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THERMAL PERFORMANCE OF AN ENERGY EFFICIENT HOUSE IN A DRY TEMPERATE CLIMATE

Elizabeth Karol and Terrance McMinn

Summary of

Actions Towards Sustainable Outcomes

Environmental Issues/Principal Impacts

- Energy used for space heating and cooling in homes creates high levels of greenhouse gases.
- The cost of this energy creates a financial burden for home occupants.
- In a dry temperate climate such as that in Perth, both of these negative impacts can be greatly reduced with negligible impost on building cost or lifestyle through the use of simple climatically sensitive and user friendly designs.
- Passive designed buildings exemplify the importance of occupant involvement in maintaining indoor thermal comfort.
- Town planning decisions can have an important impact on energy efficient design, particularly solar access to windows, and solar collectors.

Basic Strategies

In many design situations, boundaries and constraints limit the application of cutting EDGe actions. In these circumstances, designers should at least consider the following:

- Minimise the need for space heating and cooling through passive solar design.
- Consider the importance of providing 'driving instructions' for occupants to enable them to understand the passive solar design strategies of the building, and therefore maximise building performance.
- Use computer modelling to carry out thermal simulation of the house at design stage.

Cutting EDGe Strategies

- At design stage use an integrated approach to maximise thermal performance.
- Ensure occupants are well informed about passive solar design features.
- Monitor the thermal performance of completed and occupied buildings, to provide an educational tool for designers and confirm the thermal comfort of occupants.

Synergies and References

- *BEDP Environment Design Guide:*
  GEN 12: Residential Passive Solar Design, by Gareth Cole
  DES 4: Thermal Mass in Building Design, by David Baggs and Neal Mortensen
  DES 20: Enhanced Natural Ventilation in Hot Arid Lands, by Emilis Prelgauskas
- Olgyay, V, 1963, Design with Climate, Princeton University Press, New Jersey, USA

BEDP ENVIRONMENT DESIGN GUIDE

THERMAL PERFORMANCE OF AN ENERGY EFFICIENT HOUSE IN A DRY TEMPERATE CLIMATE

Elizabeth Karol and Terrance McMinn

In 2003 a demonstration home was constructed by a local authority in Perth to raise public awareness of practical ways to reduce the energy needs for heating and cooling. The house was sold in 2006 to a couple, who conscientiously try to manage indoor temperatures through passive means. The house was thermally monitored in summer and winter and computer simulated using AccuRate 1.1.4.1, a thermal simulation program. The results of both the simulation and monitoring indicate that in Perth, passive solar design that achieves an AccuRate star rating of around 7 stars can generally enable indoor temperatures to be maintained within comfort conditions if the house is effectively 'driven'.

Keywords

thermal simulation, thermal monitoring, energy efficient design, passive solar design

Figure 1: South elevation (front)
(Source: Author, 2006)

1.0 INTRODUCTION

In Australia post-occupancy thermal monitoring of housing is unlikely to form part of the client-builder project home construction agreement. However simulation of thermal performance of housing increased during the 1990s with the ready availability of validated computer simulation software (Delsante 1995). The incorporation of energy efficiency requirements in Amendment 12 of the Building Code of Australia (ABCB 1996) led to a further increase in the simulation of thermal performance of housing at design stage.

This paper uses a case study, the Subiaco Sustainable Demonstration Home (SSDH), to argue that although simulation of energy efficiency at design stage is a very useful design strategy, a post-occupancy evaluation of thermal performance provides an equally important gauge of potential energy use for thermal comfort.

1.1 BACKGROUND

In 2001 the City of Subiaco, a local authority in Perth, Western Australia, commissioned the design of the SSDH in order to raise awareness of practical

Seasonal climatic averages for Perth

	Mean daily max. DBT (°C)	Mean daily min. DBT (°C)	Mean 9am DBT (°C)	Mean 9am RH (%)	Mean 3pm DBT (°C)	Mean 3pm RH (%)	Mean 3pm wind speed (km/hr)	Mean daily sunshine (hours)
January	29.7	17.9	23.6	50	27.9	41	20.2	10.7
July	17.4	9.0	12.1	81	16.4	59	14.9	5.4

Table 1: Seasonal climatic averages for Perth
(Adapted from: Bureau of Meteorology, 1999)

and innovative measures to reduce the environmental impact of housing. It was acknowledged that the term 'sustainable' in the context of SSDH primarily related to reducing energy consumption for space heating, space cooling and water heating as well as reducing the need for mains water. The house was formally opened to the public in March 2004. Over a two year period approximately 20,000 people visited the SSDH including school groups, professional organisations and the general public. In 2006 the house was sold to a couple who were keen to maximise the thermal benefits of the design through active application of the designers' intent, and were interested in its thermal performance. The architect of the project in consultation with the occupants, decided to monitor indoor temperatures after the house was occupied.

1.2 Details of climate, site and building

Perth has latitude of 31°55'S, longitude of 115°52'E and an elevation of 24.9 metres. The seasonal climatic characteristics of Perth are warm to hot summers with medium to low humidity and cool to mild winters. Table 1 shows the key climatic features for January and July (the months when the SSDH was monitored) based on long term mean values of weather data measured by the Bureau of Meteorology.

The SSDH is a two storey house in the inner Perth suburb of Subiaco. It is on a corner site with an area of 316m². The front elevation, facing south, is shown in Figure 1. The longer sides of the block face east and west. There is a rear laneway on the north side of the site with two-storey houses abutting the northern boundary of the laneway. The height of these adjacent houses is contrary to what had been indicated in the design brief for the SSDH, and these neighbouring houses reduce the winter solar access to the rear outdoor area and ground floor northerly glazing in the SSDH. The location of the carport on the north side of the SSDH was predetermined by the planning authority and also adversely impacts winter solar access to the outdoor area and the indoor living areas at ground floor level.

Figure 2: Upper level living area (north glazing)
Source: (Author 2006)

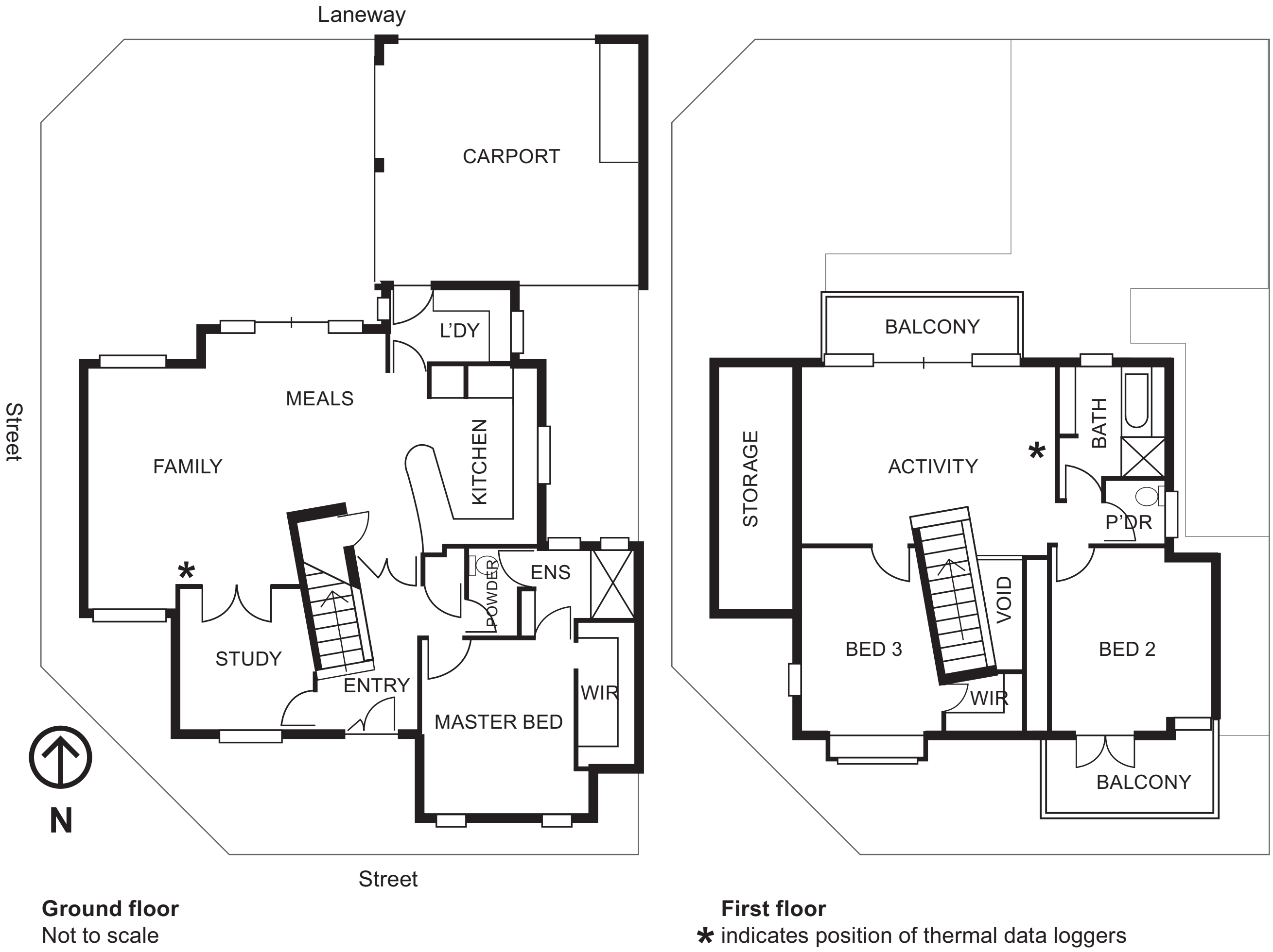

Figure 3: Floor Plans
Source: (Author 2003)

The house has a total occupiable indoor floor area of 221 m² and total area of north facing glazing to living areas of 26m² comprising 11m² at ground floor level and 15m² at first floor level. A significant area of northerly glazing at ground floor level is shaded until midday in winter by either the carport or the neighbouring houses on the north side of the rear lane. All glazing on the north, east and west sides is fully shaded in summer. Aluminium louvres are used to shade first floor glazing while ground floor glazing is shaded with a combination of louvres or shade cloth which is seasonally adjusted.

The construction method was one commonly used in project homes in Perth with a concrete slab on ground, a concrete first floor slab, generally external uninsulated cavity brick walls, internal block walls, single glazing in aluminium frames, plasterboard ceilings with R2.5 insulation and metal deck roofing laid over reflective foil, on a timber framed roof. Floors in north facing habitable rooms are finished in ceramic tiles. Other floors in habitable rooms have an overlay of bamboo floorboards. Internal louvre shutters cover most of the north facing glazing except for the 3.7m² of triangular shaped high level windows at first floor level on the north side, which can be observed in Figure 2. Off-the-shelf fittings and fixtures were used, and features such as automatic window opening and shading devices were excluded on the grounds of cost.

2002 NatHERS 5 out of 5 stars	
heating load	10.9 MJ/m² annum
sensible cooling load	54.8 MJ/m² annum
latent cooling load	8.8 MJ/m² annum
total energy load	74.5 MJ/m²
2008 AccuRate 7.3 out of 10 stars	
heating load	24.4 MJ/m² annum
sensible cooling load	21.7 MJ/m² annum
latent cooling load	3.2 MJ/m² annum
total energy load	49.3 MJ/m² annum

Table 2: Simulated thermal performance

There are three unusual elements in the construction of SSDH, two of which are not visible to the casual observer. The west wall of the ground floor family room is reverse brick veneer and incorporates closed cell foam reflective insulation and R1.5 bulk insulation, and the west cavity brick wall to the study and bedroom 3 has closed cell foam reflective insulation in the cavity. Further, there is a 300mm thick internal insitu wall

	Summer	Winter
Dry Bulb Temperature	36°C max. 18°C max.	19°C min. 9°C min.
Wet Bulb Temperature	24°C max.	9°C min.

Table 3: Design day temperatures for Perth
(Source: Szokolay, 1982)

constituted from rubble (from the demolished former building on the site) and bound with cement to form the stair shaft.

Water is heated via an electrically boosted solar system with one solar panel located on the east facing roof and one panel on the west facing roof. These were originally intended to be located on the north side of the main roof, however they were repositioned when it was realised their planned location on the carport roof was now to be shaded by adjoining buildings, thus requiring photovoltaic panels to be moved from the carport to the main roof.

2.0 METHOD OF EMPIRICAL TESTING

Two simulation tools using engine software developed for Australian climatic conditions by CSIRO, NatHERS Version 2.31 and AccuRate Version 1.1.4.1 were used to simulate the project. The software incorporates 69 weather files based on postcodes and forty year weather patterns around the country. The software engine is used in most Australian computer thermal modelling systems for residential buildings and incorporates nationally agreed criteria of occupational patterns based on studies conducted with project homes (Lee and McKinnon 1996).

NatHERS was the accepted simulation tool in Western Australia at the time the SSDH was being designed (2001) and thus was used at design stage. The house achieved a five-star rating, the highest available on a scale of zero to five. In 2008 an AccuRate simulation was run using version 1.1.4.1 of the software. A rating of 7.3 stars was computed from a possible maximum rating of 10 stars.

The difference in the cooling energy load can be attributed to the improved capacity of AccuRate version 1.1.4.1 to simulate natural ventilation, while the difference in the heating load is the result of the shading of ground floor north facing windows that occurred during construction as mentioned in 1.1 above. The data from the AccuRate simulation is utilised in this paper.

3.0 METHOD OF MONITORING

Both summer and winter conditions were monitored, as variations in Perth's outdoor dry-bulb temperatures frequently exceed the upper limit of comfort in summer and lower limit of comfort in winter. One day in summer and one day in winter were chosen for detailed analysis of the SSDH. The chosen days, referred to as design days in this paper, were days that most closely resembled what Szokolay (1982) refers to as 'design' conditions for Perth.

It is of note that for Perth, the minimum design day winter temperature is almost the same as the mean minimum winter temperature, whereas the maximum design day summer temperature is approximately 6K higher than the mean maximum summer temperature.

Only the dry-bulb air temperatures were regularly monitored in the SSDH. This procedure follows that of a number of other researchers such as Rohles (1969),

	Simulated				Monitored			
	Summer		Winter		Summer		Winter	
	Ground Floor	First Floor	Ground Floor	First Floor	Ground Floor	First Floor	Ground Floor	First Floor
Indoor temperatures (°C)								
Night (11pm–6am)	22.3	22.6	18.5	17.7	25.1	25.0	19.3	17.9
Day (7am–10pm)	25.0	26.2	19.5	20.0	25.5	25.3	20.9	18.6
Maximum	31.1	33.0	22.4	24.4	31.0	33.5	28.1	24.4
Minimum	20.0	19.8	16.9	14.6	21.9	20.5	17.3	14.8
Percentage above 29.9°C (maximum comfort)	0.3%	6.6%	0.0%	0.0%	1.2%	7.5%	0.0%	0.0%
Percentage below 17.1°C (minimum comfort)	0.0%	0.0%	0.2%	13.3%	0.0%	0.0%	0.0%	17.4%
Outdoor temperatures (°C)								
Maximum	40.7		20.7		41.5		23.3	
Minimum	9.8		1.2		11.6		0.3	

Table 4: Summary of key temperatures during 37 day monitoring period

Pryor (1984) and Vale and Vale (2000) who considered that in climates where humidity is not high in summer, dry bulb air temperature was a sufficient indicator of thermal conditions in a house. Climatic data for Perth in summer shows that mean relative humidity in the hottest months in the afternoon is no more than 44 per cent.

Indoor temperature readings were taken at 30 minute intervals. Each data logger was placed at a height above floor level of between 0.9 to 1.5 metres. The height chosen was intended to approximate head height of a seated person as referred to in ISO 7726 (1998). However the exact data logger location depended on the availability of a horizontal surface and on the location being acceptable to the occupant. The data logger was positioned away from direct sunlight or other obvious direct sources of heat or cold.

External air temperatures and relative humidity were obtained from the Bureau of Meteorology suburban monitoring station at Mt Lawley (station number 9225) for the same dates and same times as the indoor air temperatures were logged. The Bureau of Meteorology site is in a suburban area, similar to the Subiaco area, thus unlikely to give rise to pronounced urban heat-island effects. Although it is recognised that the external temperature around the SSDH may vary from that at the Bureau of Meteorology monitoring station, the observations from the monitoring station were used for the purposes of this study, as a weather station was not available to be used on site.

3.1 Data loggers

The stand alone data loggers used were Gemini 'Tinytalk II' automatic data loggers with external sensing probes. The logger is contained in a 35mm photographic film canister and thus can be positioned unobtrusively. They have a sensor range of -40 to +50°C and an accuracy of ±0.2 K, which complies with the requirements of the standard ISO 7726 (1998). A calibration test of the data loggers to ±0.2 K was carried out in summer and winter prior to placing them in the dwelling.

Data from two logger positions in the SSDH are discussed in this paper. One position was in the ground floor family/meals area and the other position was in the first floor activity area. The positions are highlighted thus '*' in Figure 3.

3.2 Driving the SSDH

Written 'driving' instructions were provided to the purchasers of the house. These instructions advised when to open/close particular windows and blinds, when to open/close particular doors and when to install and remove shade cloth. The monitored results summarised in Table 2, show that the occupants were 'driving' those parts of the SSDH that they used regularly, although there are no detailed records of how closely the occupants followed the 'driving' instructions. Anecdotally, in winter the focus was on passive solar heating. The occupants opened and closed the northerly shutters at ground floor family/meals area at appropriate times and closed the doors surrounding

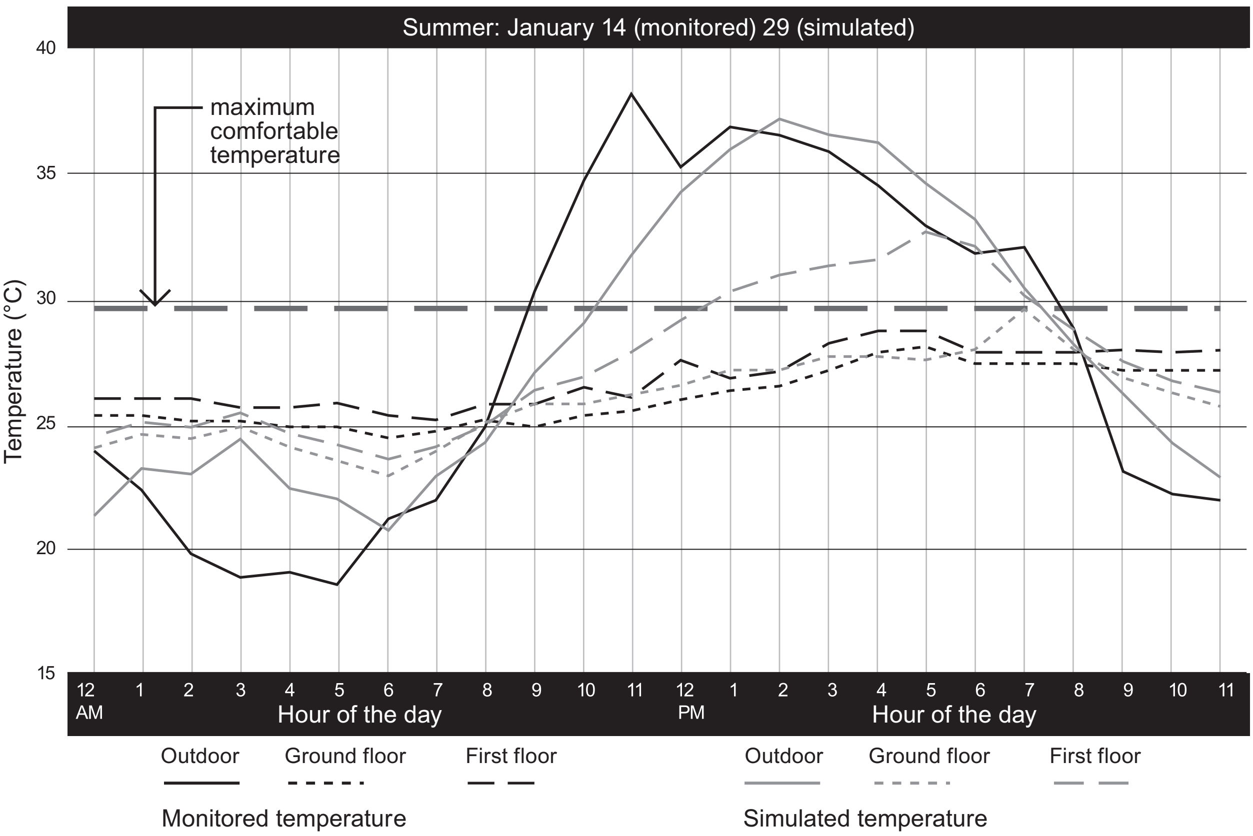

Figure 4: Monitored and simulated summer temperatures on design days

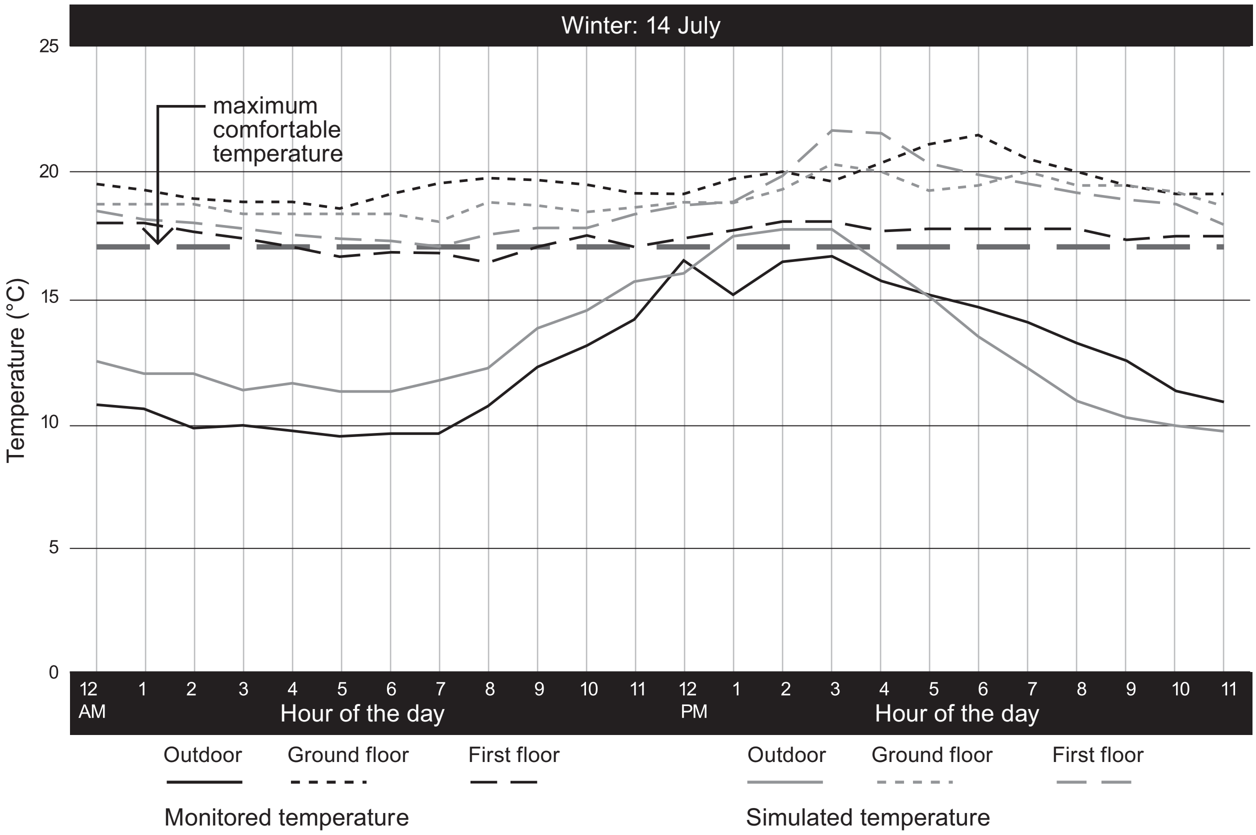

Figure 5: Monitored and simulated winter temperatures on design days

the ground floor family/meals area during the day. However, at first floor level, the northerly shutters were not always opened on winter days. The occupants sporadically used a portable electric radiator (2.4kW) in the ground floor family/meals area when relaxing in the evening although the heater was primarily for their old dog. An examination of the winter electricity bills confirms the minimal use of electric heating.

In summer the focus was on limiting heat absorption into the indoor thermal mass and removing this stored heat when external temperatures were deemed to be lower than internal temperatures. To maintain thermal comfort the northerly shutters were closed during hot days to reduce heat gain via conduction through glazing. The occupants also opened windows at night when it was cooler outside than inside. However windows at ground floor level were left open a minimal width of 100mm to maintain security overnight, whereas a much larger area of first floor windows were left open when it was cooler outside than inside.

3.3 Comfort conditions

Humphreys and Nicol (2000) suggest that, although the range of indoor temperatures considered comfortable is affected by the characteristics of a particular building and the opportunities provided to occupants to adjust to the thermal conditions, in a non air-conditioned building the optimum comfort temperature (Tc) depends on mean outdoor temperature (To). There is much evidence to show that a wider range of temperature fluctuations is acceptable to occupants of non air-conditioned buildings, compared to that for air-conditioned buildings. Humphreys and Nicol suggest that Equation 1 below is an appropriate means of determining the optimum comfort temperature:

$$Tc = 13.5 + 0.54To$$

Where:

Tc	optimum comfort temperature
To	mean outdoor temperature

Equation 1 for optimum comfort temperature

Using Equation 1, Tc = 26.4°C in summer and Tc = 20.6°C in winter in Perth. To determine the maximum and minimum acceptable temperatures, it was necessary to establish an acceptable temperature range around the optimum comfort temperature. This range can be taken as Tc ±3.5°C for 80 per cent acceptability, or Tc ±2.5°C for 90 per cent acceptability (Auliciems and Szokolay 1997). Humphreys and Nicol (2000) suggest the width of the comfort zone is determined by the opportunities available to building occupants to change their clothes, levels of activity and air movement. In private housing in general, occupants do have the opportunity to change their clothes, levels of activity and rate of air movement, thus in this analysis the wider range is adopted. Consequently a maximum temperature of 29.9°C in summer and a minimum temperature of 17.1°C in winter can be considered acceptable in Perth.

However researchers such as Givoni (1998) and Wooley (1999) suggest that air movement created by a fan can raise the limit of thermal comfort in non air-conditioned buildings in hot dry climates. Wooley (1999) states that an air speed of 1 m/s will have a cooling effect of approximately 3K, provided the indoor air temperature does not exceed 33°C. As ceiling fans have been installed in all habitable rooms of the SSDH, a maximum summer temperature of 33°C may be considered acceptable on extremely hot days.

4.0 RESULTS AND DISCUSSION

Although the simulated weather data is based on long-term average temperatures and the actual weather data was averaged one hourly data available from the Bureau of Meteorology, for outdoor temperatures over the specific 37 day periods, the maximum and minimum temperatures were similar. It is of note that the period of monitoring included days of extreme temperatures in both summer and winter. It should be noted that the actual weather data was not inserted into AccuRate as insolation data was not available from the Bureau of Meteorology.

AccuRate can be used to generate indoor temperatures, or a star rating. Table 2 summarises average and extreme temperature data based on simulated temperatures using AccuRate V 1.1.4.1 in non-rating mode and indoor monitored temperatures at the SSDH on 37 consecutive days in both summer (31 December–6 February) and winter (8 July–14 August). The averages for the monitored data were computed using averages of all half-hourly data monitored indoors over the 37 days.

In the ground floor family/meals area the temperature in the monitored summer period is above the still air maximum comfort temperature 1.2 per cent of the time and the minimum temperature in winter is always above the minimum comfort temperature. In the first floor activity area the summer temperature exceeds the still air maximum comfort temperature 7.5 per cent of the time and is below the minimum winter comfort temperature of 17.1°C for 17.4 per cent of the time.

Higher than expected monitored temperatures in summer may be explained by considering the security concerns of the occupants. Although the SSDH was designed with the potential for excellent cross ventilation in all habitable rooms, at night the occupants only opened ground floor windows to a width of 100mm rather than fully open. This limits the amount of cross-ventilation available overnight when cooler external air is relied upon to cool the thermal mass of the interior. Efficient night-time cross ventilation is critical in providing low early morning baseline temperatures. In Figure 4 it can be seen that a relatively slow decrease in internal temperatures occurs compared to the outside temperatures in the early morning period.

First floor windows were left open with greater confidence than windows at ground floor level. The simulated results do not take into account the fact that operable windows may not be opened when outdoor temperatures are lower than indoor temperatures in summer.

In winter the first floor activity area minimum temperatures in both the simulated and monitored situations are below the acceptable temperature despite the availability of high levels of solar gain. This can be attributed, in the monitored case, to closed shutters blocking solar access through 11.3m² of northerly glazing and the high levels of heat loss at night through the 3.7 m² of triangular high level glazing in front of the raised ceiling coffer that can be seen in Figure 2. This high level glazing does not have internal shutters due to its awkward triangular shape, as does the remainder of the northerly windows.

In addition to the above mentioned factors, temperature volatility in the first floor activity area is greater than in the ground floor family/meals area. This is partly due to a lower ratio of thermal mass to glass area in the first floor activity area (ratio of 4.7:1 compared to 9.0:1 at ground floor family/meals area) and partly due to the connection between the first floor activity area and the stairwell creating greater air stratification.

4.1 Design day summer performance

Figure 4 shows outdoor and indoor temperatures on the summer design day together with the preceding 12 hour temperatures. Temperature patterns were examined on January design days that were chosen from the simulated data (January 29 shown as 'outdoor*') and from the monitored data (January 14 shown as 'outdoor'). Minimum indoor summer temperatures in both the monitored and the simulated case regularly occurred at approximately 6am, approximately one hour after minimum outdoor temperatures.

The maximum monitored temperature of 28.7°C was reached on the summer design day in the late afternoon between 4pm and 5pm, approximately five hours after the maximum outdoor temperature was reached. The temperature shows a gradual rise from 6am to 5pm and a maximum range of 3.6K. The outdoor temperature range was 19.6K.

The temperature pattern of the design day in the simulation was the closest in temperature pattern to the actual outdoor temperature on the monitored day. The simulated results for the ground floor family/meals area show a temperature range of 6.1K. This may reflect the assumed occupation patterns where additional internal sensible and latent heat gains occur at evening meal time (Lee and McKinnon 1996) and may also be partly due to assumed use of all available window openings for greater night cooling. The simulated temperature pattern in the first floor activity area has a maximum range of 9.1K.

4.2 Design day winter performance

Figure 5 shows outdoor and indoor temperatures on the winter design day together with the preceding 12 hour temperatures. The simulated and the monitored climatic data included a typical design day, 14 July, as shown in Figure 5. It is clear from Table 2 that the maximum monitored winter indoor temperature of 28.1°C reflects the use of space heating in the ground floor family/meals area. This very high temperature was the result of a one off event when the occupants used the electric heater for an extended period in the ground floor family/meals area to warm their old dog. Generally the occupants had found it necessary to only occasionally use their heater. This heater use can be clearly seen in Figure 5 in the ground floor family/meals area when temperatures rise by approximately 1.5K between 6am and 8am and again between 4pm and 6pm.

It can also be observed in Figure 5 that the monitored and simulated temperatures in the ground floor family/meals area are very similar. The difference between the maximum and minimum monitored temperatures is 3.1K and the difference between the maximum and minimum simulated temperatures is 2.2K. A factor contributing to this high level of thermal stability in the ground floor family/meals area is the high ratio of thermal mass area to area of glass being 9.0:1.

Surprisingly the monitored temperatures in the first floor activity area are lower than in the ground floor family/meals area during the day time. This difference can be attributed, at least in part, to the closed window shutters over the northern windows (except for 3.7 m² of triangular window) as the occupants did not regularly go up to the first floor activity area to open and close the shutters. Thus the temperature falls below the minimum acceptable temperature of 17.1°C in the first floor activity area 17.4 per cent of the time.

3.0 CONCLUSION

Monitoring of the SSDH when occupied by residents who were keen to maximise the thermal benefits of the design, shows that the indoor temperatures were, on the ground floor, nearly always within the acceptable temperature range, and on the first floor, more than 80 per cent of the time within the acceptable temperature range. Using the AccuRate v 1.1.4.1 simulation software the SSDH achieved a star rating of 7.3 and, on typical design days, performed in a manner similar to the monitored results.

In order to improve the thermal performance of the SSDH, design modifications are required and occupant behaviour would need to be modified. The design modifications would be additional solar collection in the ground floor family/meals area to compensate for the unexpected overshadowing by neighbouring properties, reduction of thermal transmission through the 3.7 m² of triangular shaped high level window on the north side of the first floor activity area and the inclusion of security screens at operable windows. In addition to the current 'driving' being done by the occupants, the occupants would need to open upstairs northerly shutters on winter days and fully open windows on summer nights to make use of the excellent cross ventilation opportunities at SSDH. Alternatively if occupants could afford automation of the window and shutter operation, the house performance could be maximised, however this project was deliberately designed with the affordable project home market in mind.

Some guidance can be drawn from this demonstration house in relation to practical ways to reduce energy needs for mechanical space heating and cooling. Firstly an effective design strategy for climatically sensitive and user friendly design must be adopted. In Perth's climate an effective design strategy includes an adequate area of northerly solar collectors, total shading of glazing in summer, limited total area of glazing to control heat gains and losses through conduction, adequate insulation of roof and walls, adequate indoor thermal mass and excellent cross ventilation that does not compromise occupants' security. It appears that a design that achieves a minimum of approximately 7.0 star rating using AccuRate v 1.1.4.1 may provide confirmation of an effective design. Secondly well-informed users must be prepared to 'drive' a non-automated home towards thermal comfort.

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BIOGRAPHY

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