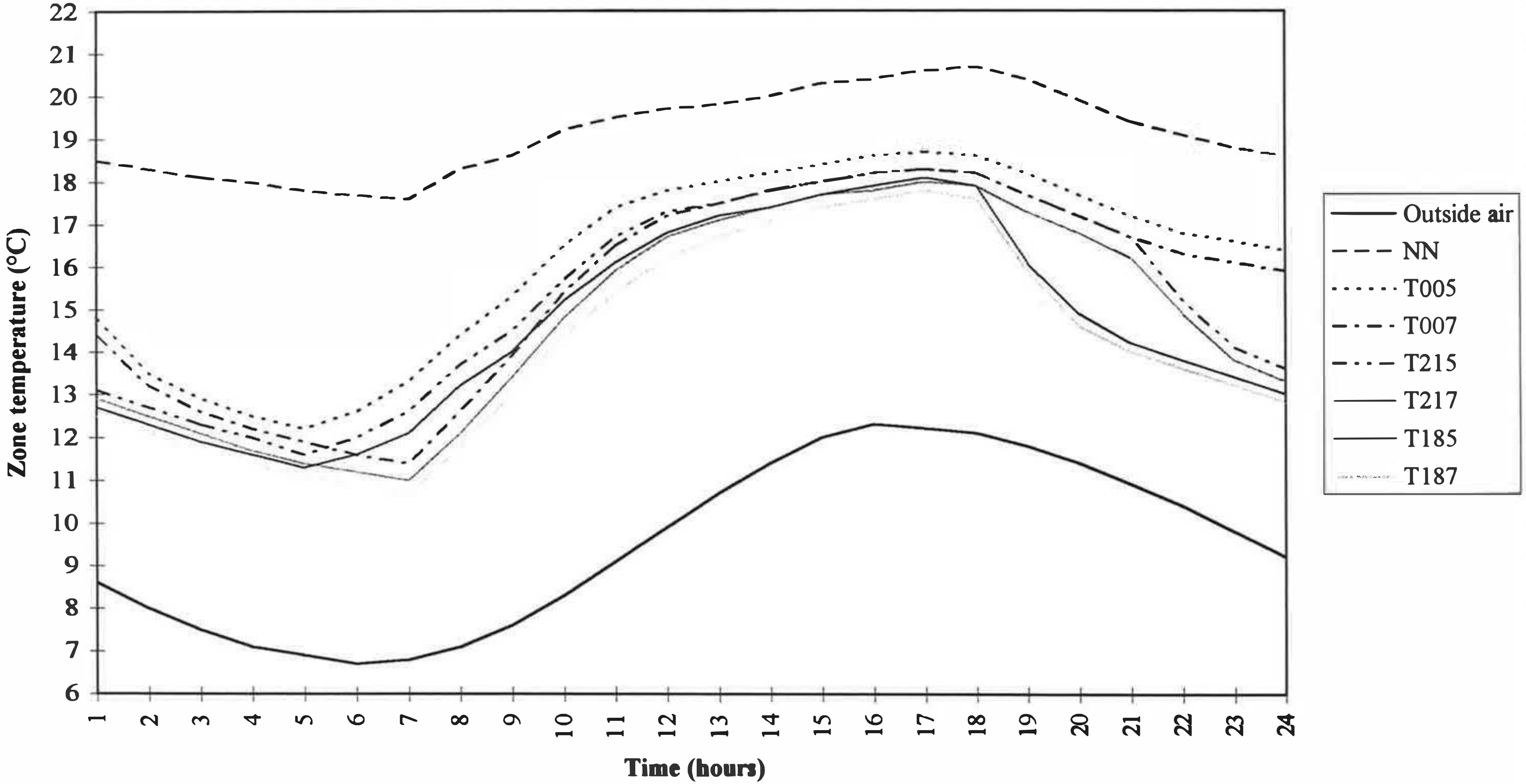
Figure A2.2



Legend details
NN= No night cooling, T005= Timeclock control (00.00-05.00), T007= Timeclock control (00.00-07.00), T215= Timeclock control (21.00-05.00), T217= Timeclock control (21.00-07.00), T185= Timeclock control (18.00-05.00), T187= Timeclock control (18.00-07.00)

COMPARISON OF NIGHT COOL PERIOD- SPRING DAY

Figure A2.3

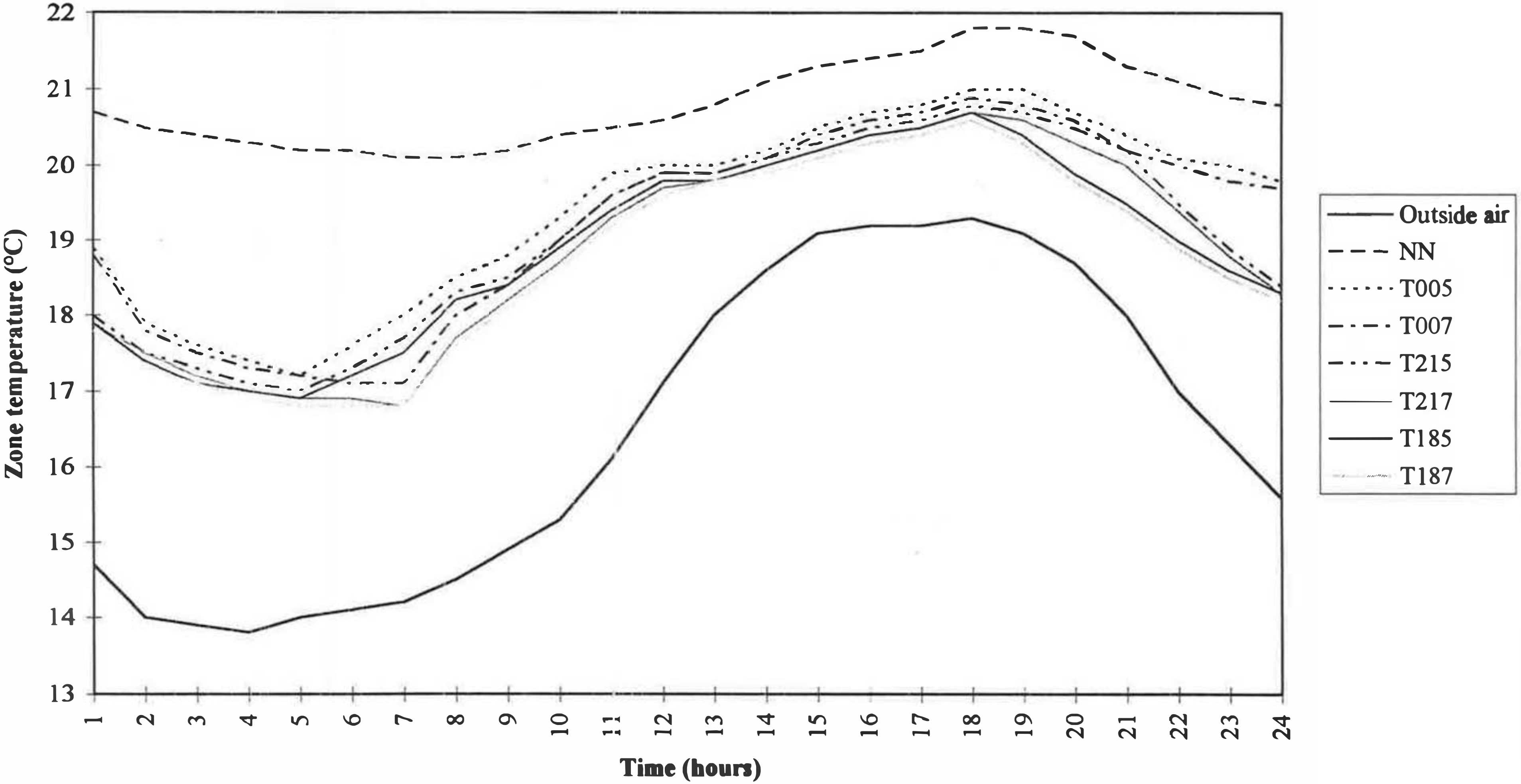


Legend details

NN= No night cooling, T005= Timeclock control (00.00-05.00), T007= Timeclock control (00.00-07.00), T215= Timeclock control (21.00-05.00), T217= Timeclock control (21.00-07.00), T185= Timeclock control (18.00-05.00), T187= Timeclock control (18.00-07.00)

COMPARISON OF NIGHT COOL PERIOD- TYPICAL DAY

Figure A2.4

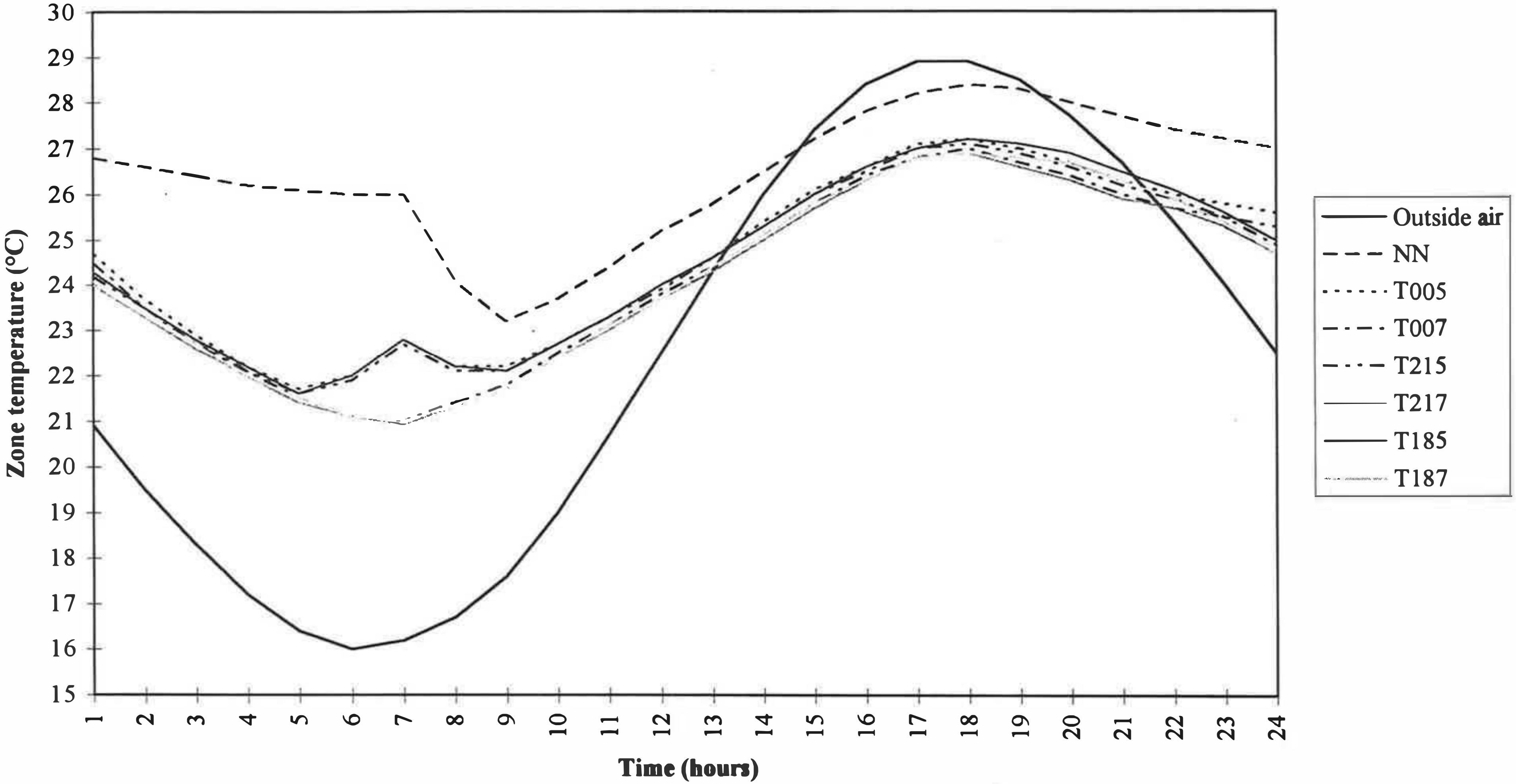


Legend details

NN= No night cooling, T005= Timeclock control (00.00-05.00), T007= Timeclock control (00.00-07.00), T215= Timeclock control (21.00-05.00), T217= Timeclock control (21.00-07.00), T185= Timeclock control (18.00-05.00), T187= Timeclock control (18.00-07.00)

COMPARISON OF NIGHT COOL PERIOD- PEAK DAY

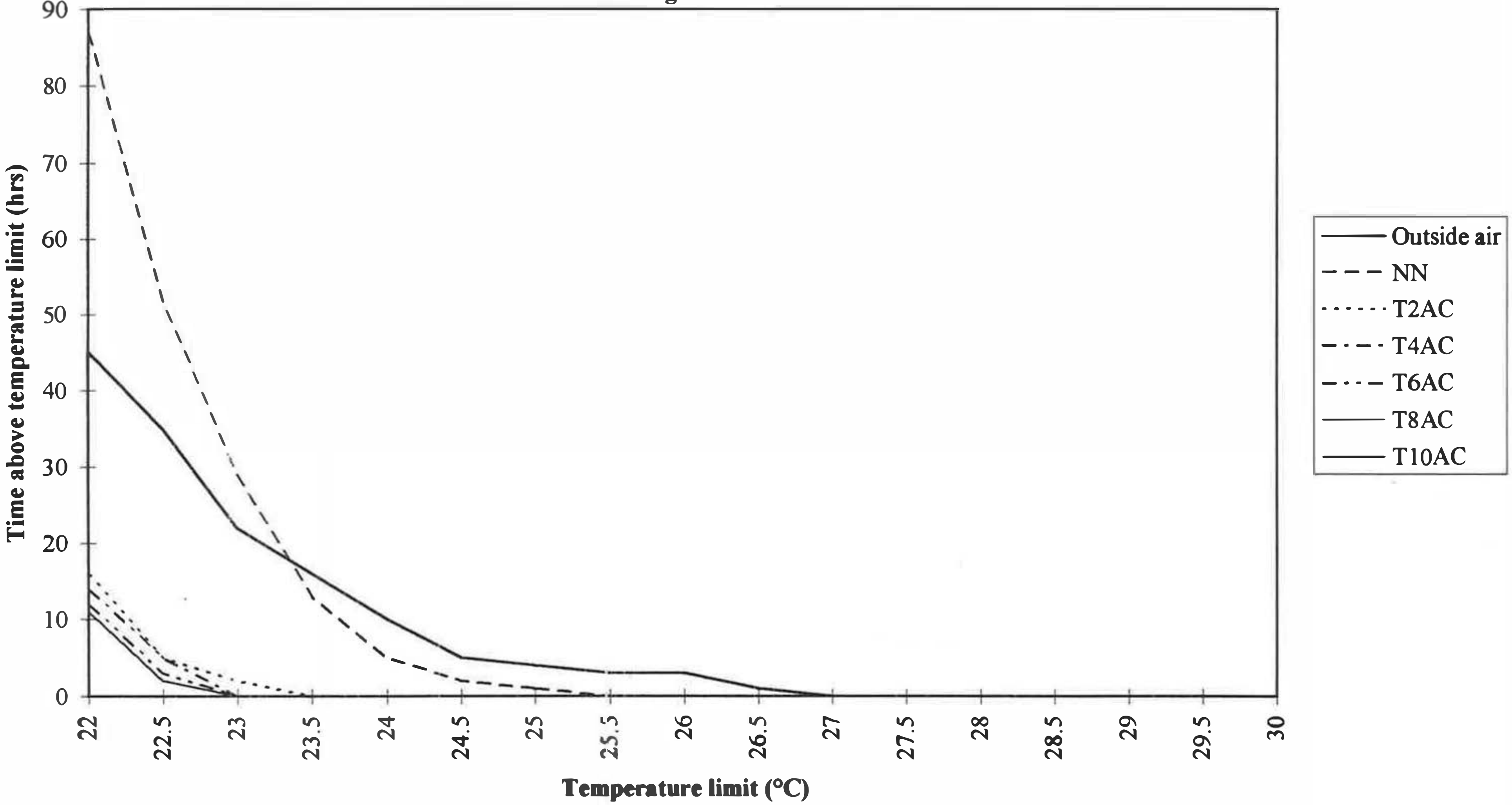
Figure A2.5



<u>Legend details</u>
NN= No night cooling, T005= Timeclock control (00.00-05.00), T007= Timeclock control (00.00-07.00), T215= Timeclock control (21.00-05.00), T217= Timeclock control (21.00-07.00), T185= Timeclock control (18.00-05.00), T187= Timeclock control (18.00-07.00)

MECHANICAL NIGHT COOL RATE TEST- TYPICAL SUMMER

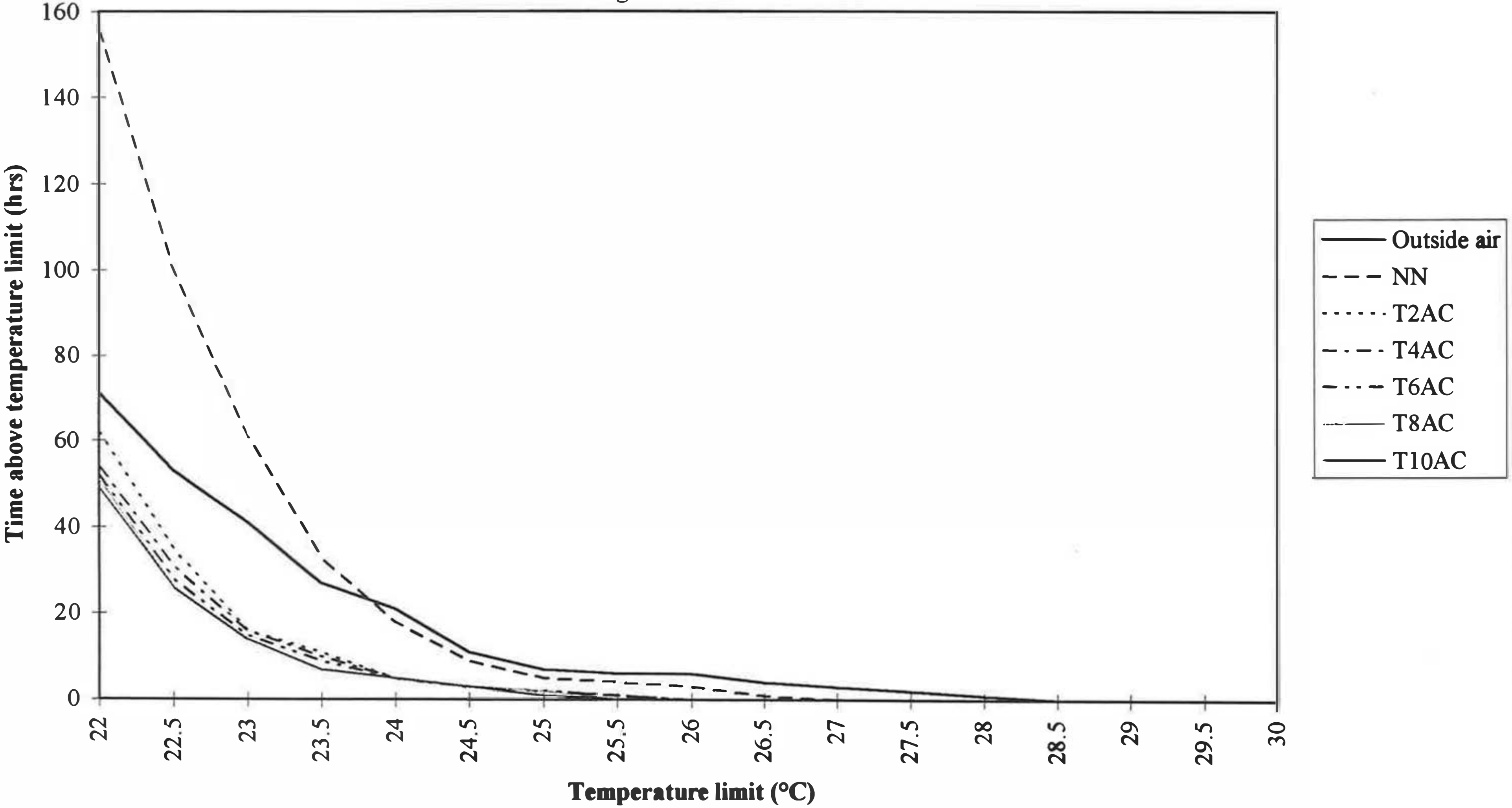
Figure A2.6



Legend details
NN= No night cooling, T2AC= Timeclock control (night mech vent 2ac/h), T4AC= Timeclock control (night mech vent 4ac/h),
T6AC= Timeclock control (night mech vent 6ac/h), T8AC= Timeclock control (night mech vent 8ac/h), T10AC= Timeclock control (night mech vent 10ac/h)

MECHANICAL NIGHT COOL RATE TEST- PEAK SUMMER

Figure A2.7

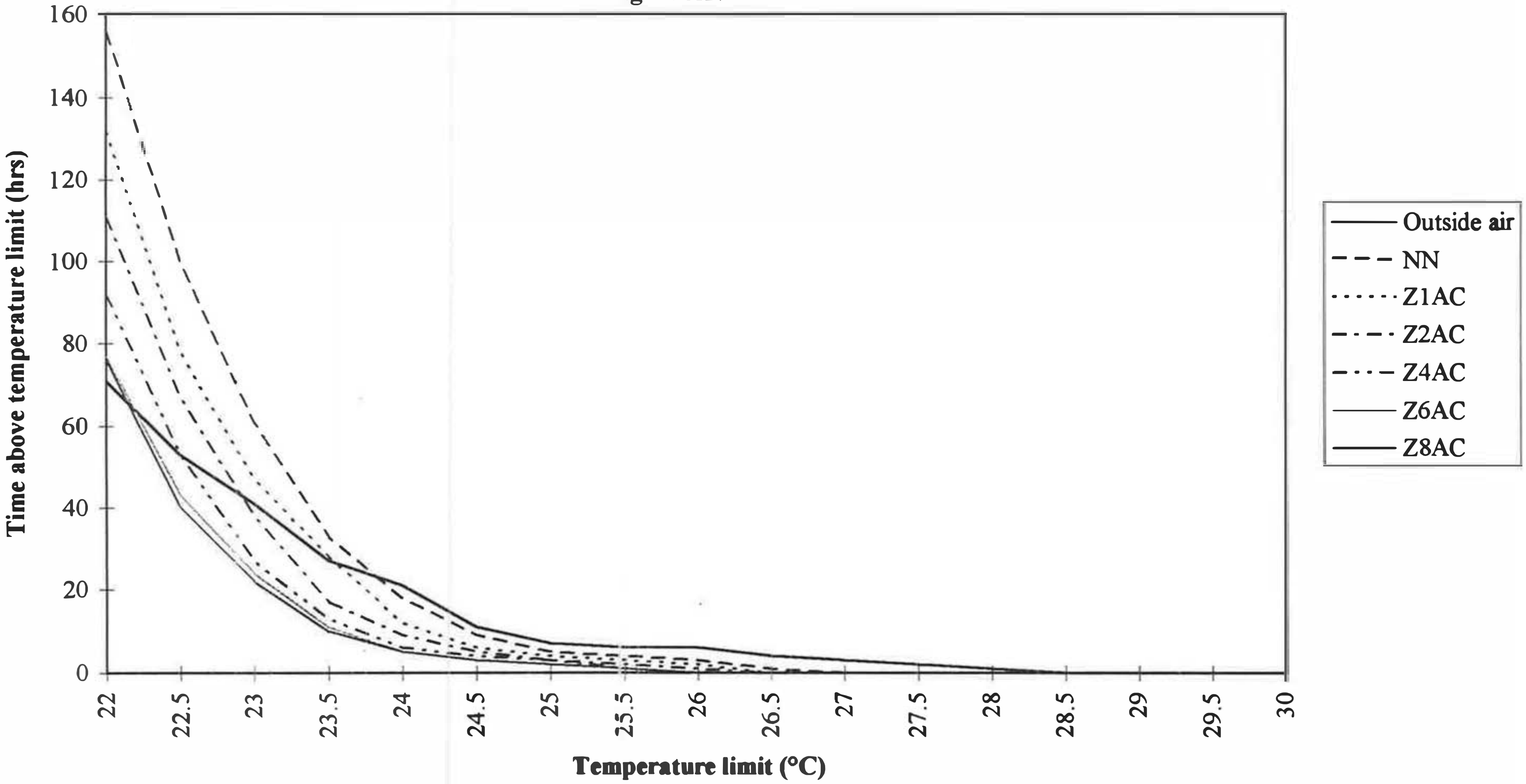


Legend details

NN= No night cooling, T2AC= Timeclock control (night mech vent 2ac/h), T4AC= Timeclock control (night mech vent 4ac/h), T6AC= Timeclock control (night mech vent 6ac/h), T8AC= Timeclock control (night mech vent 8ac/h), T10AC= Timeclock control (night mech vent 10ac/h)

ZONE CONTROL WITH NIGHT COOLING FROM A CONSTANT NATURAL VENTILATION RATE ONLY- PEAK SUMMER

Figure A2.8

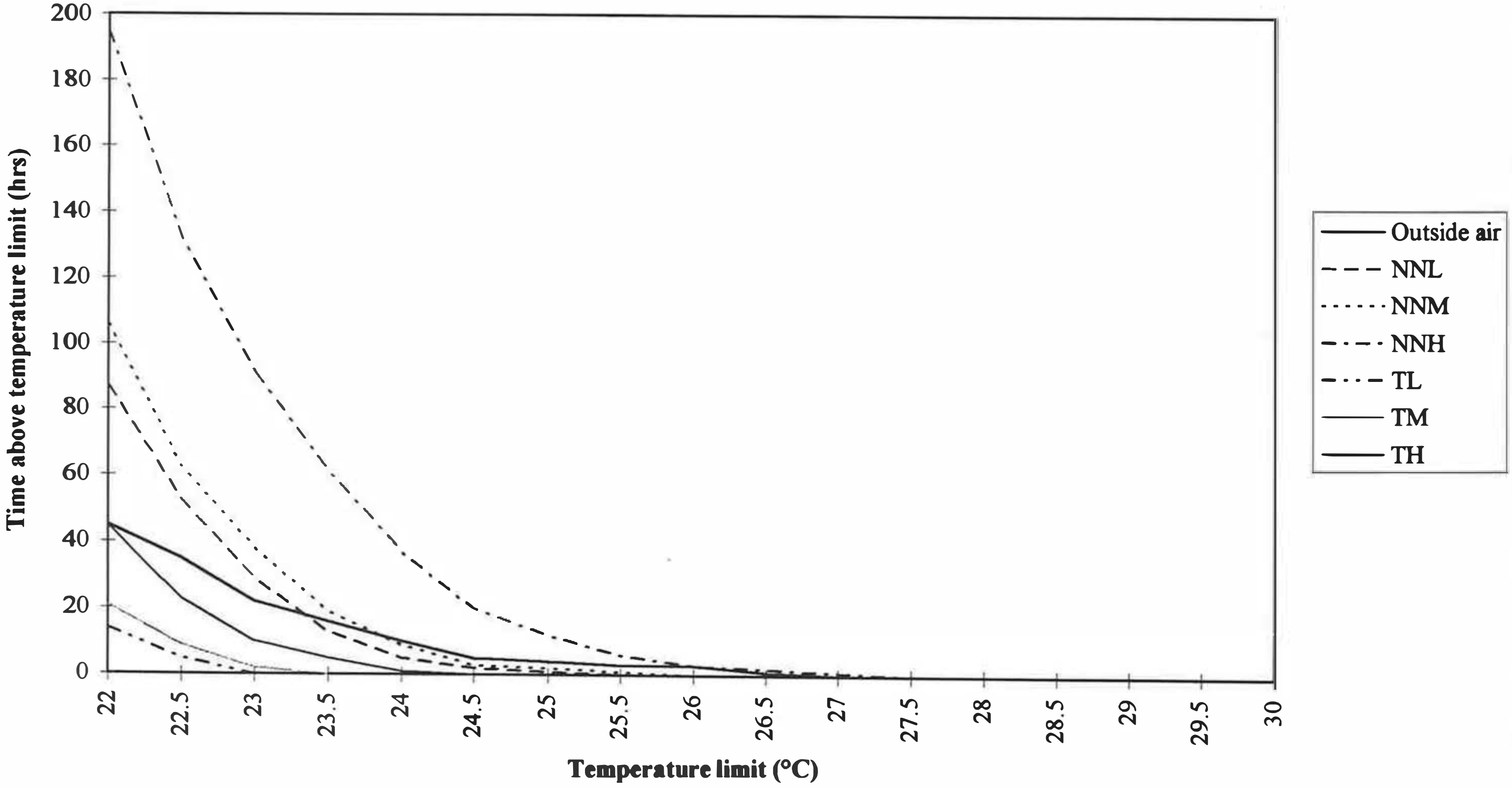


Legend details

NN= No night cooling, Z1AC= Zone control (1 ac/h fixed night cooling rate), Z2AC= Zone control (2 ac/h fixed night cooling rate), Z4AC= Zone control (4 ac/h fixed night cooling rate), Z6AC= Zone control (6 ac/h fixed night cooling rate), Z8AC= Zone control (8 ac/h fixed night cooling rate)

SOLAR GAINS TEST- TYPICAL SUMMER

Figure A2.9

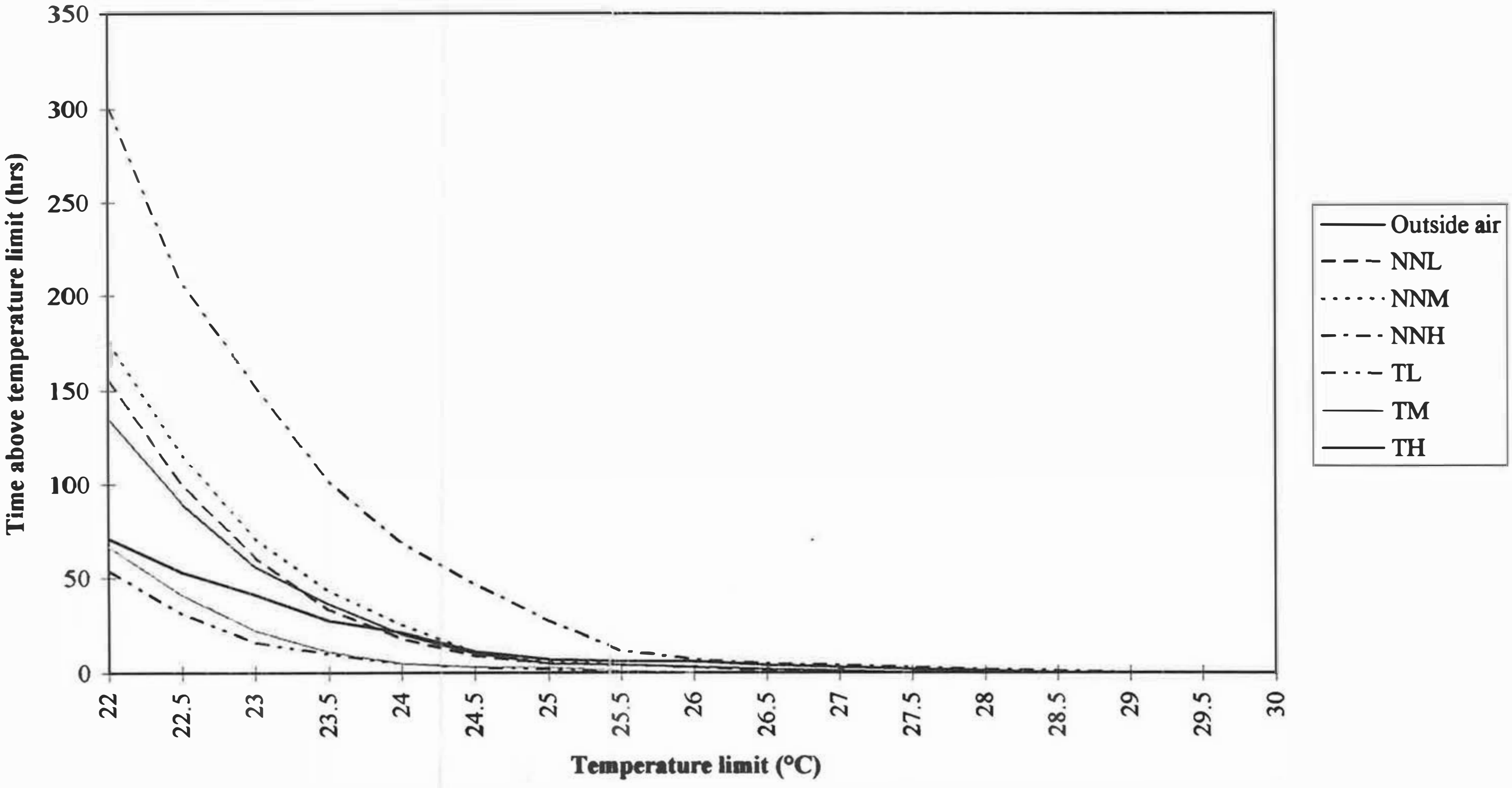


Legend details

NNL= No night cooling (low solar gains), NNM= No night cooling (medium solar gains), NNH= No night cooling (high solar gains), TL= Timeclock control (low solar gains), TM= Timeclock control (medium solar gains), TH= Timeclock control (high solar gains)

SOLAR GAINS TEST- PEAK SUMMER

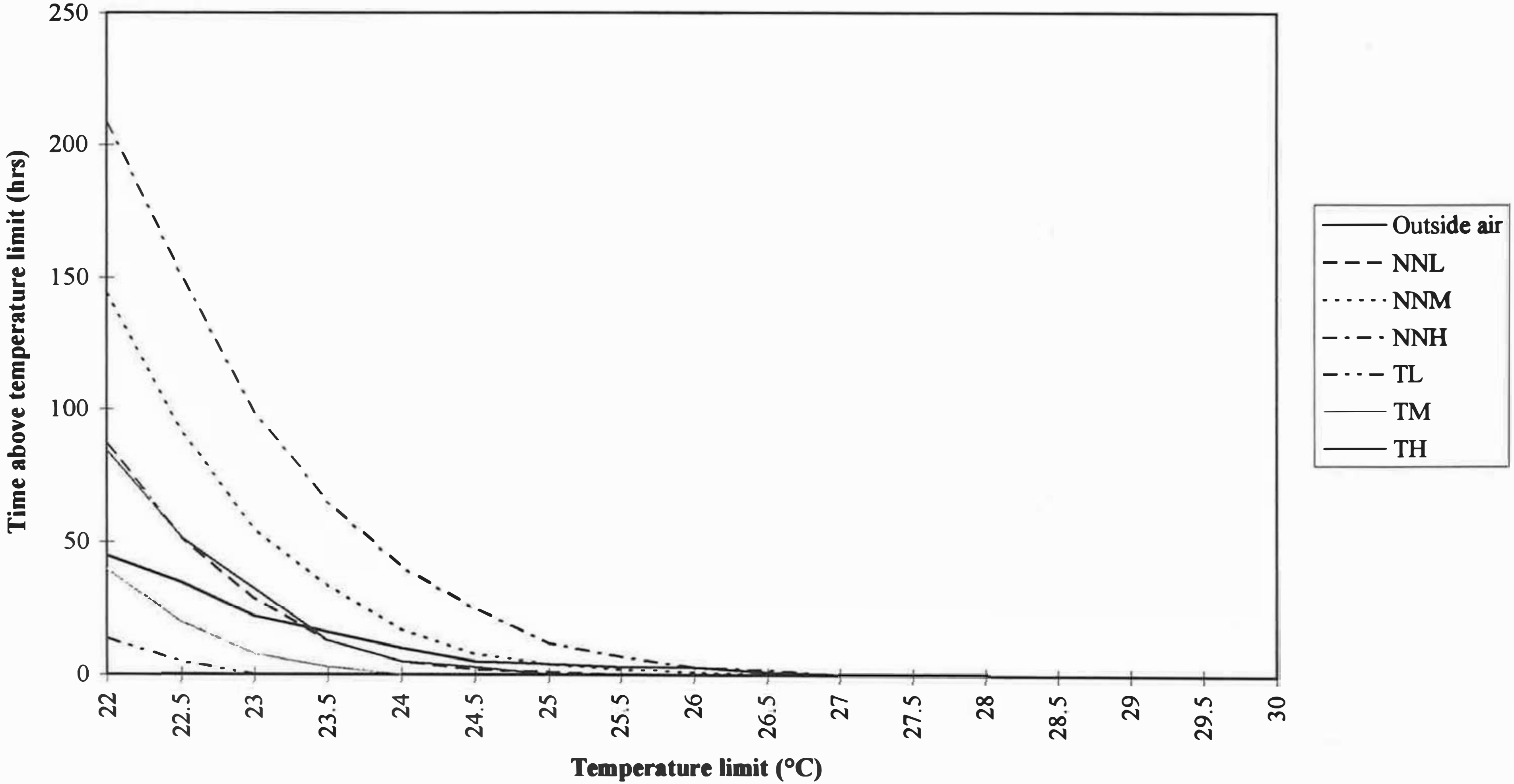
Figure A2.10



Legend details
NNL= No night cooling (low solar gains), NNM= No night cooling (medium solar gains), NNH= No night cooling (high solar gains),
TL= Timeclock control (low solar gains), TM= Timeclock control (medium solar gains), TH= Timeclock control (high solar gains)

CASUAL GAINS TEST- TYPICAL SUMMER

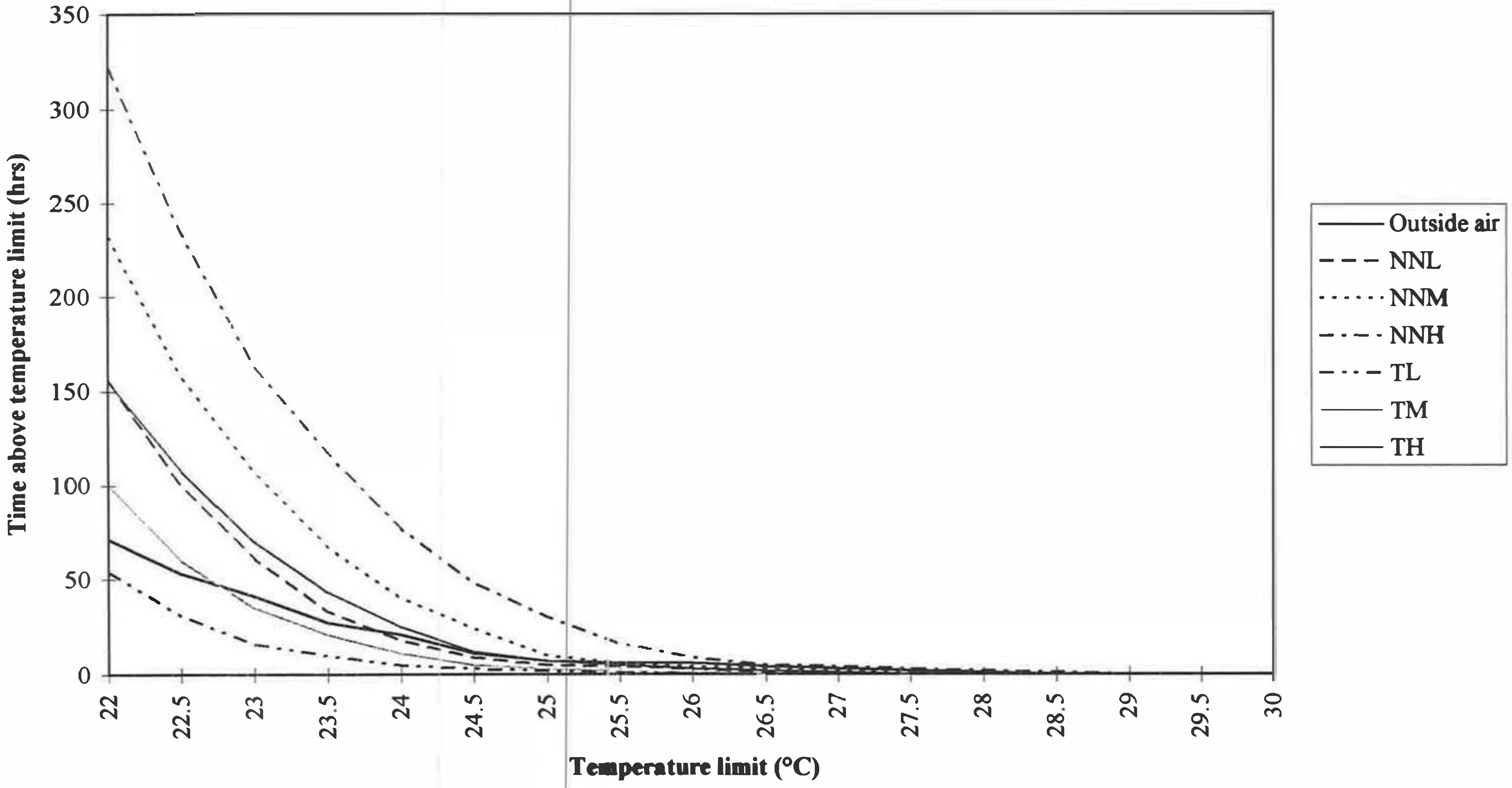
Figure A2.11



Legend details
NNL= No night cooling (low casual gains), NNM= No night cooling (medium casual gains), NNH= No night cooling (high casual gains),
TL= Timeclock control (low casual gains), TM= Timeclock control (medium casual gains), TH= Timeclock control (high casual gains)

CASUAL GAINS TEST- PEAK SUMMER

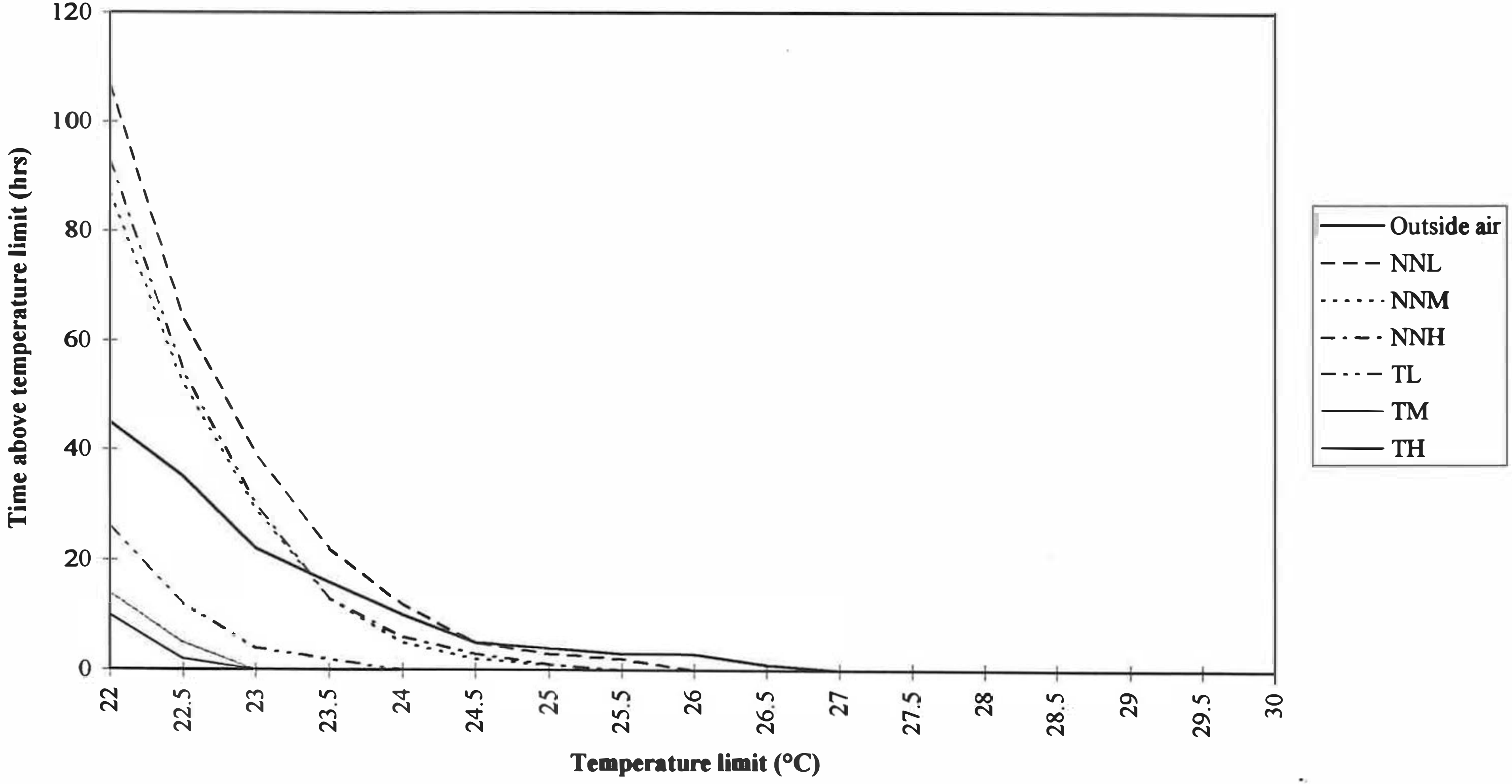
Figure A2.12



Legend details
NNL= No night cooling (low casual gains), NNM= No night cooling (medium casual gains), NNH= No night cooling (high casual gains),
TL= Timeclock control (low casual gains), TM= Timeclock control (medium casual gains), TH= Timeclock control (high casual gains)

SLAB MATERIAL TEST- TYPICAL SUMMER

Figure A2.13

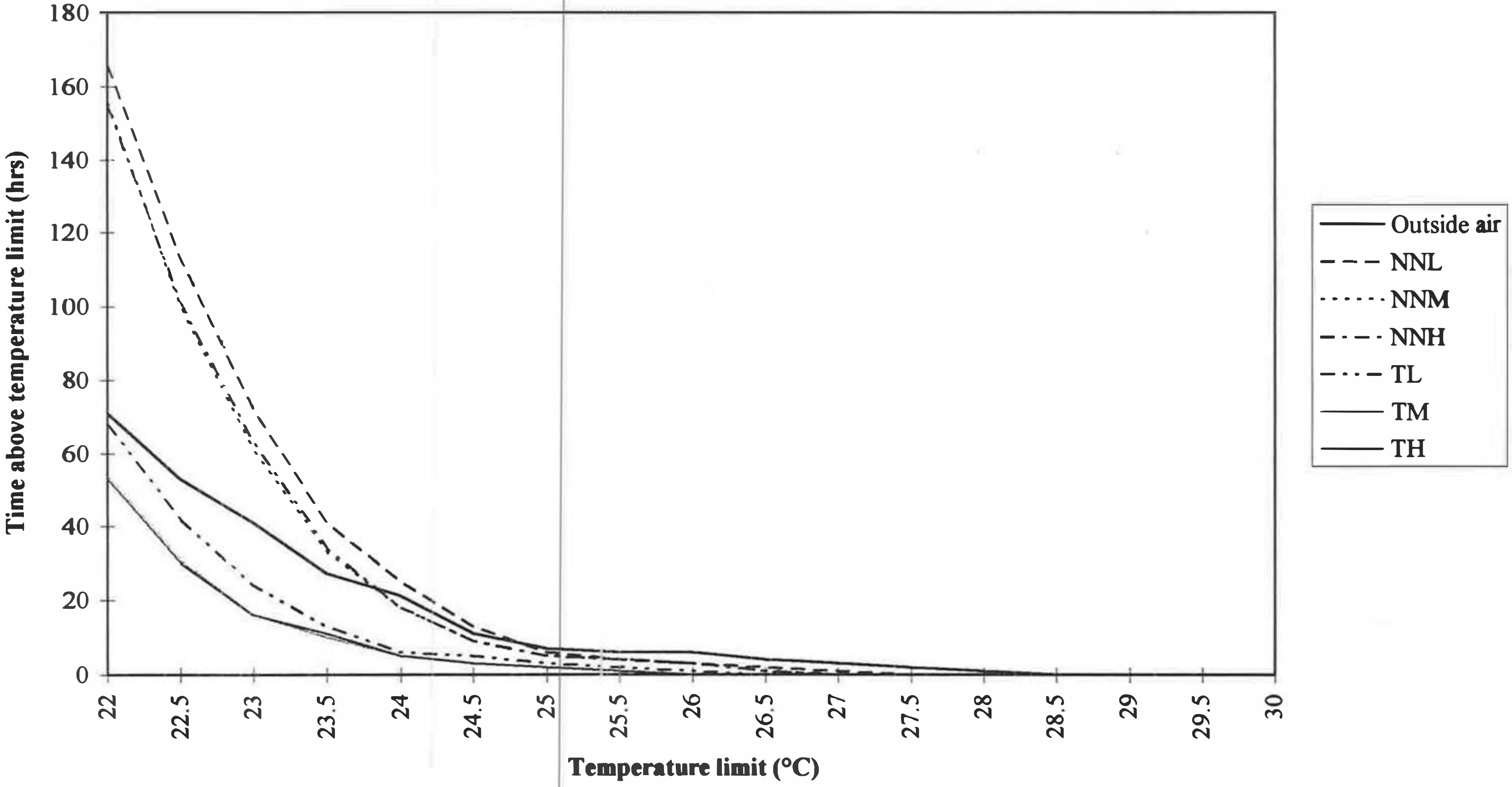


Legend details

NNL= No night cooling (lightweight slab), NNM= No night cooling (mediumweight slab), NNH= No night cooling (heavyweight slab), TL= Timeclock control (lightweight slab), TM= Timeclock control (mediumweight slab), TH= Timeclock control (heavyweight slab)

SLAB MATERIAL TEST- PEAK SUMMER

Figure A2.14

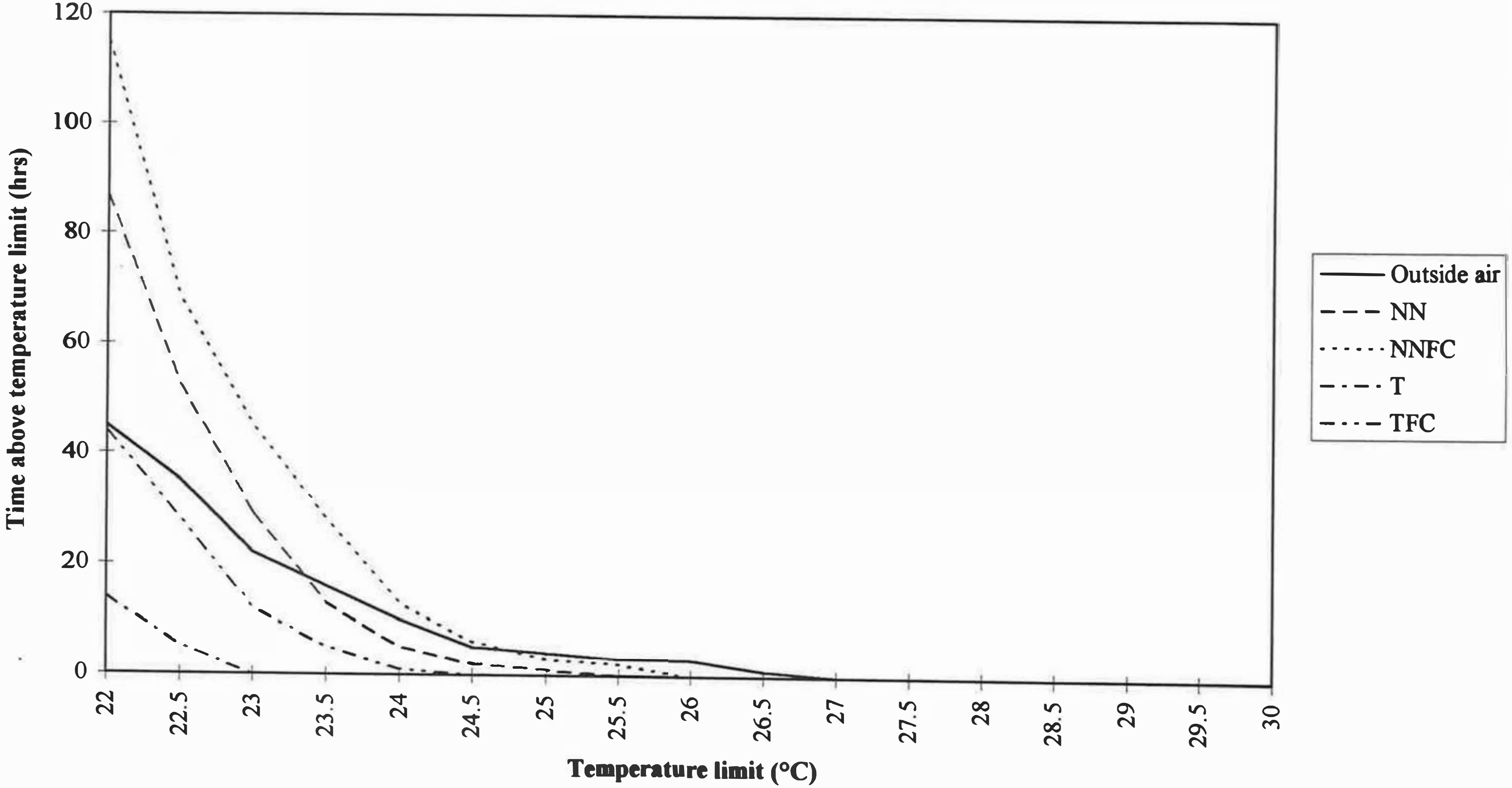


Legend details

NNL= No night cooling (lightweight slab), NNM= No night cooling (mediumweight slab), NNH= No night cooling (heavyweight slab), TL= Timeclock control (lightweight slab), TM= Timeclock control (mediumweight slab), TH= Timeclock control heavyweight slab)

SLAB COVERING TEST- TYPICAL SUMMER

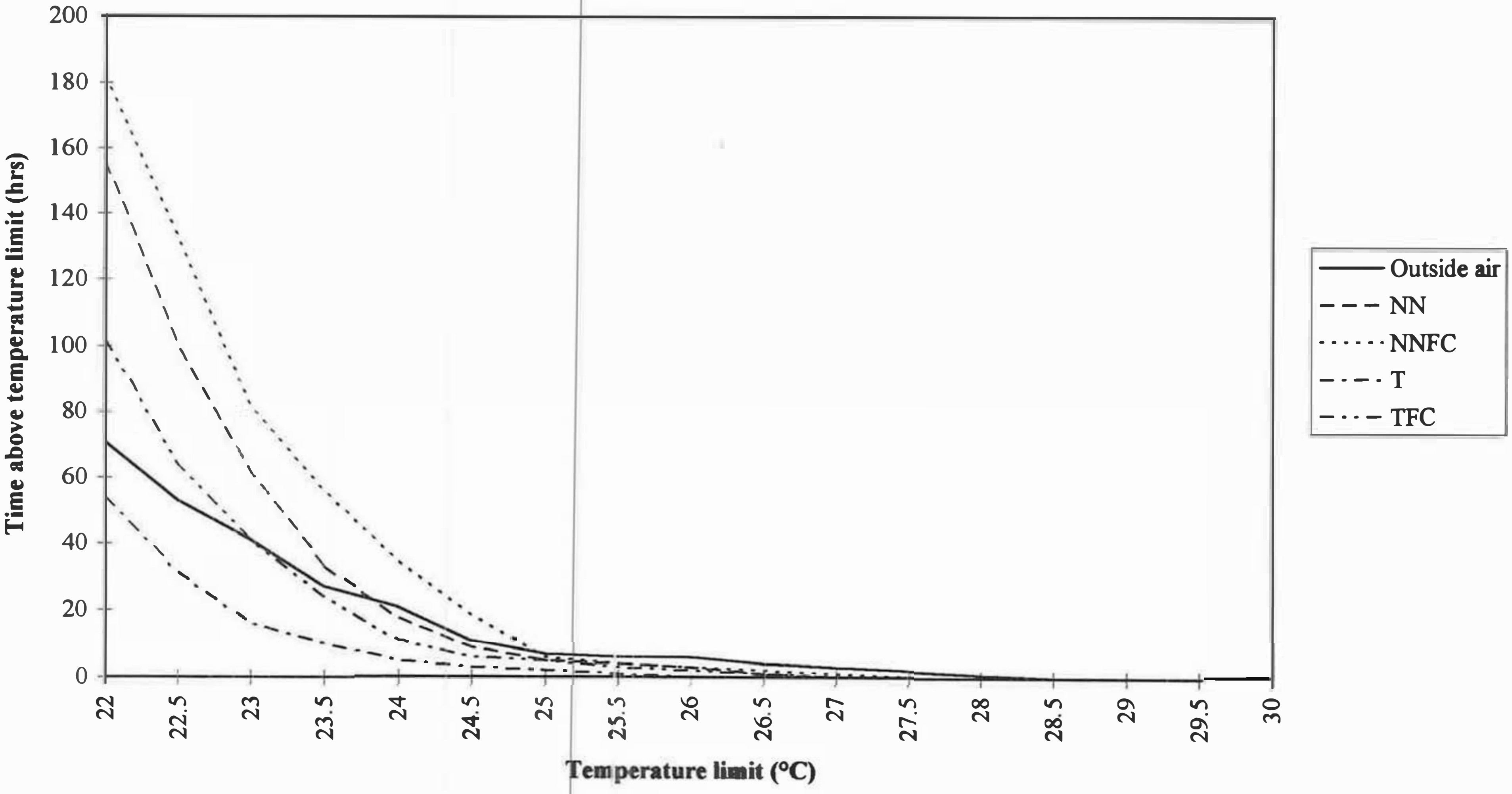
Figure A2.15



Legend details
NN= No night cooling, NNFC= No night cooling (false ceiling),
T= Timeclock control, TFC= Timeclock control (false ceiling)

SLAB COVERING TEST- PEAK SUMMER

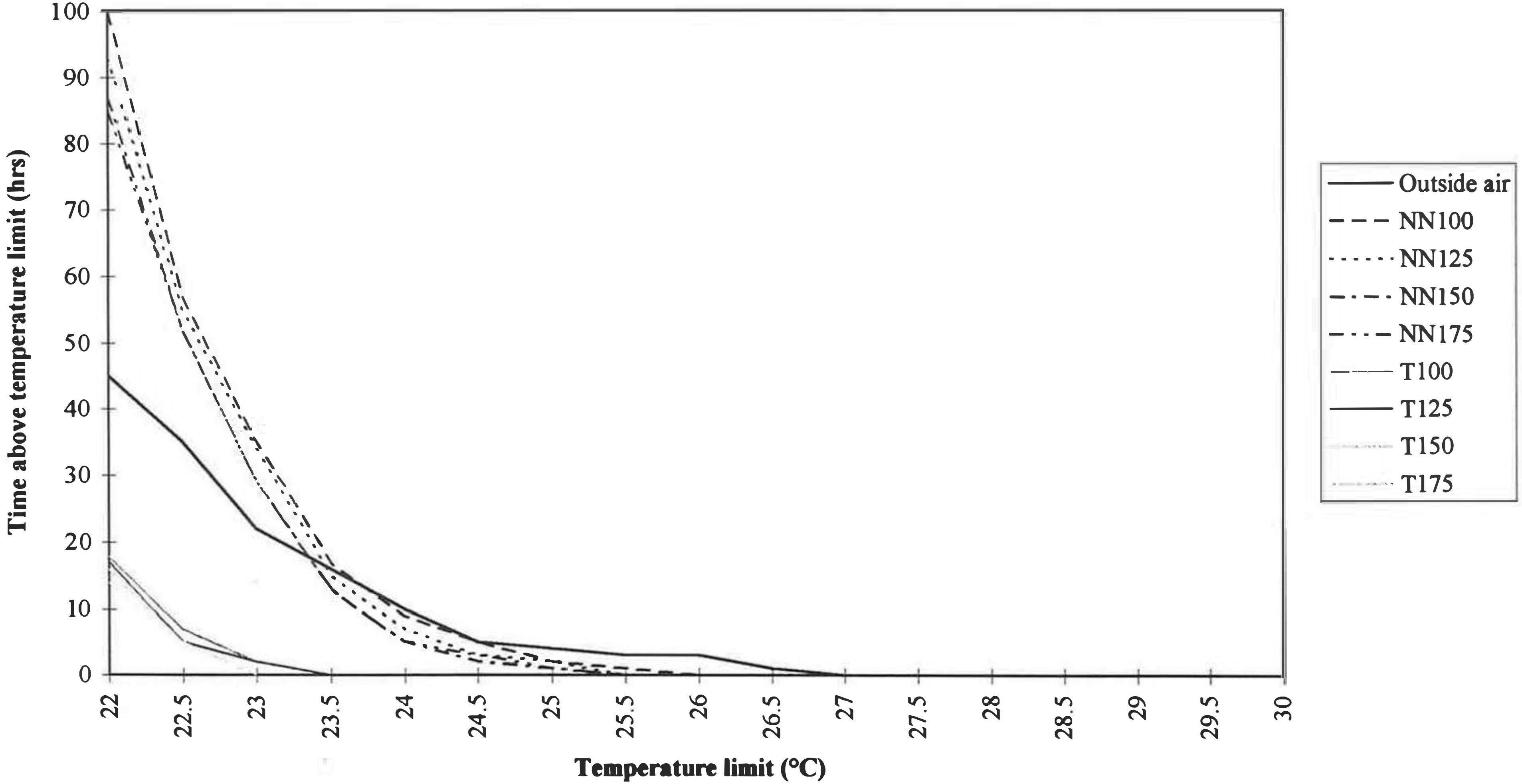
Figure A2.16



Legend details
NN= No night cooling, NNFC= No night cooling (false ceiling),
T= Timeclock control, TFC= Timeclock control (false ceiling)

SLAB DEPTH TEST- TYPICAL SUMMER

Figure A2.17

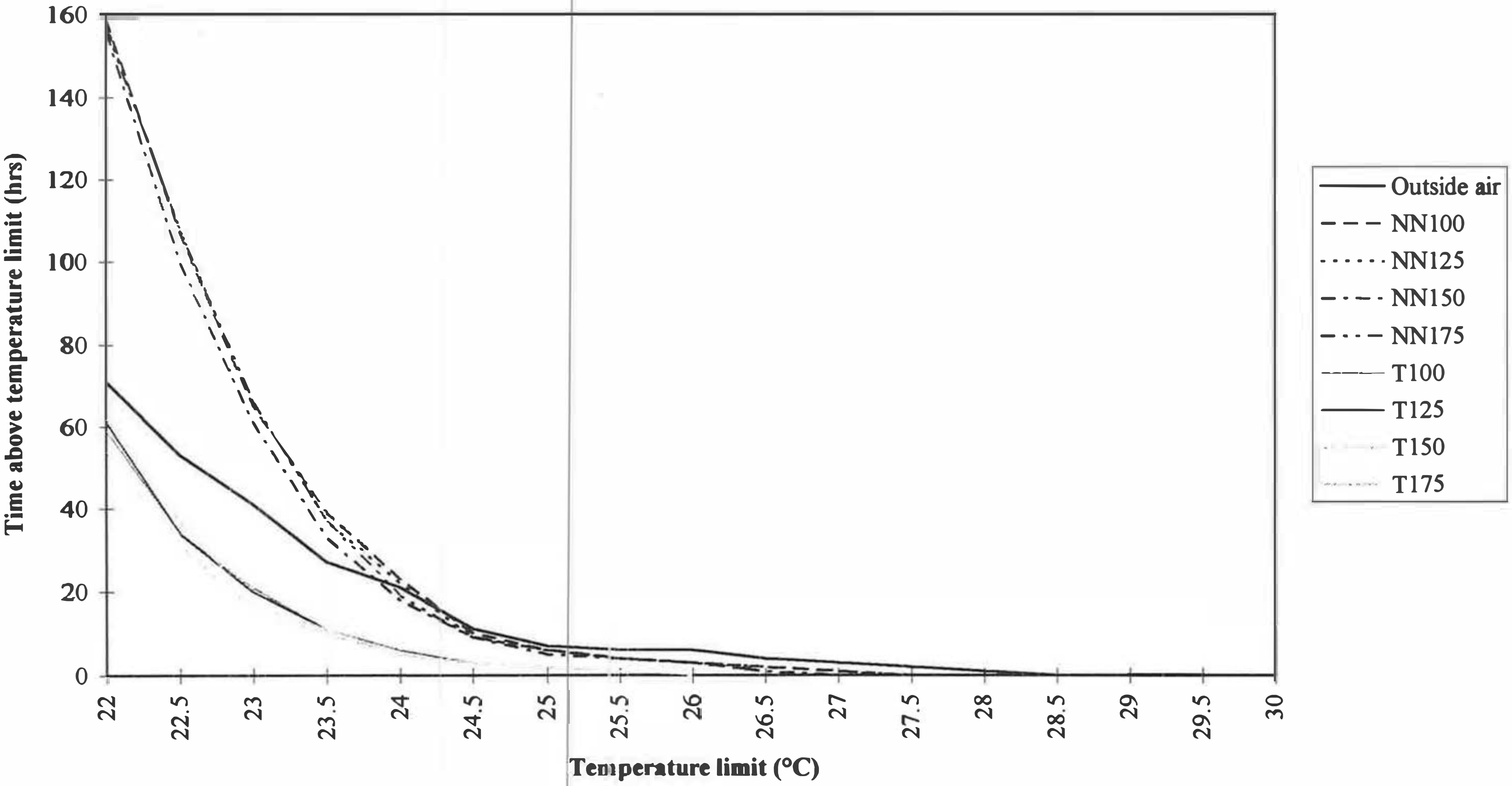


Legend details

NN100= No night cooling (100mm slab), NN125= No night cooling (125mm slab), NN150= No night cooling (150mm slab), NN175= No night cooling (175mm slab), T100= Timeclock control (100mm slab), T125= Timeclock control (125mm slab), T150= Timeclock control (150mm slab), T175= Timeclock control (175mm slab)

SLAB DEPTH TEST- PEAK SUMMER

Figure A2.18



Legend details

NN100= No night cooling (100mm slab), NN125= No night cooling (125mm slab), NN150= No night cooling (150mm slab), NN175= No night cooling (175mm slab), T100= Timeclock control (100mm slab), T125= Timeclock control (125mm slab), T150= Timeclock control (150mm slab), T175= Timeclock control (175mm slab)

Table A2.1 Heating requirements of initial tests

(i) Casual gains

	Typical summer						Peak summer					
	NNL	NNM	NNH	TL	TM	TH	NNL	NNM	NNH	TL	TM	TH
Pre-heat (MJ)	3563	3094	2761	7279	7063	6896	3016	2634	2368	6601	6398	6231
Heating (MJ)	12902	8387	6659	54402	44708	33657	11294	7714	6048	45457	36637	27654

(ii) Solar gains

	Typical summer						Peak summer					
	NNL	NNM	NNH	TL	TM	TH	NNL	NNM	NNH	TL	TM	TH
Pre-heat (MJ)	3563	3363	2391	7279	7182	6769	3016	2889	2156	6601	6536	6155
Heating (MJ)	12903	10985	5010	54403	50335	39264	11294	9679	4562	45457	42102	32769

(iii) False ceiling

	Typical summer				Peak summer			
	NN	NNFC	T	TFC	NN	NNFC	T	TFC
Pre-heat (MJ)	3563	4227	7279	7443	3016	3597	6601	6790
Heating (MJ)	12903	12306	54403	43631	11294	11061	45457	36553

(iv) Slab depth

	Typical summer								Peak summer							
	NN 100	NN 125	NN 150	NN 175	T 100	T 125	T 150	T 175	NN 100	NN 125	NN 150	NN 175	T 100	T 125	T 150	T 175
Pre-heat (MJ)	3771	3694	3563	3609	7276	7276	7279	7308	3166	3117	3016	3064	6629	6619	6601	6622
Heating (MJ)	13893	13169	12903	12247	54157	53345	54403	52120	12155	11530	11294	10749	45649	44803	45457	43338

(v) Slab material

	Typical summer						Peak summer					
	NNL	NNM	NNH	TL	TM	TH	NNL	NNM	NNH	TL	TM	TH
Pre-heat (MJ)	3955	3563	3589	7314	7279	7441	3300	3016	3033	6680	6601	6600
Heating (MJ)	13997	12903	13268	52044	55403	59497	12553	11294	11573	43927	45457	46136

(vi) Mechanical night cool rate

	Typical summer						Peak summer					
	NN	T2AC	T4AC	T6AC	T8AC	T10AC	NN	T2AC	T4AC	T6AC	T8AC	T10AC
Pre-heat (MJ)	3563	7136	7279	7364	7421	7457	3016	6445	6601	6701	6767	6812
Heating (MJ)	12903	51879	54403	56370	57662	58686	11294	43129	45457	47041	48156	49043

(vii) Fixed natural ventialtion night cool rate with zone control

	Peak summer					
	NN	Z1AC	Z2AC	T4AC	Z6AC	z8AC
Pre-heat (MJ)	3016	3335	3564	3764	3840	3881
Heating (MJ)	11294	11378	11435	11450	11453	11457

(viii) Night cool period

	Typical summer							Peak summer						
	NN	T005	T007	T215	T217	T185	T187	NN	T005	T007	T215	T217	T185	T187
Pre-heat (MJ)	3563	6122	7014	6482	7197	6644	7279	3016	5334	6371	5673	6536	5815	6601
Heating (MJ)	12903	36416	44682	43597	50546	48414	54403	11294	30154	37265	35761	42241	39798	45457

Floor area = 529m²

Key to table

(i) Casual gains

NNL	-	No night cooling, low casual gains (20 W/m²)
NNM	-	No night cooling, medium casual gains (30 W/m²)
NNH	-	No night cooling, high casual gains (40 W/m²)
TL	-	Timeclock control (18.00 - 07.00), low casual gains
TM	-	Timeclock control (18.00 - 07.00), medium casual gains
TH	-	Timeclock control (18.00 - 07.00), high casual gains

(ii) Solar gains

NNL	-	No night cooling, low solar gains (internal blind + external overhang)
NNM	-	No night cooling, medium solar gains (internal blind)
NNH	-	No night cooling, high solar gains (no solar protection)
TL	-	Timeclock control (18.00 - 07.00), low solar gains
TM	-	Timeclock control (18.00 - 07.00), medium solar gains
TH	-	Timeclock control (18.00 - 07.00), high solar gains

(iii) False ceiling

NN	-	No night cooling, exposed ceiling
NNFC	-	No night cooling, false ceiling
T	-	Timeclock control (18.00 - 07.00), exposed ceiling
TFC	-	Timeclock control (18.00 - 07.00), false ceiling

(iv) Mechanical night cooling ventilation rate

NN	-	No night cooling
T2AC	-	Timeclock control 2 ac/h
T4AC	-	Timeclock control 4 ac/h
T6AC	-	Timeclock control 6 ac/h
T8AC	-	Timeclock control 8 ac/h
T10AC	-	Timeclock control 10 ac/h

Note: Natural ventilation rate was unchanged and applied from 18.00 - 07.00
Mechanical ventilation was applied from 00.00 - 07.00

(v) Slab material

NNL	-	No night cooling, lightweight slab
NNM	-	No night cooling, mediumweight slab
NNH	-	No night cooling, heavyweight slab
TL	-	Timeclock control (18.00 - 07.00), lightweight slab
TM	-	Timeclock control (18.00 - 07.00), mediumweight slab
TH	-	Timeclock control (18.00 - 07.00), heavyweight slab

(vi) Slab depth

NN100	-	No night cooling, slab depth 100mm
NN125	-	No night cooling, slab depth 125mm
NN150	-	No night cooling, slab depth 150mm
NN175	-	No night cooling, slab depth 175mm
T100	-	Timeclock control (18.00 - 07.00), slab depth 100 mm
T125	-	Timeclock control (18.00 - 07.00), slab depth 125 mm
T150	-	Timeclock control (18.00 - 07.00), slab depth 150 mm
T175	-	Timeclock control (18.00 - 07.00), slab depth 175 mm

(vii) Fixed natural ventilation night cool rate with zone control

NN	-	No night cooling
Z1AC	-	Zone control (fixed night ventilation rate 1 ac/h)
Z2AC	-	Zone control (fixed night ventilation rate 2 ac/h)
Z4AC	-	Zone control (fixed night ventilation rate 4 ac/h)
Z6AC	-	Zone control (fixed night ventilation rate 6 ac/h)
Z8AC	-	Zone control (fixed night ventilation rate 8 ac/h)

Note: Natural ventilation rate was unchanged and applied from 18.00 - 07.00
Mechanical ventilation was applied from 00.00 - 07.00

(viii) Night cool period

NN	-	No night cooling
T005	-	Timeclock control between 00.00 - 05.00
T007	-	Timeclock control between 00.00 - 07.00
T215	-	Timeclock control between 21.00 - 05.00
T217	-	Timeclock control between 21.00 - 07.00
T185	-	Timeclock control between 18.00 - 05.00
T187	-	Timeclock control between 00.00 - 07.00

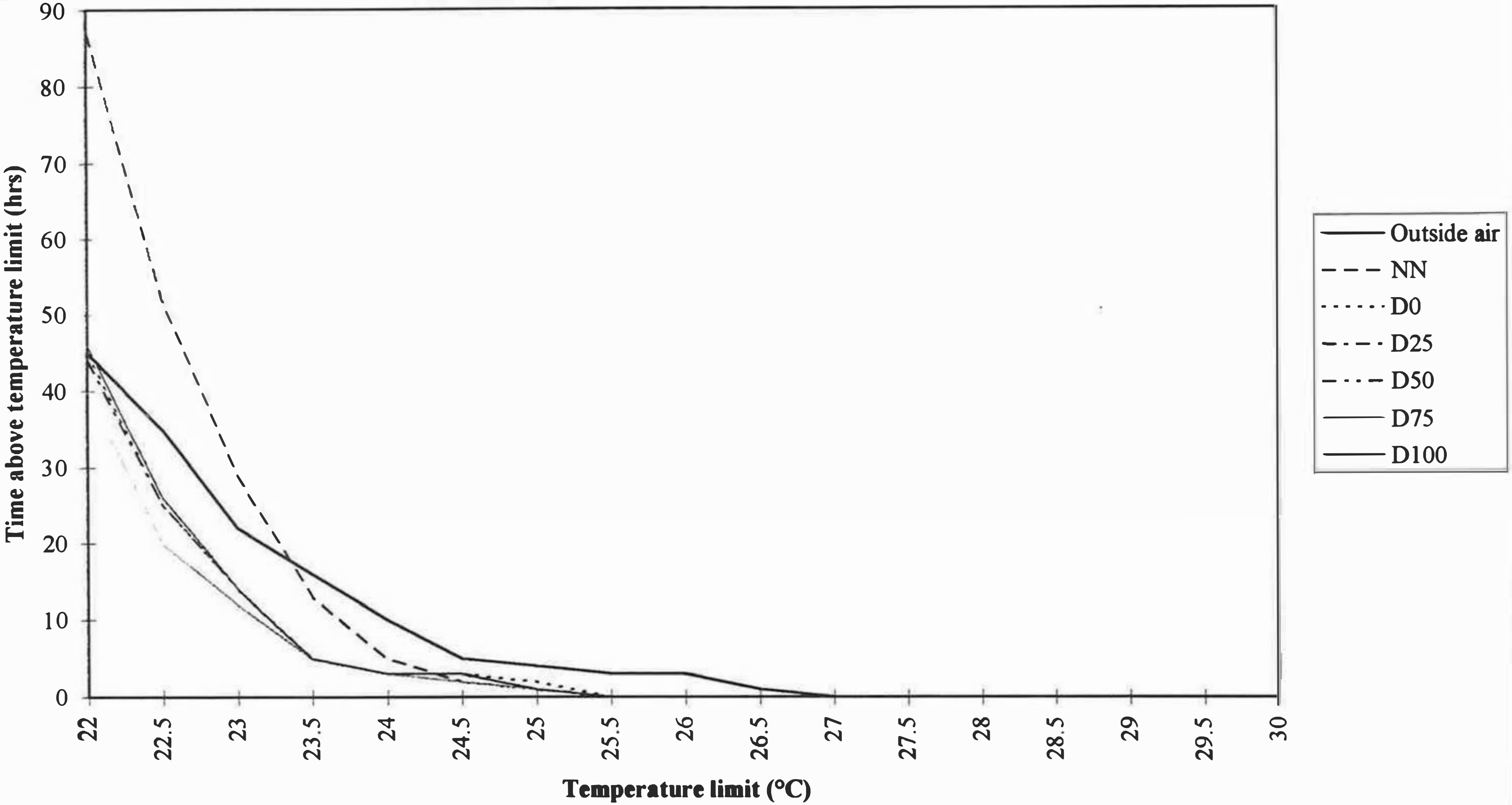
APPENDIX A3

RESULTS OF SPECIAL TESTS

No. of pages: 7

"DURRINGTON" CONTROL SENSOR DEPTH TEST- TYPICAL SUMMER

Figure A3.1

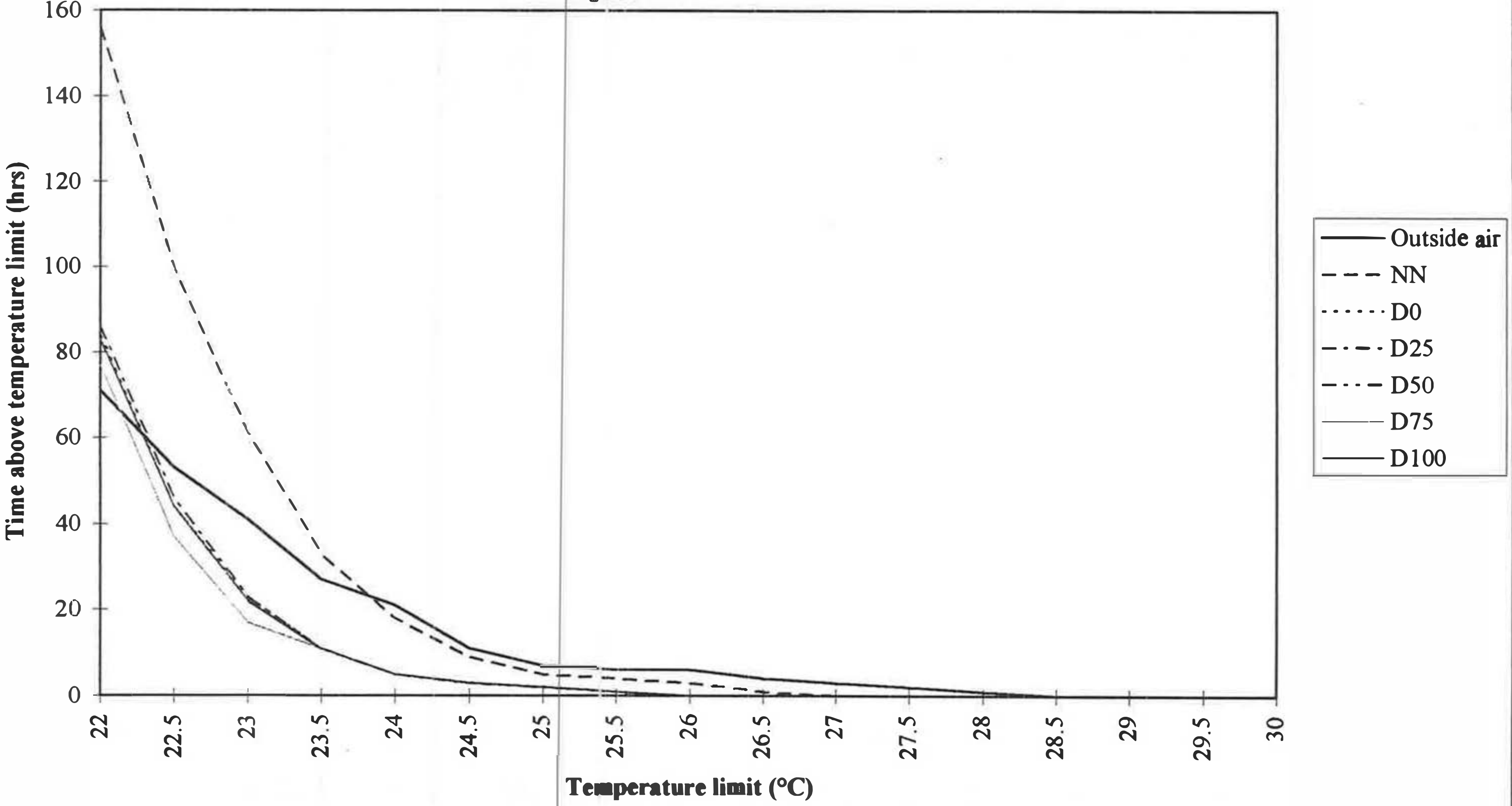


Legend details

NN= No night cooling, D0= Durrington control (sensor depth 0mm), D25= Durrington control (sensor depth 25mm),
D50= Durrington control (sensor depth 50mm), D75= Durrington control (sensor depth 75mm), D100= Durrington control (sensor depth 100mm)

"DURRINGTON" CONTROL SENSOR DEPTH TEST- PEAK SUMMER

Figure A3.2

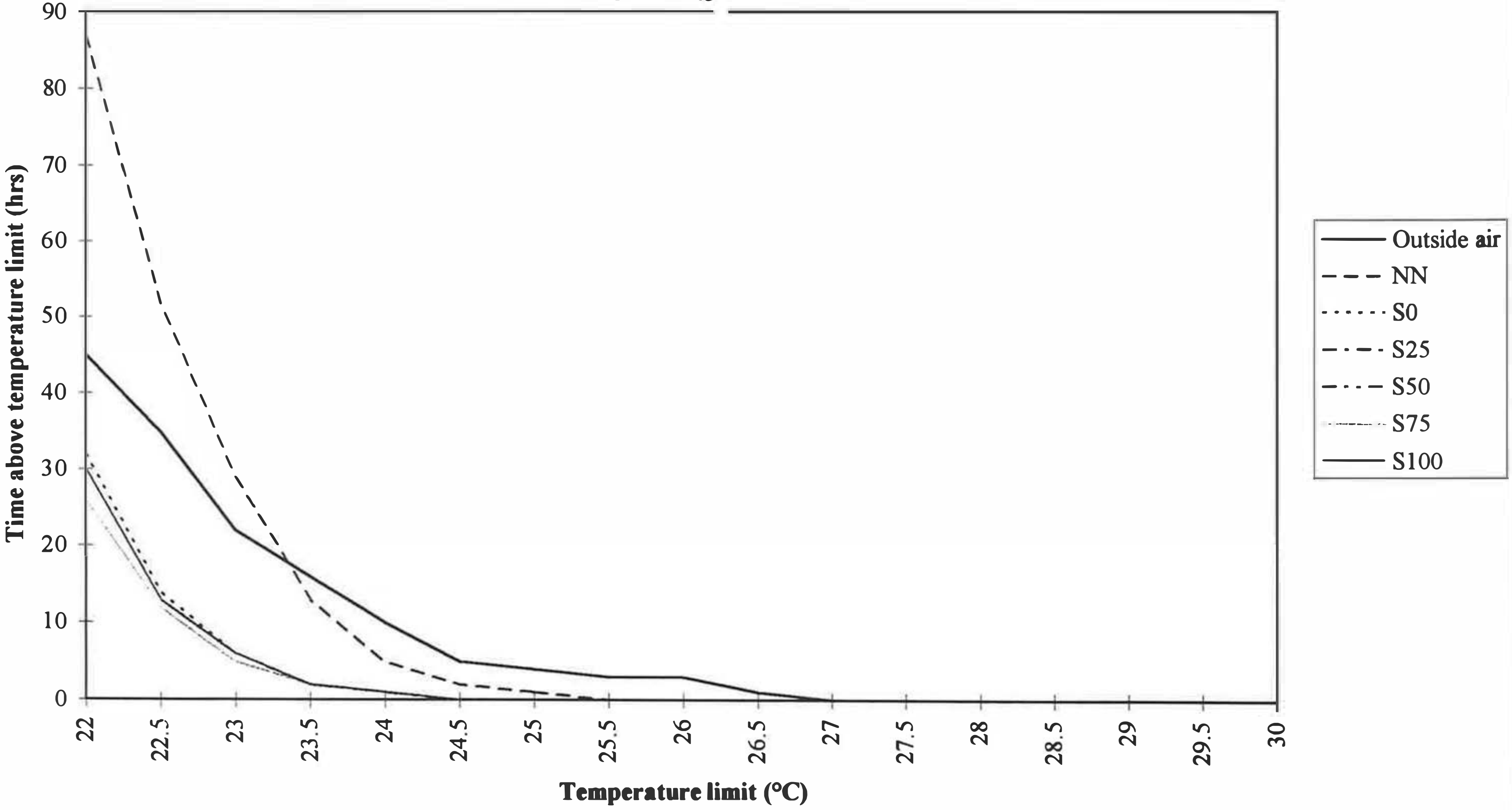


Legend details

NN= No night cooling, D0= Durrington control (sensor depth 0mm), D25= Durrington control (sensor depth 25mm), D50= Durrington control (sensor depth 50mm), D75= Durrington control (sensor depth 75mm), D100= Durrington control (sensor depth 100mm)

"SLAB CONTROL" SENSOR DEPTH TEST- TYPICAL SUMMER

Figure A3.3

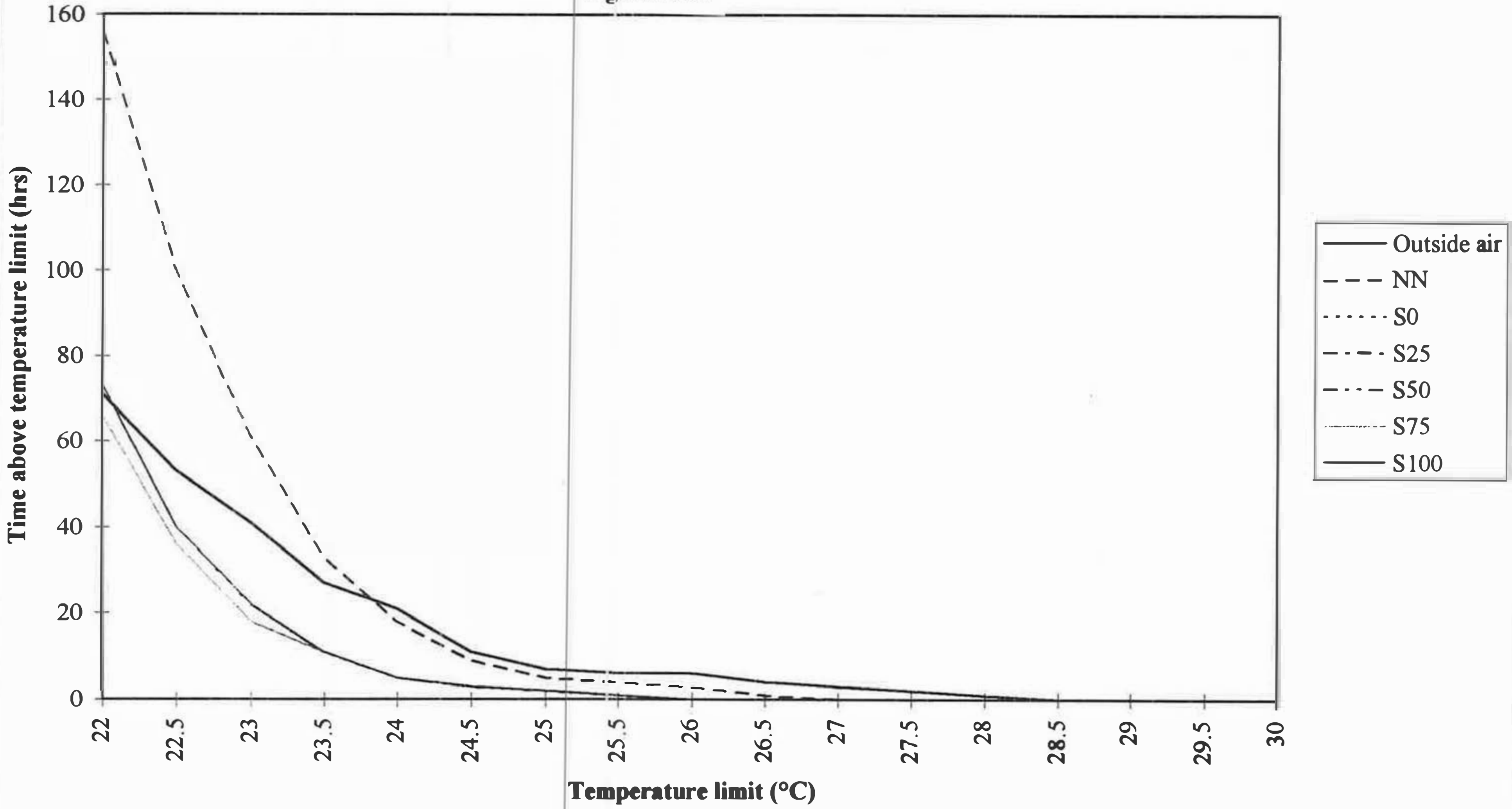


<u>Legend details</u>

NN= No night cooling, S0= Slab control (sensor depth 0mm), S25= Slab control (sensor depth 25mm),
S50= Slab control (sensor depth 50mm), S75= Slab control (sensor depth 75mm), S100= Slab control (sensor depth 100mm)

"SLAB" CONTROL SENSOR DEPTH TEST- PEAK SUMMER

Figure A3.4

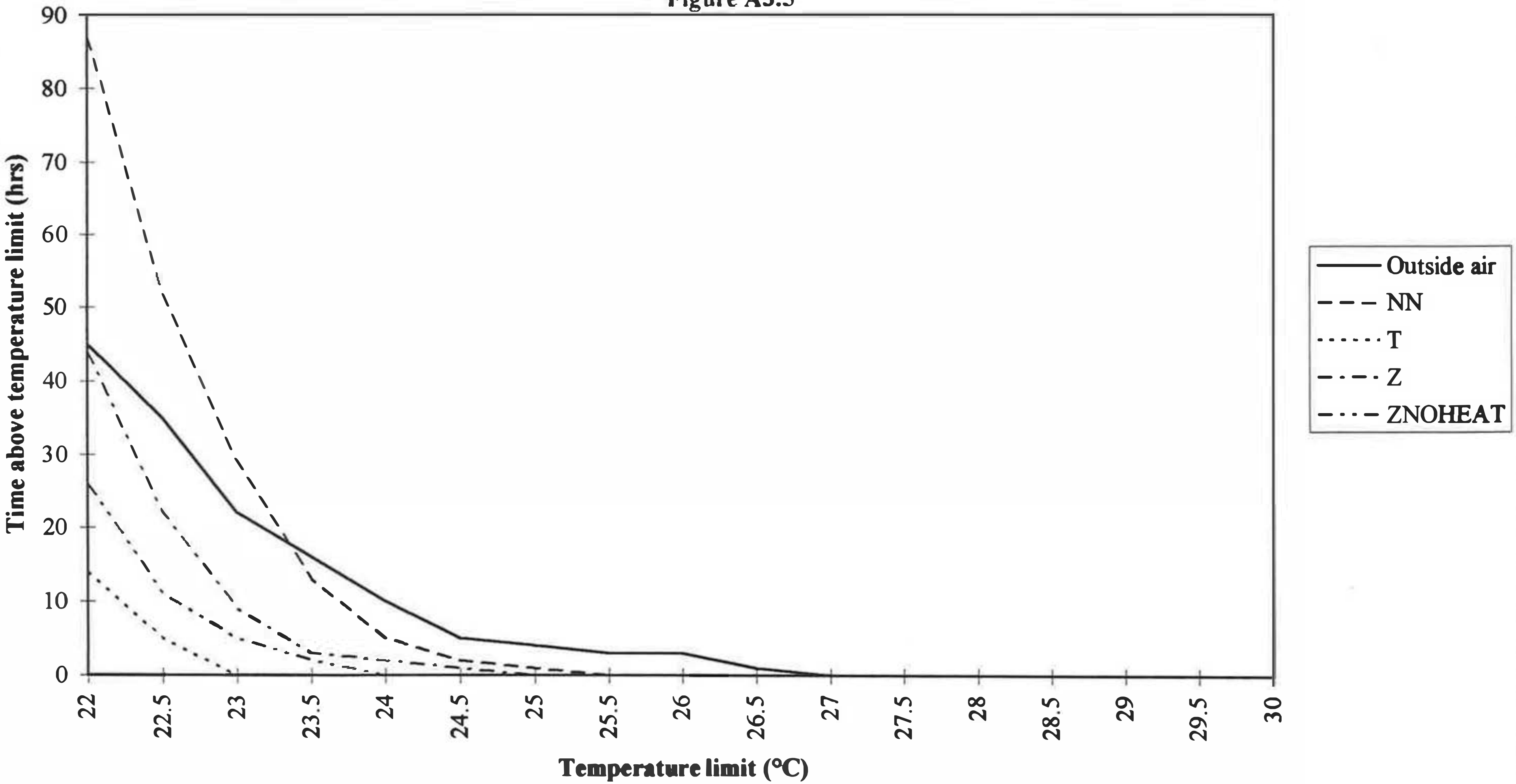


Legend details

NN= No night cooling, S0= Slab control (sensor depth 0mm), S25= Slab control (sensor depth 25mm),
S50= Slab control (sensor depth 50mm), S75= Slab control (sensor depth 75mm), S100= Slab control (sensor depth 100mm)

"ZONE" CONTROL TEST WITH AND WITHOUT MINIMUM ZONE TEMPERATURE- TYPICAL SUMMER

Figure A3.5



Legend details

NN= No night cooling, T= Timeclock control, Z=Zone control, ZNOHEAT= Zone control without a minimum zone temperature setpoint

Table A3.1 Summary data from the special tests

(i) Test of zone temperature control with and without minimum zone temperature setpoint (typical summer only)

Job file	Preheat (MJ)	Heating (MJ)	Fan (MJ)	Night cooling hours
NNTS	3563	12903	1267	0
ZTS	4411	12967	1696	276
ZTSNOHEAT	6241	15265	3525	693

(ii) Test of controls with alternative slab sensor depths

Job file	Preheat (MJ)	Heating (MJ)	Fan (MJ)	Night cooling hours
Durrington				
DPSSD0	4838	12769	7792	615
DPSSD25	4749	12626	7604	589
DPSSD50	4785	12745	7656	597
DPSSD75	4713	12875	7602	602
DPSSD100	4785	12735	7670	603
DTSSD0	5941	15266	7114	636
DTSSD25	5903	15238	7032	629
DTSSD50	5887	15019	6940	614
DTSSD75	5827	15522	6992	627
DTSSD100	5902	15198	7066	625
Slab control				
SPSSD0	5224	12235	8092	730
SPSSD25	5314	12398	8304	749
SPSSD50	5369	12623	8640	762
SPSSD75	5317	12793	8446	766
SPSSD100	5398	12791	8578	770
STSSD0	5910	13413	6156	603
STSSD25	6048	13588	6418	627
STSSD50	6117	13740	6570	641
STSSD75	6072	14069	6582	647
STSSD100	6156	13821	6660	650

Floor area = $529m^2$

Key to table

Control type	Weather data	Test condition
D - Durrington S - Slab NN - No night cooling Z - Zone T - Timeclock (18.00 - 7.00)	PS - Peak Summer TS - Typical Summer	SD0 - Slab sensor depth 0mm SD25 - Slab sensor depth 25mm SD50 - Slab sensor depth 50mm SD75 - Slab sensor depth 75mm SD100 - Slab sensor depth 100mm NOHEAT - No minimum zone night cooling setpoint

e.g. DPSSD0 - Durrington control, peak summer, slab sensor depth 0mm.

APPENDIX A4

RESULTS OF MAIN TESTS

No. of pages: 13

CONTROL STRATEGY COMPARISON- TYPICAL SUMMER

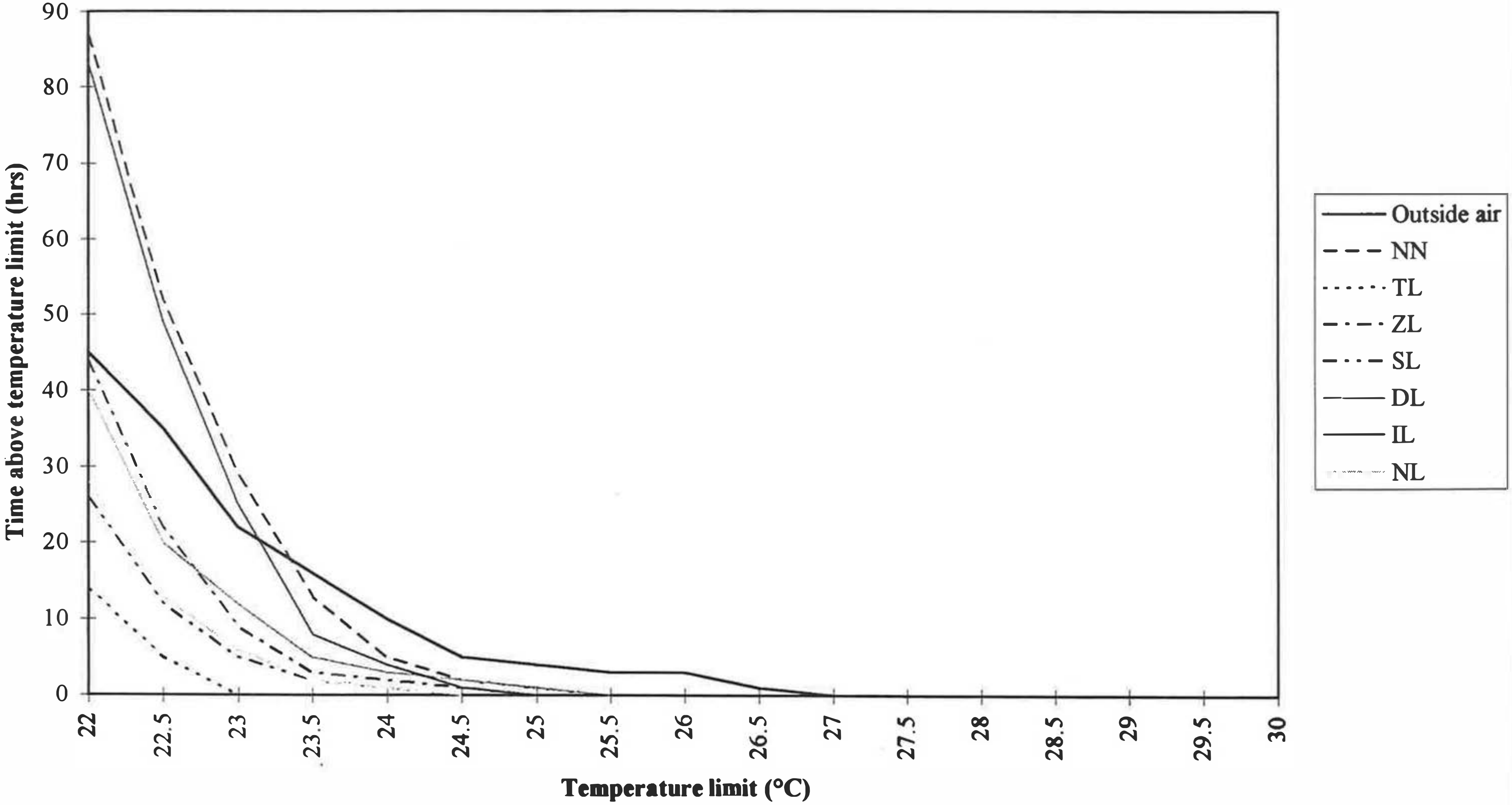


Figure A4.1

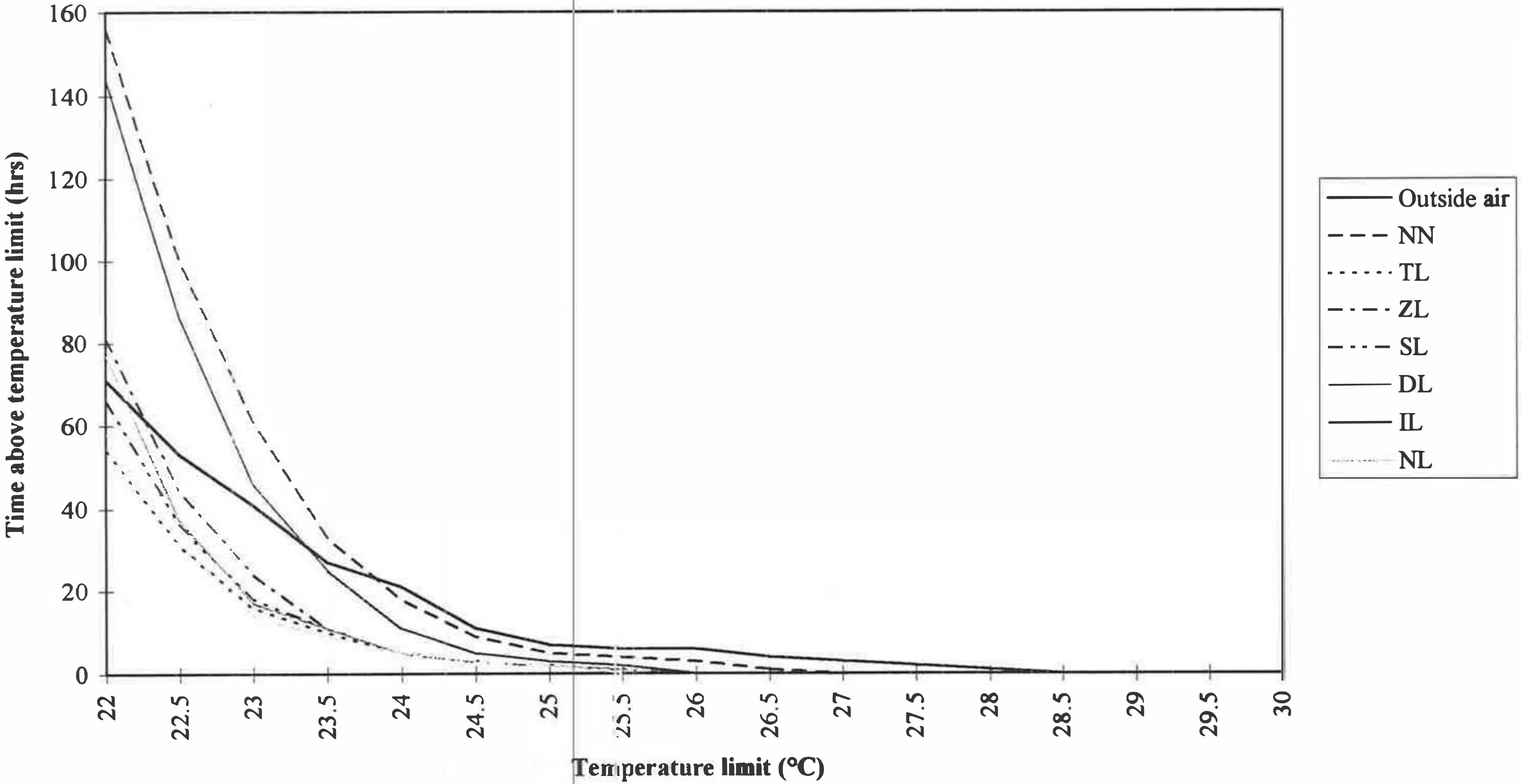
Legend details

NN= No night cooling, TL= Timeclock control, ZL= Zone control, SL= Slab control, DL= Durrington control, IL= Ionica Control, NL= Nottingham control

Note- L refers to a mechanical night cooling rate of 4 ac/h

CONTROL STRATEGY COMPARISON- PEAK SUMMER

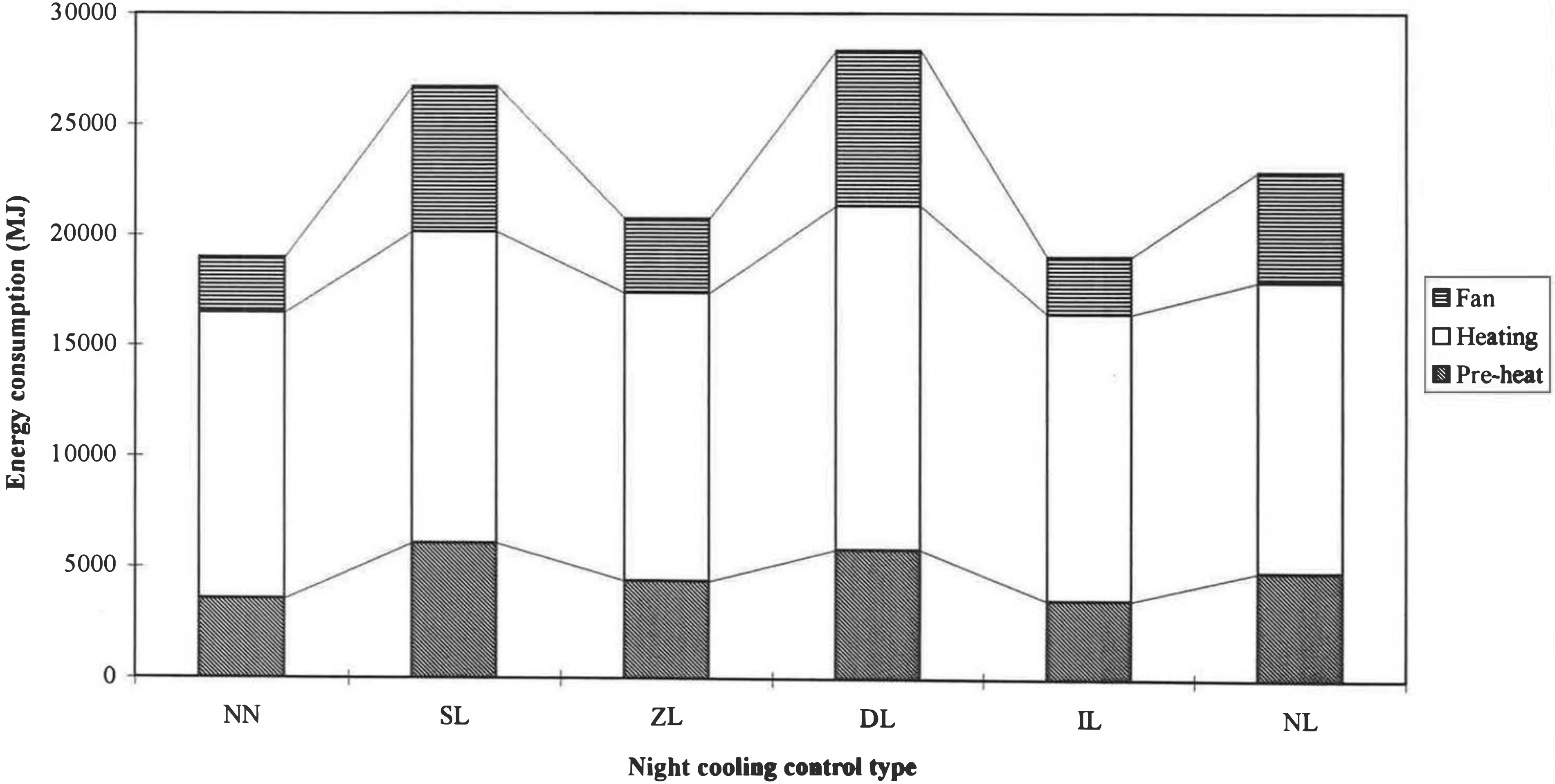
Figure A4.2



Legend details
NN= No night cooling, TL= Timeclock control, ZL= Zone control, SL= Slab control, DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

COMPARISON OF ENERGY CONSUMPTION- TYPICAL SUMMER

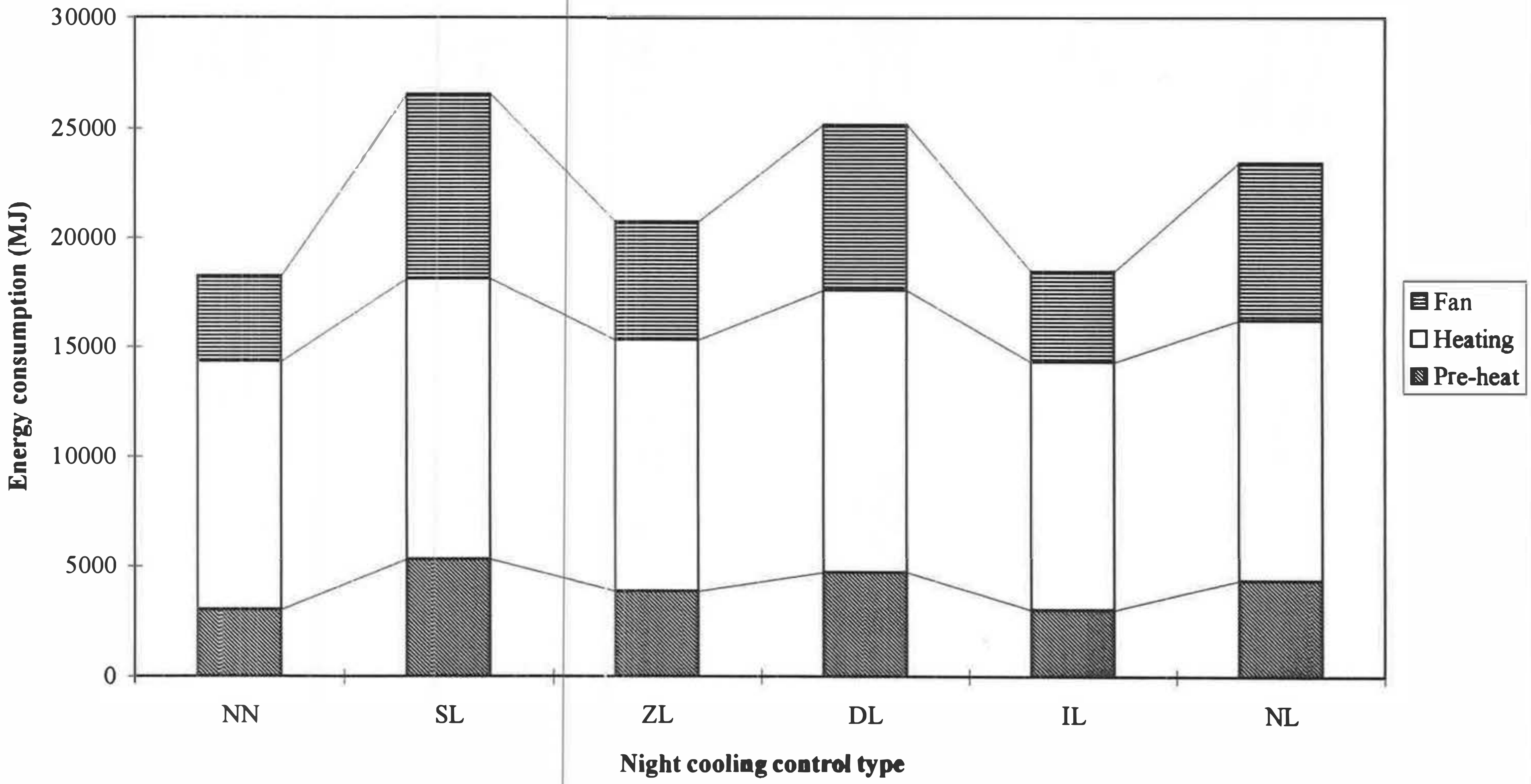
Figure A4.3



<u>Legend details</u>
NN= No night cooling, ZL= Zone control, SL= Slab control,
DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

COMPARISON OF ENERGY CONSUMPTION- PEAK SUMMER

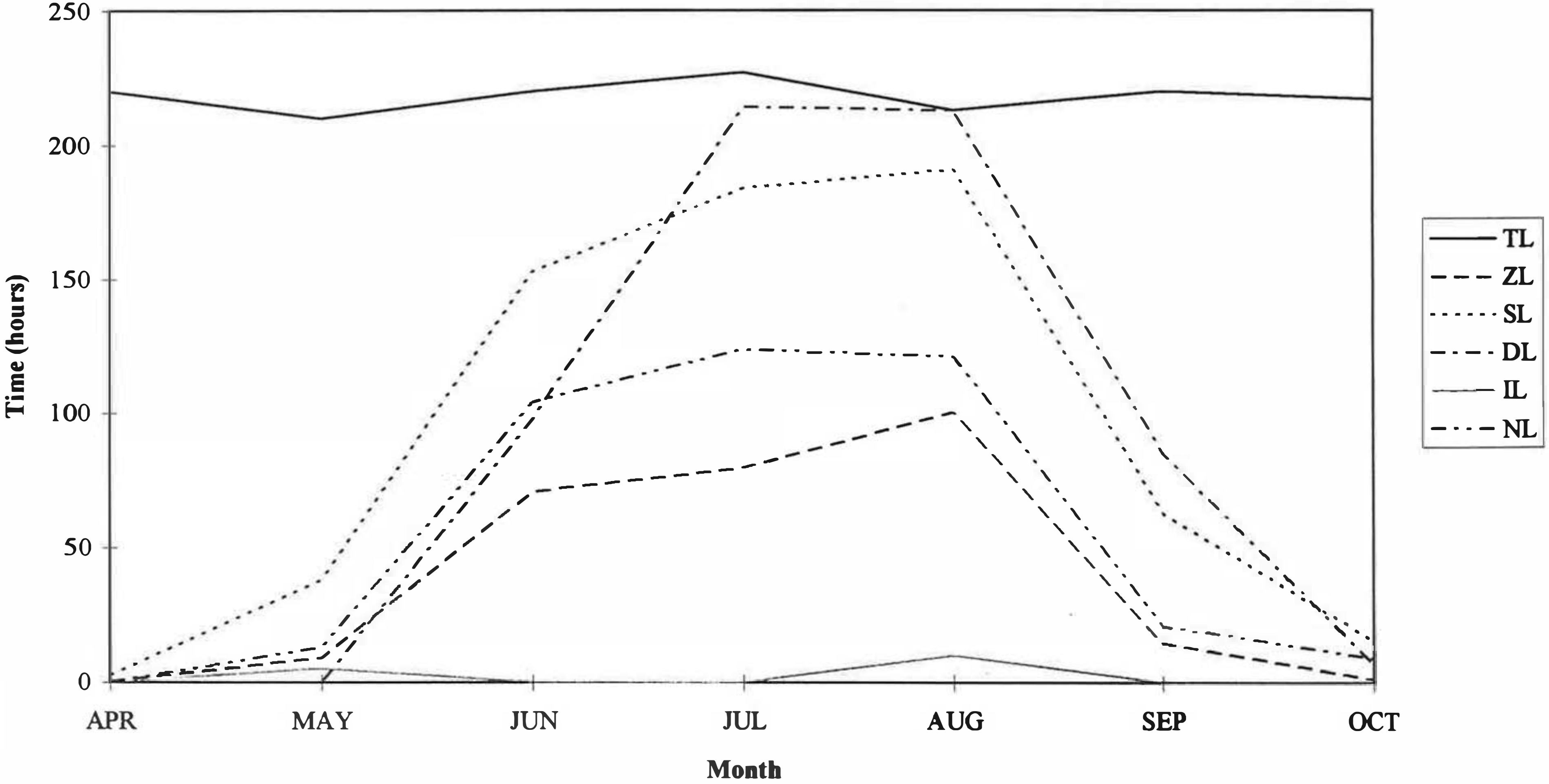
Figure A4.4



__Legend details__
NN= No night cooling, ZL= Zone control, SL= Slab control,
DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

COMPARISON OF NIGHT COOLING HOURS- TYPICAL SUMMER

Figure A4.5

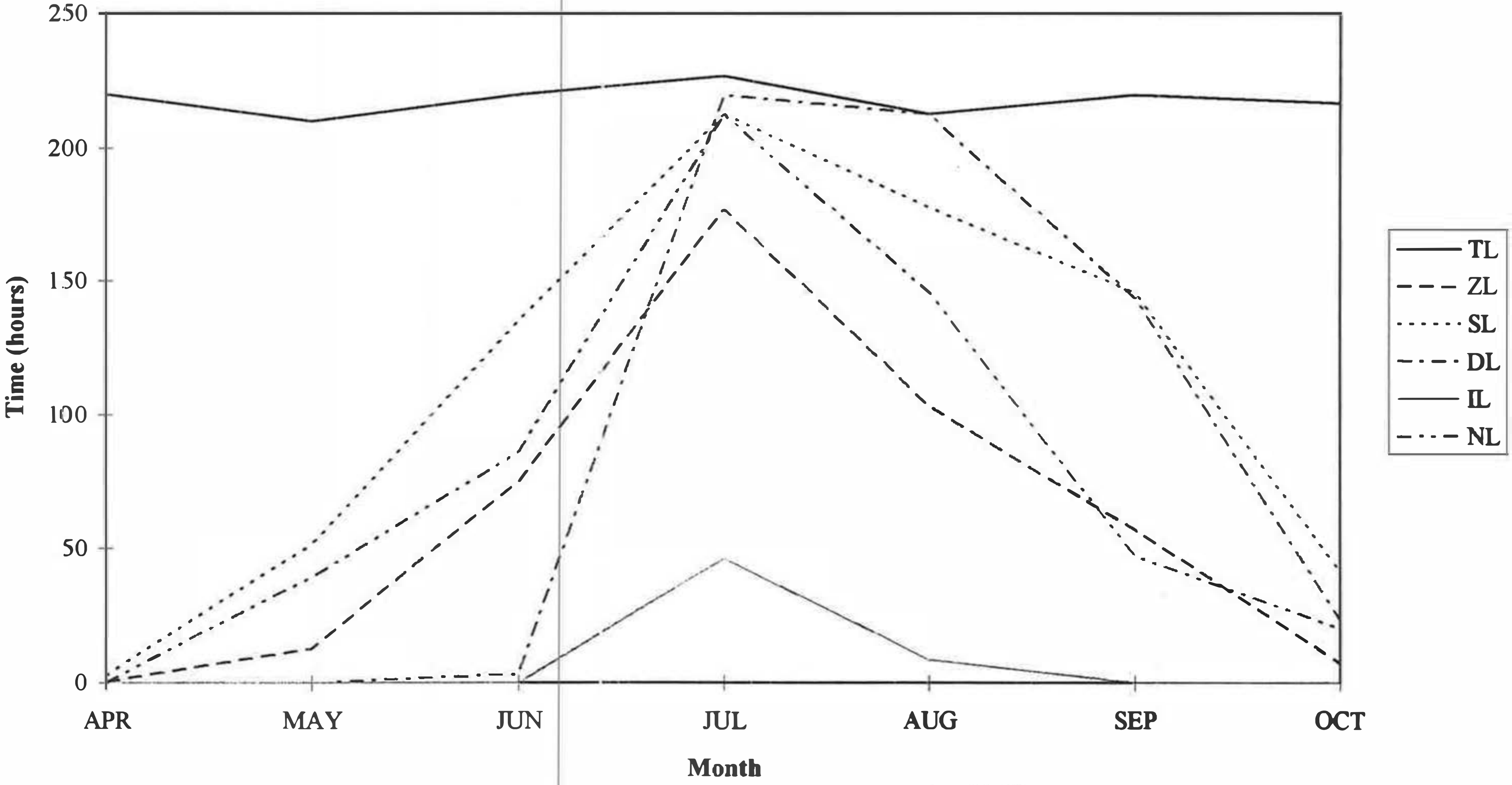


Legend details

TL= Timeclock control, ZL= Zone control, SL= Slab control,
DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

COMPARISON OF NIGHT COOLING HOURS- PEAK SUMMER

Figure A4.6

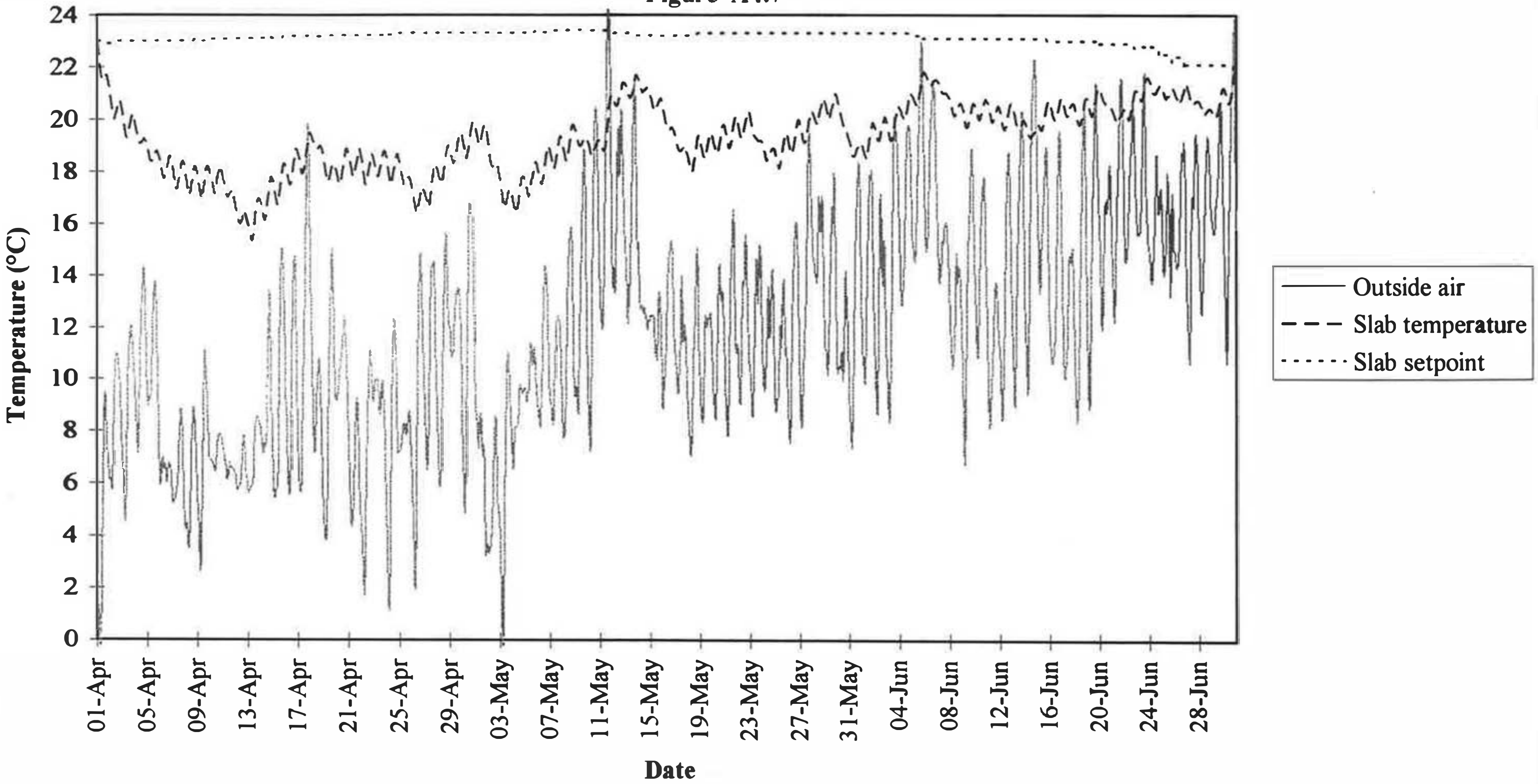


Legend details

TL= Timeclock control, ZL= Zone control, SL= Slab control,
DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

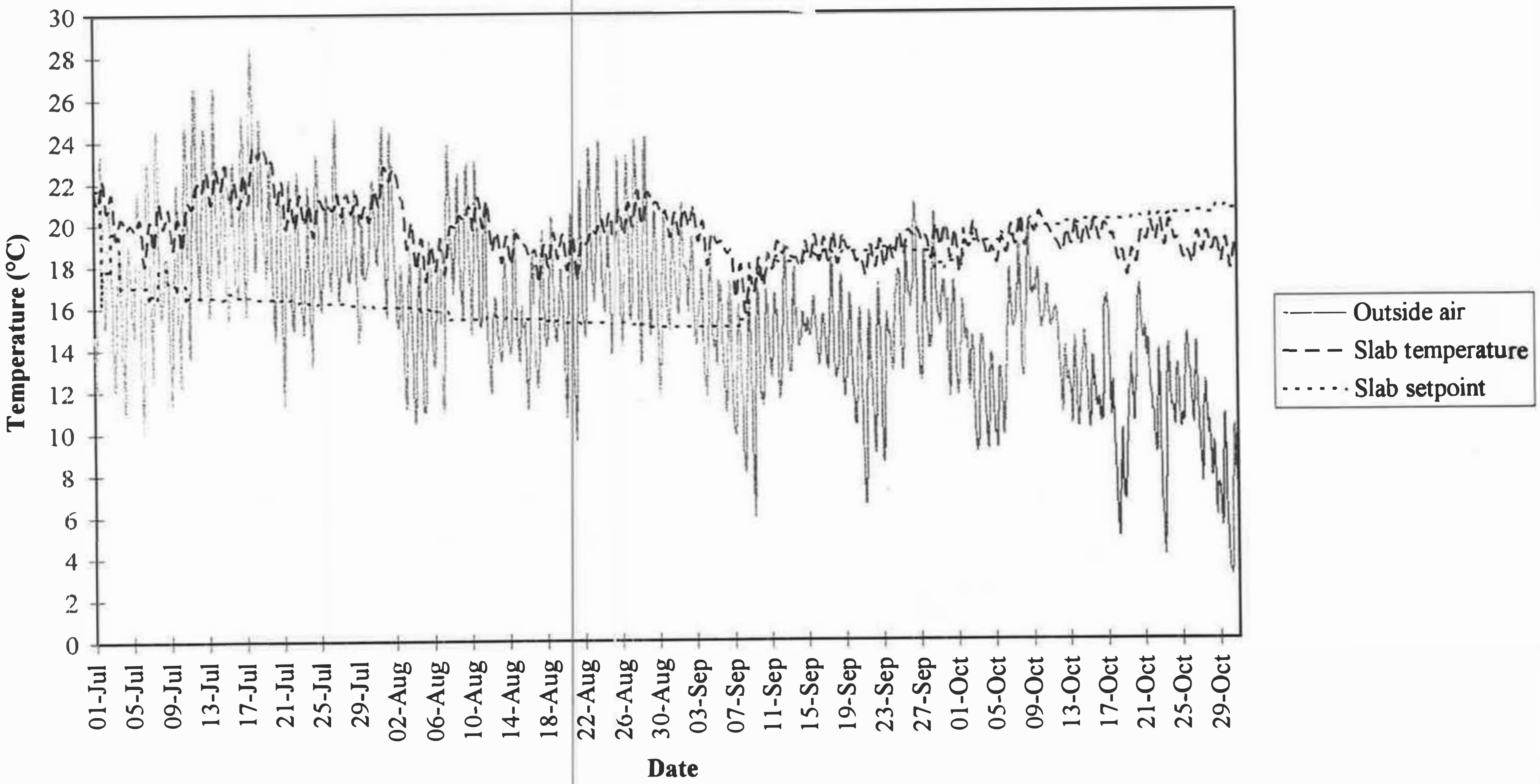
COMPARISON OF SLAB TEMPERATURE AND SLAB SETPOINT - PEAK SUMMER (APR-JUN)

Figure A4.7



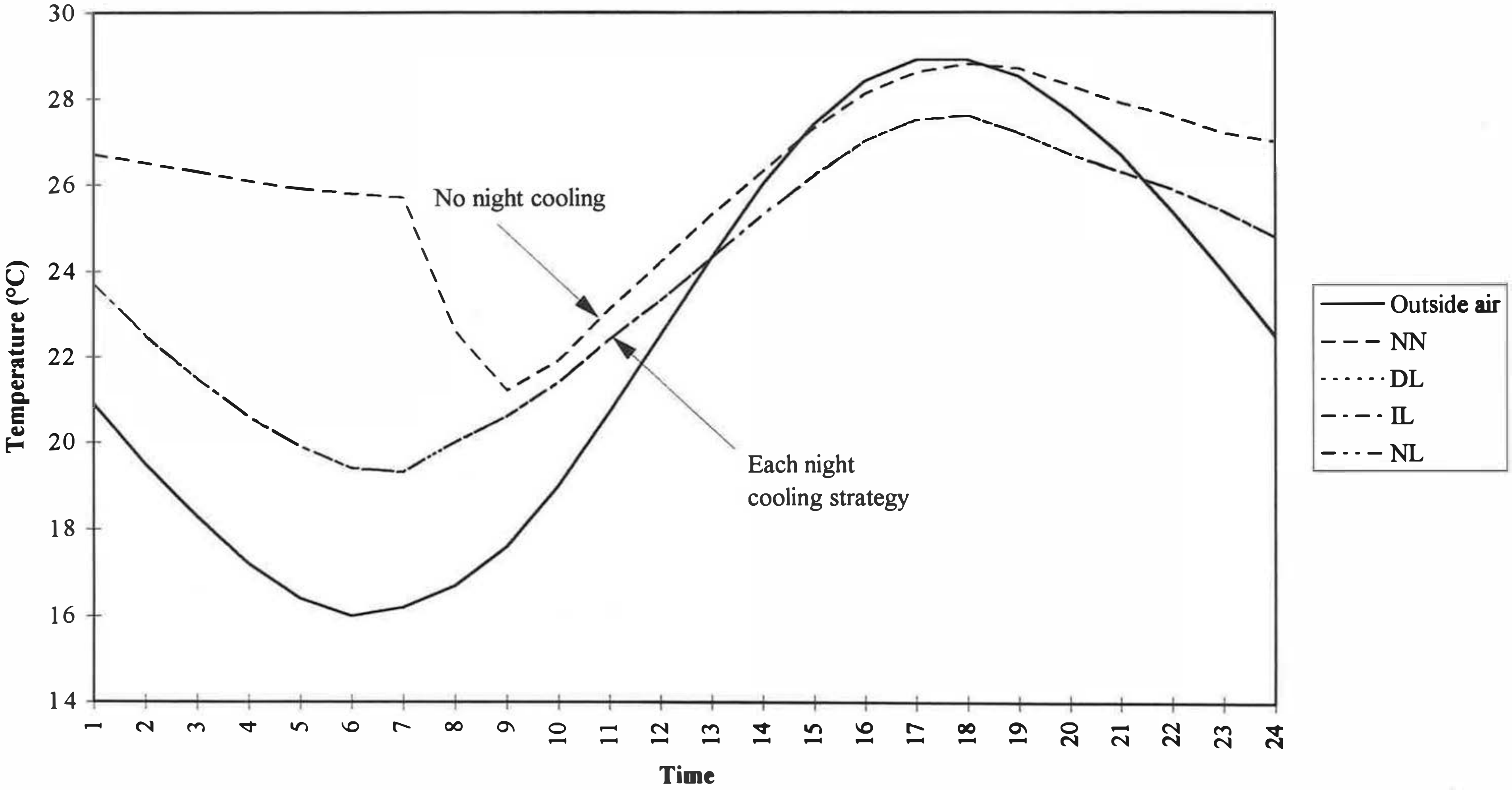
COMPARISON OF SLAB TEMPERATURE AND SLAB SETPOINT - PEAK SUMMER (JUL-OCT)

Figure A4.8



COMPARISON OF ZONE TEMPERATURE- PEAK DAY

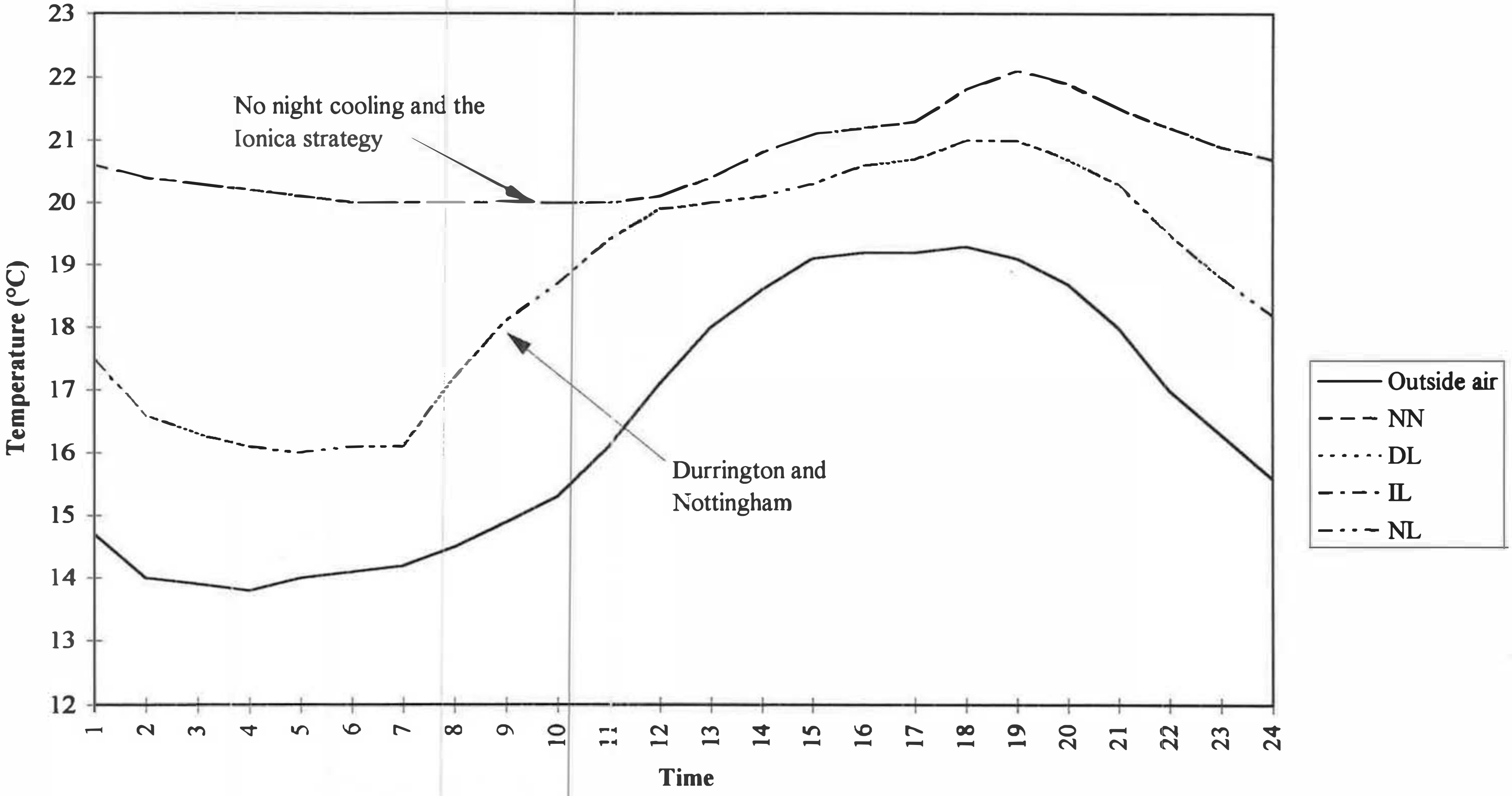
Figure A4.9



<u>Legend details</u>
NN= No night cooling, DL= Durrington control, IL= Ionica Control, NL= Nottingham control
Note- L refers to a mechanical night cooling rate of 4 ac/h

COMPARISON OF ZONE TEMPERATURE- TYPICAL DAY

Figure A4.10



<u>Legend details</u>

NN= No night cooling, DL= Durrington control, IL= Ionica Control, NL= Nottingham control

Note- L refers to a mechanical night cooling rate of 4 ac/h

Table A4.1 Summary data from the main tests

Job file	Preheat (MJ)	Heating (MJ)	Fan (MJ)	Night cooling hours
No night cooling				
NNPD	0	0	119	0
NNTD	0	0	11.6	0
NNSD	36.6	52.1	5.4	0
NNTS	3563	12903	2534	0
NNPS	3016	11294	3938	0
Timeclock				
TPDL	0	0	204	10
TPDH	0.8	0	532	10
TTDL	33.9	0	119	10
TTDH	36.9	0	467	10
TSDL	39.6	553.8	155	10
TSDH	39.6	590.7	483	10
TPSL	6536	42240	22684	1526
TPSH	6764	45989	72924	1526
TTSL	7198	50546	21944	1516
TTSH	7393	54945	71968	1516
Zone				
ZPDL	0	0	169	10
ZPDH	0.7	0	397	9.7
ZTDL	11	0	20	4.5
ZTDH	11.3	0	46	4.0
ZSDL	36.6	52.1	5	0
ZSDH	36.6	52.1	5	0
ZPSL	3851	11455	5448	433
ZPSH	3875	11456	10370	390
ZTSL	4411	12967	3392	276
ZTSH	4429	12969	5578	243
Slab				
SPDL	0	0	169	9.9
SPDH	0.7	0	397	9.7
STDL	33.3	0	83	10
STDH	36.3	0	312	10
SSDL	36.6	52.1	5	0
SSDH	36.6	52.1	5	0
SPSL	5317	12793	8446	1040
SPSH	5574	13035	23210	756
STSL	6072	14069	6582	647
STSH	6250	14100	18764	631

Job file	Preheat (MJ)	Heating (MJ)	Fan (MJ)	Night cooling hours
Durrington				
DPDL	0	0	169	10
DPDH	0.7	0	397	10
DTDL	33.3	0	83	10
DTDH	36.3	0	312	10
DSDL	36.6	52.1	5	0
DSDH	36.6	52.1	5	0
DPSL	4713	12875	7602	602
DPSH	4824	13099	19962	584
DTSL	5827	15522	6992	627
DTSH	5923	15570	19520	604
Nottingham				
NPDL	0	0	169	10
NPDH	0.7	0	397	97
NTDL	33.3	0	83	10
NTDH	36.3	56.2	312	10
NSDL	36.6	52.1	5	0
NSDH	36.6	52.1	5	0
NPSL	4356	11874	7236	550
NPSH	4586	12018	19286	550
NTSL	4863	13050	4980	392
NTSH	5046	13219	13352	392
Ionica				
IPDL	0	0	169	10
IPDH	0.7	0	397	9.7
ITDL	0	0	12	0
ITDH	0	0	12	0
ISDL	36.6	52.1	5	0
ISDH	36.6	52.1	5	0
IPSL	3010	11295	4180	54
IPSH	3016	11294	5190	50
ITSL	3580	12903	2584	15
ITSH	3575	12903	2832	14

Floor area = 529m²

Key to table

Control type	Weather data	Mechanical night cooling rate
NN - No night cooling T - Timeclock (21.00 - 07.00) Z - Zone temperature S - Slab temperature D - Durrington I - Ionica N - Nottingham	PD - Peak summer day TD - Typical summer day SD - Typical spring day PS - Peak summer (April - Oct) TS - Typical summer (April - Oct)	L - Low (4 ac/h) H - High (10 ac/h)

e.g. NPDL was Nottingham night cooling control with the peak summer day weather data and the low speed ventilation rate for the mechanical part of night cooling.