Faculty of Built Environment, Art and Design

Department of Architecture/Interior Architecture

Energy efficient design in housing of small floor area: Appropriateness in housing for the aged

Elizabeth Karol

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

Signature: ……

Date: ……December 2003

Acknowledgments

'*It's always so cold here. Why don't you turn on the heater*?' my elderly mother would say in winter when I brought her to our home for the regular Saturday lunch. In summer the comment was: '*why don't you put in an air-conditioner – how can you stand the heat*?' On winter afternoons the temperature in our energy efficient house is rarely below 20°C and in summer the temperature is rarely higher than 28°C. In her home, space heating and cooling was used extensively in spite of potentially good solar access in winter and significant shading of glass in summer.

This thesis, examining how small, medium density housing for older people could be designed to be energy efficient and thermally comfortable, rather than dependant on space heating and cooling, grew out of my mother's weekly complaint. Thus my gratitude to my mother, Eugenia Cummins, and my mother-in-law, Ronnie Wellington, both of whom were willing subjects for my endless questions about their thermal state of affairs.

Having established the research topic, a number of people assisted me in developing the research topic into this thesis. I thank them all. Particular thanks go to my research supervisors, Associate Professor Neville D'Cruz and Associate Professor Kris Cena, and to the chairperson of the thesis supervising panel, Professor Laurie Hegvold.

A special note of thanks to the volunteers who so generously participated in the case study, as well as to James Thorogood from the Department of Housing and Works, who gave freely of his time so that the case study could proceed smoothly.

Over the years I have been assisted by a number of individuals in particular Jenny Lalor who assisted with the statistical analysis, Don Stevens who provided critical comment on proposals for alternate passive heating and cooling possibilities, Angelo Delsante for his advice in the use of NatHERS, Marc Karol who provided assistance with computer generated drawings, Graham Kershaw for proof-reading the final draft and Des Thornton for assistance with production of the final document.

Lastly, heartfelt thanks to my family and friends, in particular Paul Wellington and Nina Karol, for unwavering support and encouragement during the long process.

Abstract

This thesis seeks to address energy efficient design in a temperate climate in typical small, medium density housing, particularly in housing for the aged. The connections between energy efficient design and small, medium density housing were identified as contemporary issues related to Australian Government policies in two disparate areas. One policy area is reflected in the Government's commitment to assist older people, whether they are active, early retirees or the frail elderly, wealthy or poor, to live in their chosen place of residence. Increasingly this chosen place of residence may be a small, medium density dwelling. The other policy area is that related to reducing energy consumption in buildings. This policy is reflected in recently proclaimed building regulations aimed at reducing space heating/cooling requirements in housing. The building regulations include details of acceptable construction practice for energy efficiency that may not be appropriate in small, medium density housing.

It was proposed in this thesis that extensive use of space heating and cooling in housing for the aged was required because well-established benchmarks for energy efficient design in a temperate climate were not generally appropriate in small, medium density dwellings and were particularly inappropriate in housing for the aged. 'Appropriate' in this context referred to:

- indoor temperatures being acceptable without the need for space heating and cooling;
- retaining the site planning and general form of typical, medium density aged persons housing developments in suburban Australia;
- cost effectiveness over the life of a building; and
- fitting the needs of physically and financially vulnerable older people.

The methods used to examine the notion of appropriateness commenced with a literature review that related to the general physical and economic status of older people and their needs and responses to space heating and cooling in the home. Further, the literature review considered the principles of energy efficient design and benchmark criteria for energy efficiency.

Arising from the literature review, two tools of study were used in order to develop a set of data encapsulating the salient features of small, medium density housing. The first was a multiple case study of typical housing for the aged. This was conceived as a way of determining if small, medium density dwellings could provide appropriate indoor thermal conditions and/or were designed to be energy efficient. The indoor temperatures were monitored in summer and winter and annual energy consumption was established and statistically analysed. The building designs were analysed in terms of their orientation, glazing areas, wall areas, volumes of thermal mass and ventilation capacity and compared with benchmarks for energy efficient design. The second tool involved a series of computer simulations of a typical small, medium density dwelling. The simulation process was utilised to determine if a new set of benchmarks for energy efficient small, medium density dwellings were required that would incorporate the notion of appropriateness.

From the multiple case study it was found that, irrespective of design, indoor temperatures in 98% of dwellings were above the acceptable maximum summer temperature of 27.4°C in still air and indoor temperatures in all dwellings were found to be below the acceptable minimum daytime temperature of 19.8°C. The findings also showed that some aspects of the benchmarks for energy efficient design were not appropriate in typical, medium density housing constructed specifically for the aged. From the simulation process it was discovered that acceptable temperatures could be achieved in small medium density housing if the principles of energy efficient design, incorporated within a new set of benchmarks, were integrated with appropriateness criteria for housing for the aged.

The approach taken with the new benchmarks was to create both performance based and prescriptive design solutions. The performance model differs from the current benchmarks for energy efficient design in that it establishes key functional objectives for energy efficient design. Compared to the current benchmarks, the prescriptive design solutions show significant reductions in the areas of northerly glazing and total glazing. To compensate for the reduced area of northerly glazing, both direct and indirect means of solar gain are utilised for passive heating.

The thesis outcomes have implications for three areas of the construction industry. The prescriptive design solutions presented in building regulations for energy efficiency in housing need to be qualified, the design briefs prepared for energy efficient construction of small, medium density housing need amendment and the approach taken by designers involved in energy efficient small, medium density housing needs to be reconsidered.

Table of Contents

Table of Figures

Table of Tables

1. Introduction

1.1 Overview of thesis

This thesis focuses on the applicability of energy-efficient design principles[1] to semi-detached housing of small floor area[2] in a temperate climate. The thesis uses public housing for the aged in Perth, Western Australia as a vehicle to examine the relationship between energy efficient design benchmarks, indoor temperatures and energy consumption in small, medium density housing for the aged.

Public housing for the aged is considered to be a suitable vehicle for the study as public housing developments are generally semi-detached or terrace type dwellings with a density of at least 30 dwellings per hectare which is a higher density than typical suburban housing in Australia[3] (Western Australian Planning Commission 2002). In addition, hundreds of public housing dwellings for the aged are constructed annually in Perth (State Housing Commission 1999), there is a common design brief for the dwellings that includes a number of design parameters relating to energy efficiency (Ministry of Housing 1999) and dwellings range in floor area between approximately 50 and 65 square metres.

The hypothesis of the study is that well-established benchmarks for energy efficient design, such as those produced by Baverstock and Paolino (1986) are not appropriate in small, medium density housing in general and in housing for the aged in particular.

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[1] In this thesis energy efficient design principles deal with those aspects of design that make indoor thermal conditions more comfortable by taking advantage of those features of a particular climate that contribute to natural heating and cooling.

[2] Small floor area is considered to be between approximately 50 and 65 m^2.

[3] Typical suburban housing in Australia is considered as low density with densities commonly between 12.5 and 20 dwellings per hectare.

Appropriate in this context is used to encapsulate physical features of design as well as a number of those "*unintended social repercussions of intentional human actions*" that Popper (1972, p.342) claims are inevitable when examining almost any field of social science. In this thesis energy efficient design of small medium density housing for the aged is the intentional action to be examined whilst only the repercussions that revolve around a number of dimensions of universal design criteria referred to by Demirbilek and Demirkan (1998) such as accessibility, adaptability, aesthetics and affordability are considered. Some aspects of universal design have been extended to encapsulate issues related to thermal conditions.

Appropriate is used to refer particularly to:

- being suitable to enable indoor temperatures to remain within an acceptable range, generally without the need for space heating and cooling;
- fitting into the site planning and general form of typical, medium density aged persons housing developments in suburban Australia;
- being cost effective in the medium term; and
- fitting the needs of physically and financially vulnerable older people.

It is suggested that any benchmarks for energy efficient design applied to housing for the aged need to be compatible with the needs of the occupants of the housing. In seeking out how the occupants' needs are to be met, this thesis explores two areas that provide a basis for assessing energy efficiency in housing for the aged. The first looks at the vulnerabilities of the aged in relation to thermal conditions in housing. The second area of exploration looks to past studies that have established an approach towards determining acceptable indoor temperatures in non-air-conditioned buildings.

The current thesis endeavours to assess the energy efficiency of small, medium density housing by using a number of steps, including:

- an examination of the principles of energy-efficient design in housing;
- a post-occupancy evaluation of existing public housing for the aged in Perth to establish if the housing satisfies general principles of energy efficient design, current benchmarks for energy efficient design and incidentally, the energy efficiency requirements of the design brief for the dwellings;
- the monitoring of indoor temperatures in public housing for the aged in Perth and comparing the temperatures with acceptable indoor temperatures;
- the use of a CSIRO validated computer program for Australian climatic conditions, the Nationwide House Energy Rating Scheme (NatHERS) (Delsante 1995a; 1995b) to simulate indoor temperatures in dwellings designed to accord with the benchmarks for energy efficient design;
- the use of NatHERS to simulate indoor temperatures in typical, small medium density dwellings modified to incorporate the notion of appropriateness as well as the principles of energy efficient design; and
- an assessment of the affordability of design modifications, using discounted cash flow methodology.

The key objective of using the above steps is to develop a flexible model for a design strategy for energy-efficient design that can be applied to medium density dwellings of small floor area that are occupied by the aged.

The remainder of this introductory chapter delineates why this study is being undertaken (section 1.2), how research questions have been established (section 1.3), the research approach used to undertake the study (section 1.4) and the limitations of the research (section 1.5).

1.2 Delineating the issues

A review of literature indicated that while a great deal of research has been directed at general issues of ageing and at general issues of energy efficient design, connections between the two areas of research are not generally made. This thesis sets out to make some connections between these two fields of research, through an examination of energy efficient design in housing for the aged.

Energy efficient design in housing for the aged in Australia is influenced by a confluence of at least three aspects of Australian society. One is population demographics, another is social attitudes towards housing the aged and a third is cultural attitudes towards the use of energy.

To service the predicted significant increase in population of older Australians (ABS 1998a), a significant number of dwellings are being constructed specifically for aged persons (ABS 2001). In Western Australia this includes the construction of an increased number of public dwellings for the aged by the Ministry of Housing and Works in Western Australia (Holding 2001). Concurrently, the Federal and State Governments are committed to assisting older people, whether they are active, early retirees or the frail elderly, wealthy or poor, to live in their chosen place of residence (Stimson et al. 1997). This commitment is reflected in the notion of ageing in place.

The Federal Government has also shown an intent to reduce energy consumption in residential buildings, with the introduction of energy efficiency measures in the building regulations. The national building regulations, the Building Code of Australia (BCA) (ABCB 1996), was amended in 2002 to incorporate requirements for energy efficiency of domestic buildings. These provisions are to be adopted in Western Australia in 2003. The BCA amendment describes a range of measures, based on accepted benchmarks for energy efficient design, that can be used to reduce the energy required for general domestic space heating and cooling.

As a result of the two government policies, namely to assist older people to remain in their homes and the mandatory requirement for improved energy efficiency in construction of housing, aged persons housing will have to meet this cohort's life style needs and limited finances, and also provide comfortable thermal conditions whilst enabling occupants to minimise energy consumption.

This has not been the case in housing for the aged constructed in the 1990's. The author found in a study of non-government retirement villages in Perth, that mechanical heating and cooling was generally required to provide acceptable indoor conditions and older people who could afford to do so, made extensive use of space heating and cooling (Karol 1997). It appears from the monitored results of the present study (maximum mean indoor temperature on a typical hot summer day was 28.9°C and minimum mean indoor temperature on a typical winter day was 17.7°C) that the current designs of public housing for the aged also require mechanical heating and cooling on a regular basis if acceptable indoor temperatures are to be achieved.

The current thesis suggests that, although the elderly are being encouraged to live for as long as possible in housing being constructed specifically for them, they are simultaneously being committed to using space heating and cooling to make indoor temperatures acceptable. This financial commitment is occurring irrespective of the affordability of space heating or cooling and irrespective of the various tiers of government's advocacy of measures to improve energy efficiency in buildings since the early 1990's (BRR 1990).

These considerations raise the question whether it is possible to use the accepted design benchmarks for energy efficiency to design small, medium density housing for the aged. Coldicutt (1992) provides some guidance in how to tackle such a question as she provides a model for environmental decision making[1] in situations where the context is complex and fluid. The complexity of energy efficient design of housing arises largely because the main players (the financiers, the construction industry and the public as housing occupants) have limited commitment to energy efficient design. The fluidity of the situation is a result of housing for the aged being subjected to political vacillations.

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[1] Energy efficient design is one element of environmental decision making as it impacts on operational energy required for space heating and cooling.

Coldicutt's model highlights the potential weaknesses in discussions of energy-efficient design, if assumptions on the component parts of decision making are not addressed. Coldicutt claims that assumptions are regularly made about inter-connected components, called 'ends' and 'means'[1], that impact on decision making.

In Coldicutt's terms, the main 'end' in this thesis would be identified as the provision of a design strategy to assist in the delivery of energy-efficient housing for the aged. One way of achieving this end in this thesis would be to consider it as a narrow problem involving only the manipulation of building elements, with precise 'means' of resolution. The means could be limited to a hypothetical typical home that is accurately computer modelled according to current benchmarks for energy efficient design with a selected number of variables, such as orientation and area of glazing, and mathematically assessed to produce a design solution.

However the main objective ('end') of this thesis involves more than a building design. The search is for a design strategy. That strategy should take into account both the objectives of passive subjects for whom decisions are made (the elderly occupants living in energy-efficient housing who are not party to the design process) and active subjects (those who establish the design brief, carry out the design, approve and finance the design of energy-efficient housing for the aged). If the means used to address the problem do not take into account the different perspective of the passive and active subjects towards energy-efficient design, the solution could be quite limited.

Thus in formulating any research questions in the current thesis, emphasis needs to be placed on the notion of <u>appropriateness</u> as a way of addressing passive subjects' ends and on the relationships between benchmarks for energy efficient design, existing designs and hypothetical designs to address active subjects' ends. Two such research questions have been formulated to examine the hypothesis.

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[1] Coldicutt (1992 p.5) refers to 'ends' as "goals, aims, purposes" and 'means' as "concepts, theories, intuitions, formulas, dreams".

1.3 Research questions

The principles surrounding the research questions are identified and used in the current thesis to assess the applicability of the current benchmarks for energy-efficient design in small, medium density housing, including housing for the aged.

1.3.1 Indoor temperatures in and design of housing for the aged

People in the developed world have come to expect temperatures in their homes to be within a comfortable temperature range (Henderson 1992). This thesis is of the view that those living in housing for the aged in Australia have the same entitlement to comfortable indoor temperatures.

If it is acknowledged that physiological changes in older people may make them less sensitive and less responsive to their thermal environment so they may not respond appropriately to conditions that are too cold (Wagner & Horvath 1985) or too hot (Sagawa et al. 1988), should the construction of housing for the aged be more responsive than other housing types to outdoor conditions, irrespective of the behaviour of the occupants? Further, with the drive towards energy conservation, it is unclear how long the option of extensive use of space heating and cooling will remain affordable for those living in housing for the aged. The view of this thesis is that the design and construction of housing for the aged should be responsive to outdoor conditions.

These two views suggest that public housing for the aged in Perth should be designed to be energy efficient. The design brief for public housing for the aged in Perth supports this expectation with a number of clauses that refer to minimising energy use and maximising passive solar design techniques (Ministry of Housing 1999) but, as ascertained in the current study, typical housing designed specifically as public housing for the aged varies markedly in the attention paid to matters of energy efficiency.

This finding is in line with evidence from a survey by Rossit (1993) on the level of emphasis placed on energy efficiency in housing design. His survey indicates that designers are far more enamoured with the concept of energy efficient design than with the application of appropriately oriented glazing, insulation and adequate distribution of thermal mass. This is supported by data from the Australian Bureau of Statistics, which shows that although approximately 93% of Western Australians live in the southern part of the state where winter sun is desirable for heating (ABS 1998b), 50% of Western Australians' dwellings have no sun penetration into living areas in winter and 87% have mechanical space heating (ABS 1987a). In addition, only 60% of Western Australian households have roof or ceiling insulation (ABS 1998c) and the use of air-conditioning has risen steadily during the past decade so that 45% of dwellings now have air-conditioners (ABS, 1998c). It is reasonable to surmise that the results of Rossit's survey are also generally applicable to the design of housing for the aged.

These matters lead to the first research question.

> Research Question 1. Does existing small, medium density housing for the aged in Perth:
>
> (a) satisfy the principles of energy efficient design; and/or
>
> (b) provide acceptable indoor temperatures?

1.3.2 Design benchmarks for energy efficiency in small, medium density housing

Studies by Balcomb (1984; 1987), Baverstock and Paolino (1986) and Yannas (1994) provide readily accessible benchmark information[1] regarding energy-efficient design for suburban type houses in various climatic zones. In a temperate climate such as that experienced in Perth, that information can be used to design energy-efficient housing that can provide acceptable indoor temperatures without the use of air-conditioning or mechanical heating (Reardon 2001). But housing developments

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[1] The benchmark information includes the following factors of design related to floor area – area of equator facing glazing, total area of glazing, area or volumes of thermal mass and levels of insulation.

for the aged have characteristics that are not typical of Australian family homes because they are:

- medium density dwellings that are in closer proximity to neighbours than typical suburban housing;
- generally provided with glazing on only two opposite sides;
- small in floor area (public housing for the aged is between approximately 50 and 65 square metres); and
- highly likely, at some stage, to be occupied by an older person who will have difficulty dealing with some typical aspect of energy efficient design.

So in spite of the design brief (Ministry of Housing 1999) for public housing for the aged including reference to the importance of achieving energy efficiency through correct orientation, shading of glazing in summer, ventilation for summer cooling and insulation of dwellings, it may be that compliance with current benchmarks for energy efficiency are not appropriate in housing for the aged. These matters lead to a second research question.

> Research Question 2. Are current benchmarks for energy efficient design appropriate:
>
> (a) for small, medium density housing; and
>
> (b) particularly for small, medium density housing for the aged?

1.4 Research approach

Case study methodology was used to commence the research and address Research Question 1. Yin (1994) suggests that this methodology is appropriate for examining a contemporary phenomenon in its real-life context, where 'how' or 'why' type questions are being investigated within a common parameter. As the design of public housing for the aged in Perth is a contemporary phenomenon, the designers of public housing for the aged utilize a common design brief and the component parts of the question can be considered as how and why type questions. It is appropriate, therefore, to use case study methodology. To demonstrate this later point, Research Question 1 encapsulates such sub-questions as:

- Why are indoor temperatures in public housing for the aged high in summer and low in winter?
- How does use of energy for space heating and cooling in public housing for the aged relate to design and indoor temperatures?
- How do the current designs of public housing for the aged relate to the principles of energy efficient design?

Research Question 2 is addressed primarily through empirical testing of typical dwelling designs based on examples from the case study. The tool used for empirical testing is NatHERS, a computer program nominated in the BCA as an acceptable method of verifying the energy efficiency of a house to comply with minimum building regulation requirements (ABCB 1996).

The overall approach taken in this thesis to address the notion of appropriateness of energy efficient design in housing for the aged is shown diagrammatically in Figure 1-1 as a five stage process.

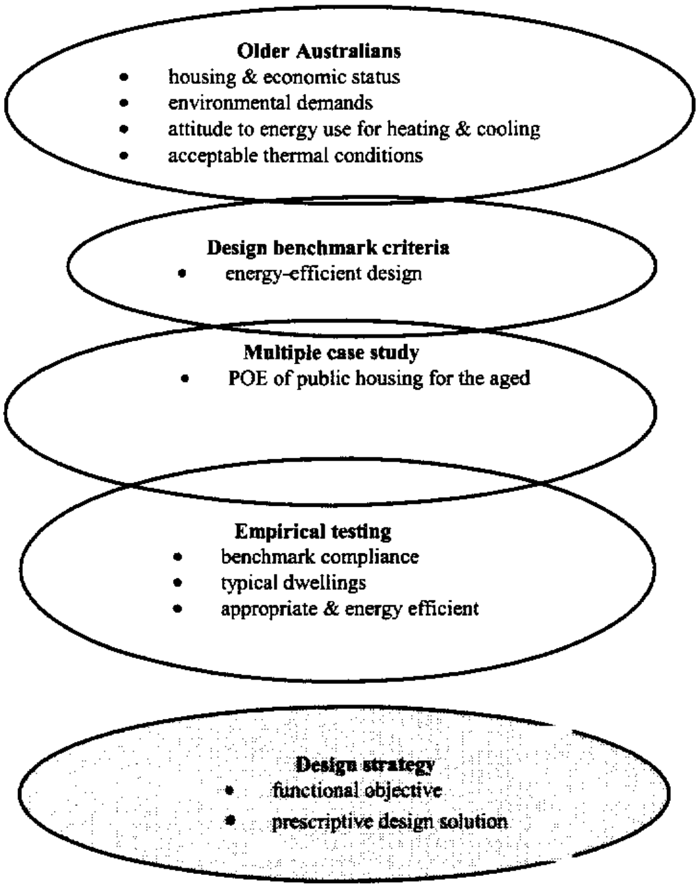

Figure 1-1 *Research approach – entwining appropriateness and energy efficiency*

Figure 1-1 shows that some matters that impact on housing for older Australians are examined to start the research. These include the demographics, housing situation and economic status of the aged, the environmental demands on older people in regard to thermal conditions and the use of energy for space heating and cooling in the home. Also included is an assessment of the indoor temperatures determined as appropriate for the aged in non-air-conditioned buildings in a temperate climate. These matters contribute to an understanding of the meaning of the term 'appropriate' referred to in the hypothesis.

Secondly, based on accepted criteria, a series of benchmarks for energy efficient design in Perth's climate is established.

Thirdly, the knowledge gained in stages one and two is then applied by addressing the first research question. A post-occupancy evaluation of 60 existing public housing dwellings for the aged in Perth is carried out. This third stage is a multiple case study of seven aged persons' developments. The case study explores the design features of these seven developments. Particular consideration is given to how traditional energy saving design features are incorporated into public housing for the aged. Individual dwellings are examined to investigate design possibilities for reducing dependence on space heating and cooling.

In the fourth stage, empirical testing of the thermal performance of a number of small, semi-detached dwellings is carried out. The building envelopes and the volumes of internal mass are adjusted to determine if indoor temperatures can be brought within an acceptable range without the use of space heating or cooling.

Finally, the thesis draws together the strands of appropriateness and energy efficient design. A key assertion here is that there is a relationship between energy efficient design that results in acceptable indoor temperatures and the appropriateness of the design for the occupant. It is suggested that for housing for the aged, this relationship can be expressed as a design strategy that may have a bearing on current benchmarks for energy efficient design. In order to develop the design strategy for energy efficient, small, medium density dwellings, including dwellings for the aged, each design requirement was examined in terms of its functional objective. A prescriptive design solution to meet the functional objective could then be determined from the results of the empirical testing.

1.5 Limitations of research

Coldicutt's (1992) model highlights some limitations in this study. Firstly in the context of housing for the aged, the complexity of decision-making is coloured by local, state and federal politics in the areas of housing, social services and finance. This study does not attempt to address such issues as how frail an aged person can be before he or she starts to need special thermal conditions, nor how much an older person can afford to spend on space heating and cooling. Secondly, the intentions of active subjects, in this case the Department of Housing and Works[1] and building designers, in regard to energy-efficient design are not objectively determined. The questions of whether designers understand the implications of the Ministry of Housing's design brief and why designs that do not satisfy the design brief are accepted for construction was considered to be outside the scope of the current study.

Another limitation is that no physiological assessment of the occupants was undertaken. Thus the thesis cannot confirm that the temperatures generally considered to be acceptable in non-air-conditioned buildings using the adaptive approach to thermal comfort (de Dear & Schiller Brager 1998) are also acceptable in housing for the aged. All that can be confirmed is that the upper and lower temperature limits considered to be acceptable in the current thesis conform with the acceptable temperature limits determined using the adaptive approach to thermal comfort and these limits are higher in winter and lower in summer than the temperatures monitored in the vast majority of dwellings in the post-occupancy evaluation. Finally, if energy efficient housing includes unfamiliar elements, there is no attempt in this study to gauge their acceptance by designers or building occupants.

1.6 Order of presentation

This thesis is made up of nine chapters. Chapter 2 starts by considering some of the pertinent aspects of the social context of housing for the aged in Australia. The chapter then focuses on the environmental needs of older people in their homes and the implications of those needs on design, particularly energy-efficient design. This chapter considers a number of factors that contribute to an understanding of the term 'appropriate' in housing for the aged.

Chapter 3 commences by examining an approach towards establishing appropriate indoor thermal conditions, referred to as the adaptive approach to thermal comfort. It is used to determine acceptable temperatures for non-air-conditioned housing in

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[1] Ministry for Housing, WA was renamed Department of Housing & Works in 2001.

Perth. The chapter then explores the theory behind energy-efficient design in a temperate climate. In this chapter the implication of extending the current benchmarks for energy-efficient design to buildings of small floor area are demonstrated. Chapters 2 and 3 underpin the assessment process of the subsequent multiple case study and provide the keys to determining a relationship between energy efficient design and 'appropriateness' in housing for the aged.

Chapter 4 utilises the general research approach described in the present chapter to develop the research framework for a multiple case study of public housing developments for aged persons in Perth, Western Australia. The details of the multiple case study are described in relation to the identification, collection and analysis of data. Measuring instruments and analytical tools used to assess the data are described. It also describes the approach taken towards empirical testing of typical designs of small, medium density housing.

Chapter 5 presents the results of the post-occupancy evaluation of the current thermal conditions in public housing developments for the aged in Perth while in Chapter 6 the results of an empirical analysis of thermal conditions in small, medium density housing are presented. The data used for the post-occupancy evaluation and the empirical analysis is included on the CD attached.

Chapter 7 reviews the findings and discusses the meaning and significance of the outcomes of the two research questions that were developed to support the hypothesis. In Chapter 8 a new design strategy for energy efficient design in small, medium density housing is developed and discussed. Chapter 9 provides the conclusion to the thesis. The research process and findings are summarised and recommendations for future research are proposed.

2. Housing for the aged in context

2.1 Preamble

In this chapter that part of the hypothesis relating to housing for the aged being appropriate for the elderly is considered within a broad framework of general housing needs of the aged. In section 2.2 there is an elucidation on the social context of housing for the aged, including an overview of the ageing population, the housing situation of older Australians and their economic status.

In section 2.3 the environmental demands of older people are discussed. The environmental demands are examined by considering the abilities of older people to manage their domestic environment, both in physical terms and in relation to thermal conditions. This provides a basis on which decisions can be made regarding the design parameters for energy efficient housing for the aged.

Attitudes towards energy use for space heating and space cooling are examined in section 2.4. This raises an awareness of the influence of building occupants' behaviour on any assessment of the possible success of energy efficient design.

2.2 Social context

The aged are identified as a particular cohort in society. However there is great diversity within this cohort (Stimson et al. 1997). This diversity has implications on the notion of appropriateness in housing for the aged. In order to establish how these matters may impact on the design of appropriate housing for the aged, this section describes Australia's ageing population, the housing situation of older Australians and their economic status.

2.2.1 The ageing population

2.2.1.1 Classifying the aged

Classifying the aged depends on the purpose of the classification. The most commonly used definition is chronological age. Statistics, produced by the Australian

Bureau of Statistics, that relate specifically to the aged generally refer to people over 65 years, the age at which retired men become eligible for the aged pension. In terms of eligibility for entry into housing specifically for the aged, the entry age is 55 years.

In relation to housing, reference to people in the aged cohort needs to reflect not just their chronological age but also their changing characteristics, over a 30 to 40 year period. As a result, three stages of the lifecycle of the aged are referred to by those involved in health care (Boldy & Denton 1998), financial services (Johnson 1999) and designers of retirement facilities (Goodman & Smith 1992) as well as by the Australian Commission for the Future (1992). These studies provide useful reference points when considering the future design of housing for older people. The three stages in the classification include chronological age as well as functional capacity, which is most relevant to housing needs. The three stages in the classification of the aged are:

- young-old (those people usually between 55 and 74 years and most likely healthy and active);
- old (those people usually between 75 and 84 years);
- old-old (those people usually over 85 years and most likely becoming frail and less independent).

2.2.1.2 Ageing demographics

Australia's population is ageing. Projections show that the number of people in the older age groups will increase as an inevitable result of the 'baby boom' generation reaching retirement age, falling fertility levels over the last fifty years and, at the same time, a decline in mortality rates (ABS 1998a). In Australia the population aged 65 years and over is projected to rise both in terms of numbers and as a proportion of the total population as indicated in Figure 2-1.

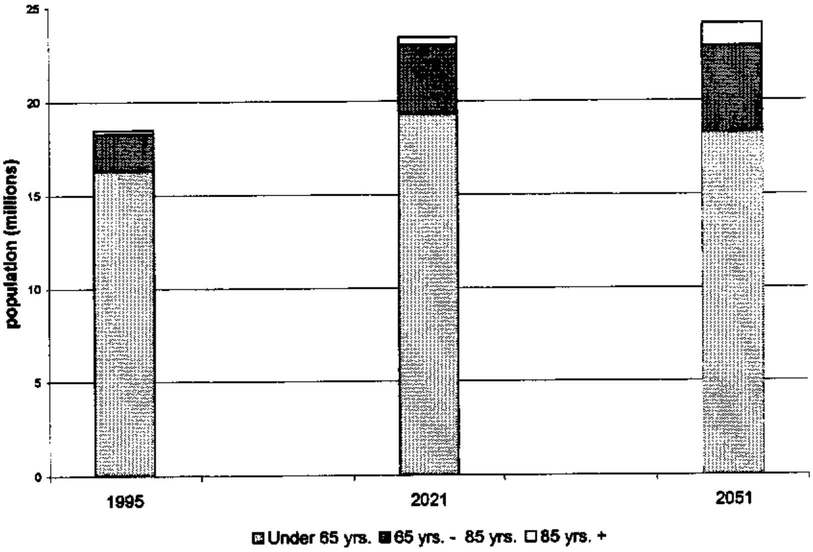

Figure 2-1 *Projected rise in Australia's aged population (ABS 1998a)*

In 1995 there were 2.2 million in this age group. This number is projected to rise to between 4.0 and 4.1 million in 2021 and between 5.8 and 7.6 million in 2051. As a proportion of the population these numbers represent an increase from 11.9% in 1995 to between 17.1% and 17.5% in 2021, increasing to between 24% and 27% in 2051 (ABS 1999).

Not only is the total population over 65 years old projected to increase, but also the make-up of this older cohort is changing and becoming less homogenous because of increased longevity of the population. The average rate of increase of the old-old (those 85 years and over) is projected to continue at its present high level (around 4% per annum) until about 2005 and then fall (to less than 2% per annum) until approximately 2030. It is then projected to increase sharply as the baby boom generation reaches old-old age (ABS 1998a). As a result, projections show that the number of old-old people will rise from 216,000 in 1997 to approximately 440,500 in 2021, to between 1.1 and 1.2 million in 2051. These projections are depicted in Figure 2-1, with those over 85 years increasing as a proportion of the population aged over 65 years, from approximately 10% in 1997 to approximately 20% in 2051 (ABS 1998a).

2.2.1.3 Ageing households and housing

The Australian Bureau of Statistics (ABS 1999a) projections show a significant increase in the number of independent households of retirees over the next two decades. Household growth of this group is projected to be faster than their growth in absolute numbers.

By 2021, 44% of households will be headed by a person aged 55 years or older compared to just 33% in 1991 (AHURI 1996). As well as the mean age of households rising, the number of single Australian households is expected to soar from 1.6 million in 1996 to between 2.4 million and 3.4 million in 2021 (ABS 1999a). These single person households are tending to occupy smaller dwellings.

There is evidence to show that the total stock of smaller, higher density housing[1] is increasing. Between 1991 and 2001, of the 1.2 million additional dwellings constructed in Australia, higher density housing represented 35% of the total increase. Considering that higher density housing in 1991 was 19.5% of the total housing stock, it is clear that the demand for higher density housing has increased (ABS 2003a).

The majority of people occupying higher density housing are lone person households, either those under 35 years of age or those over 65 years of age (ABS 2003b). Based on current household patterns, by 2021, between 35% and 40% of these lone person householders are projected to be over 55 years old (AHURI 1996). Further, if the current pattern of female lone person households continues (around 75% of households in the 75 years and over category are single females) this may influence certain aspects of housing policy, such as the number of people choosing to relocate to smaller, higher density housing including retirement villages (Stimson et al. 1997).

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[1] Higher density housing is defined in ABS data as the combination of semi-detached houses, row houses, terrace houses, town houses, flats, units and apartments (ABS 2003a).

2.2.1.4 Significance of the ageing population

Two primary consequences of the ageing population are relevant to this study. Firstly, within the next twenty years, a large number of higher density dwellings will be built and a significant number of people occupying these dwellings will be over the age of 55. If current design shortfalls of such housing are not addressed, they will be perpetuated for future generations of older people. Secondly, a significant number of these elderly people will be over 85 years and may be living alone. This means that any features incorporated in the design of higher density dwellings, particular in housing specifically for the aged, must be sensitive to the limitations of the older people in general as well as the old-old.

2.2.2 Housing situation and economic status of older Australians

A number of issues related to the current and future housing situation of older people are considered. These include housing tenure, the security of housing tenure including the role of public housing, the type of housing occupied and issues of recurrent expenses related to housing tenure.

2.2.2.1 Housing tenure

An overview of the various forms of housing tenure among Australians, particularly older Australians, is shown in Table 2-1 (AHURI 1996). These figures exclude the nearly 10% of older Australians living in some form of institutional care.

Housing tenure	**55-64 years**	**65-74 years**	**75+ years**	**Total households**
Outright owner	72.0	78.0	76.7	41.3
Purchaser	11.5	5.7	3.2	29.4
Private renter	7.4	4.9	4.1	17.9
Public renter	6.3	9.3	10.6	7.2
Other (including retirement village)	2.8	2.1	5.3	4.3

Table 2-1 *Approximate percentage of older Australians, compared to the total number of Australians in various housing tenures (Based on AHURI 1996, p.39)*

From Table 2-1 it can be seen that outright home ownership is by far the most common form of housing tenure amongst older Australians. In 1994 more than 70% of older Australians owned their dwellings outright compared to 41% of all households who were outright owners. The transition to outright ownership occurs substantially over the age of 54 years. Table 2-1 also shows that the proportion of older people renting public housing increases with age with over 10% of those over 75 years living in public housing compared to approximately 6% in the 55 to 64 age bracket and approximately 7% of total households.

The significance of these figures lies in a number of areas. According to the National Strategy for an Ageing Australia (1999), the high percentage of those over 55 years who are outright home owners and purchasers confirms the strong preference of older Australians, after retirement, to stay in their home. Current government social policies also encourage this 'ageing in place'[1] as it is seen as crucial for the morale and life satisfaction of older people (Davison et al. 1993). It is also cheaper for government than providing institutional care (Stimson et al. 1997). A further benefit according to the National Strategy for an Ageing Australia (1999) is that outright own-

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[1] Ageing in place revolves around older people being assisted to remain in their place of residence, whether it be the family home, rental accommodation or a retirement village, through the provision of appropriate support, including assistance with domestic chores, transport, personal care and the like (Heumann & Boldy 1993).

ership implies lower housing costs and provides an asset that may be realized for consumption in old age. It is unclear how these patterns of accommodation will change in the future although there is some indication that the current trend of falling home ownership rates of those under 35 years (Yates 1998) may translate into a less affluent cohort of retirees in the 2030s.

The figures in Table 2-1 point to the desire for the more secure forms of housing tenure (outright ownership or public renting) as people grow older. After the age of 64, the highest percentage of Australians are outright owners whilst the second highest percentage are public renters. This is different to the pattern of housing tenure for the total population when security of tenure does not appear to be such a driving force.

2.2.2.2 Security of tenure

Ageing in place depends on future generations of older people having an appropriate, secure and affordable residence. Government policy regarding such security and affordability for the elderly poor appears more ambivalent than at any time since World War II, with a national housing policy debate about the construction of public housing. The debate revolves around whether the Commonwealth - State Housing Agreement (CSHA) should be changed from a system of capital grant funds to the states for the construction of public housing, to an alternate system where funds are used primarily to subsidise rent for low-income private renters (Wulff & Maher 1998). Already in Western Australia public housing construction commitments are declining as capital grant funds are reduced[1].

If the CSHA is more heavily oriented towards greater numbers of low-income people being subsidised to rent private accommodation, this could be problematic for older renters. This is due to the dependency of older people on appropriateness of accommodation as they age, as well as on long-term affordability and security of tenure (Stimson et al. 1997). In the public sector it is possible to address all three of these

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[1] This advice was provided by the Director of Housing Policy, A. Arnold, at the Department of Housing and Works on 31st October 2000.

factors, but for those in the private rental market, affordability through financial rent assistance is the only factor that can be addressed.

For those in the affluent baby boom generation, ageing home owners will face other concerns related to ageing in place. Typical houses and gardens of baby-boomers are large, are located in car-oriented suburbs away from services and effective public transport, and may present major difficulties in old age. This may encourage the occupants to move to more conveniently located, smaller accommodation, including retirement villages (ibid).

Assertive consumerism of housing during the working lives of baby boomers will probably continue in retirement, with high expectations of any new accommodation, including expectations for thermal comfort. This will be in contrast to the current group of older people, who lived through the depression and World War II and had modest expectations in regard to material possessions at every stage in their lives (Goodman & Smith 1992).

The implications of ageing in place on the children of the baby boomers are even more difficult to foresee. Yates (1998) discusses the predicted housing experience of the children of the baby boomers (Generation X) based on observed trends. The Generation X cohort will have faced reduced opportunities for secure jobs, a great disparity of incomes, a deregulated housing finance market and an apparent substantial reduction by the Federal Government of implicit home ownership policies, such as heavily subsidised infrastructure costs on cheap land in outlying areas. These factors will continue the current trend of falling home ownership rates amongst those under 35 years old. It is therefore possible that a significant proportion of those reaching retirement age in the 2030s will have never owned a home but will have lived in mainly private rented accommodation all their lives. As a result, in old age a significant proportion of Generation X may have no security of housing tenure, limited assets and limited income. In old age, a large and affluent baby-boom cohort may be followed by a smaller and possibly less advantaged cohort (Kendig & Neutze 1999).

2.2.2.3 Economic status related to housing tenure

A study by Stimson et al (1997) shows that average income typically falls as a household ages. Households headed by a person 65 years or older have an average income that is 66% of the average income of households in the general population (Whiteford & Bond 1999). Further, 61% of all aged persons are considered as low-income earners[1] (compared to 16% of the total labour force).

The level of financial stress[2] experienced by the elderly is strongly related to housing tenure. This has a marked impact on disposable income, as indicated in Table 2-2. If maintenance costs are excluded, for those over 65 years the average cost associated with accommodation is much lower for home owners than for any other group (National Strategy for an Ageing Australia 1999). Those in public housing appear to have the second lowest costs associated with accommodation.

Housing tenure	**Average weekly accommodation costs**
Private renters	$97.50
Owners with mortgages	$70.30
Public renters	$53.00
Owners	$21.00

Table 2-2 *Average costs associated with accommodation (excluding maintenance) for people over 65 years old in 1996 (National Strategy for an Ageing Australia (1999)*

In Australia, even with rent assistance provided by the Government, many older renters experience financial stress, particularly in the private rental market. According to Howe (1992a), 68% of older people who are private tenants and 14% of older people who are public tenants are in financial stress. As discussed in the previous section, the study by Yates (1998) shows that if more people reach retirement without owning a home, financial stress could become more prevalent for those renting accommodation.

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[1] Stimson et al. (1997) refer to low-income earners as those receiving $20,000 or less per annum.

[2] The level of financial stress is defined in the National Housing Strategy (1991) as requiring more than 25% or 30% (depending on particular circumstances) of gross household income to be spent for housing.

2.2.2.4 Significance of housing tenure and economic status of older Australians

The patterns of housing tenure of older Australians and the resulting level of older people's financial stress, impact on the study of energy efficient design in housing occupied by the aged in the following ways:

- Although the majority of elderly Australians will not be directly affected by potential improvements in energy efficiency in higher density housing, there is a significant projected increase in the numbers of old and old-old people moving into higher density housing including public housing for the aged.
- The high expectations of housing of the baby boom generation, whether rich or poor, may translate into even higher demands for energy in dwellings occupied by the aged, with a resulting increase in expenditure on energy.
- The majority of older Australians receive a relatively low income whilst those renting public housing generally survive on some form of pension. For financially vulnerable older people, any reduction in ongoing expenditure on energy bills for heating and cooling will reduce their financial stress. Also, although the future price of energy in Australia is unpredictable (Harman 2002), any rises in price will increase financial stress or reduce the use of space heating and cooling.
- Housing stock in Australia increases at a rate of less than 2% per annum. The accommodation constructed primarily for the ageing baby boom generation may have to adequately accommodate a subsequent generation of elderly (Generation X) who are less affluent and perhaps unable to afford space heating and cooling.

2.3 Environmental demands

In this section the domestic physical environment is examined in relation to older people's changing physiology and the need for housing to be supportive of people as they move through the ageing cycle. Knowledge of the frailties of older people will be used to consider the potential willingness and ability of older people to utilise particular energy efficient features in their homes.

2.3.1 Physical and sensory needs of older people

The ageing process creates physical, mental and psychological changes in people (Haigh 1993). The rates of these changes depend on the individual, but the inevitable accumulation of impairments impacts on old people's ability to manage their daily living patterns. The following sections address some of the changes and the impact of those changes on the home environment of older people.

2.3.2 Physical environment

Because older people gradually become less adept at managing their home environment, including the thermal environment, that environment should be designed to be user-friendly. However, being user-friendly depends on the changing relationship between the physical environment and the symptoms of the ageing process. For the aged, Newcomer and Weeden (1986) suggest that the domestic physical environment can be considered as a housing continuum with a great variety of housing types able to accommodate older people when they have a high level of independence whilst only a very limited number of housing types can satisfactorily accommodate older people with a high level of dependence. However, they argue that if there was an integration of housing design policy with arrangements for social services for the aged, older people may be able to remain in their chosen accommodation rather than having to move into more supportive housing as their level of independence falls. Similarly, Soldo (1986) discusses the dynamic relationship between occupant health, housing characteristics and household type. She concludes that modifying the home environment to meet the needs of a diverse group of occupants is more satisfactory than personnel-intensive ways of providing support for the aged as they become less independent. But these researchers do not explain under what conditions the aged as a group or as individuals are satisfied with and able to function within their home environment.

A theoretical approach to assessing satisfaction with the home environment was developed by Lawton, Windley and Byerts (1982). This approach describes two crucial factors of satisfaction. The first factor requires an assessment of a person's competence to carry out all the necessary functions of living independently, and the second factor describes how readily the home environment can be adjusted and controlled to satisfy declining physical abilities.

Lawton (1989) developed the two factors of satisfaction, naming them 'personal competence' and 'environmental demand'. He produced a model revolving around these two factors of satisfaction, that showed how three functions of the residential environment were particularly important to older people in providing personal satisfaction and enhanced well-being. These functions are called maintenance, stimulation and support. Maintenance is the term used to describe the state of affairs when the normal daily habits of the individual in relation to the familiar components of the residential environment can be taken for granted. For example a person is able to get out of bed, know how the floor surface will feel, know how many footsteps to take to the bathroom and be confident that there will be no obstacles en route. Ranged on either side of the function of maintenance are stimulation and support. Stimulation is the state experienced by the person when some sort of unfamiliar activity or unexpected delight is presented. Support is described as the state experienced when the environment allows a lesser degree of response to satisfy needs, for example when a carer provides support in an environment where bathing has become difficult. Lawton's model is represented diagrammatically in Figure 2-2 below.

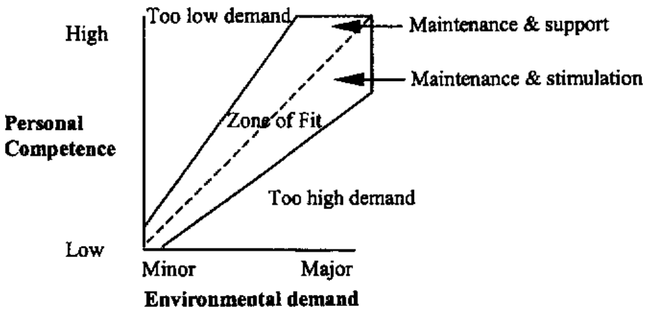

Figure 2-2 *Matching levels of personal competence to levels of environmental demand (Adapted from Lawton 1989)*

On the vertical axis, 'personal competence' represents the level of biological and cognitive well-being, and sensory and motor functioning of the person ranging from low at the bottom to high at the top. On the horizontal axis, 'environmental demand' is the extent to which the environment expects a response from the person, ranging from minor on the left to major on the right. The dashed line represents the theoretical point at which the environmental demand is exactly matched by the competence of the person. The area enclosed describes a 'zone of fit' where the *maintenance* function dominates and a person with a particular level of competency in an established environment can be satisfied. Outside of that 'zone of fit', either demands are too high so the person is anxious, stressed and cannot cope, or demands are too low and the person becomes unnecessarily dependent and dissatisfied. Clearly if a person declines in competence in a residential environment that cannot be adjusted, either they will need more personal support, or in the longer-term will be required to move to an environment that makes less environmental demand.

Lawton's model is recognised as a simplification of reality as the 'dimensions' on each axis are a large number of integrated factors combined into one. Some of those factors within a dimension may even act in opposition to each other.

For example, a person's mobility may be declining while sensory and cognitive skills may be increasing to compensate, so the actual position on the personal competence axis may not appear to change. Similarly on the environmental demand axis, reducing major physical environmental demands through change of housing may also increase psychological environmental demands because of reduced confidence in day-to-day activities. For example, a person may move from a house they have occupied for 30 years, which has steps and inappropriate bathing facilities, to a retirement village dwelling where there are no major physical environmental demands. Long familiarity with the physical deficiencies of the first dwelling has, overall, enabled the occupant to remain in the zone of fit, whereas in the new situation, stimulation and a new physical environment that is theoretically far less demanding, must compensate for the need to establish new daily living habits.

By recording older people's observations about their homes, Davison et al. (1993) provide some insight into why a new housing situation creates a greater demand on an older person. They describe the universal tendency of older people to make a precise mental map of the home and their pattern of occupation of the home. Thus anything new within the home requires a change to this well-established mental map, whilst relocation to a new home requires the development of a completely new mental map.

Despite the simplifications of Lawton's model, the general implications arising from his model assist in the search for a situation in the home in which a person and their environment can remain in the 'zone of fit', even though personal competencies change and the environment may deteriorate. Some older people try to ignore these personal and environmental changes, as the desire for independence overrides other considerations such as convenience, comfort, safety or ease of use of the home (McDonald & Kippen 1999). However there is an onus on those advocating ageing in place to also promote appropriate housing design rather than accept a 'Peter Pan'[1] housing market.

Appropriate in this context refers to supportive features being able to be readily incorporated in all housing types, so that the level of 'environmental demand' can meet older people's changing needs. Architects at the Building Research Institute in Japan

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[1] 'Peter Pan' housing market refers to a housing market tailored for people who never grow old (Kendig & Neutze 1999).

argue that in an ageing society the design of all housing, including public housing, should be easily adaptable to assist those with reduced physical and mental abilities (Kose & Nakaohji 1991). This is an indication that universal design[1] should go hand in hand with ageing in place. This would result in housing that could satisfy the needs of a wide range of occupants over their full life cycle. The risks of ageing in place would thereby be reduced because occupants could readily adapt their physical environment and reduce 'environmental demand' to suit their 'personal competence'.

Demirbilek and Demirkan (1998), in their examination of designing for the elderly, provide a prescriptive model for involving the elderly in the design of interior spaces, furniture and equipment in the home. They claim this involvement can lead to the creation of indoor spaces that are more physically and psychologically supportive of the elderly. Consequently this helps to preserve the independence of the elderly in the activities of daily living and thus enable them to remain in their homes. Of particular interest in the current thesis is that in their model, Demirbilek and Demirkan (1998) describe four design criteria of the concept of universal design that are especially pertinent to housing for the aged. The four criteria are accessibility, adaptability, aesthetics and affordability. Although there is no specific mention by Demirbilek and Demirkan in their model of thermal conditions or energy efficient design, as discussed below a link can be established between the universal design criteria, energy efficient design and thermal conditions.

- *Accessibility* is generally considered as enabling a person to fully utilise a space, whether they have impaired vision or use a wheelchair. While accessibility in the study by Demirbilek and Demirkan (1998) is limited to freedom from physical barriers, accessibility in this thesis is extended to include having access to thermal comfort and having access to daylight without being subjected to glare.

- *Adaptability* and *affordability* are especially important when the current or future residents plan to live in a particular dwelling for many years, and will need to

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[1] Universal design refers to the incorporation of standard design elements to meet the competencies of all people regardless of age, condition or ability (Null & Cherry 1996; Coleman 1994).

make adjustments to suit different stages of physical and mental well-being. If all dwellings were designed to be readily adaptable, then the cost of making the adaptation at some time in the future could be affordable, not only to home owners but also to renters or public housing agencies. These notions of adaptability and affordability could well apply to energy efficient design, as well as to the more obvious considerations of adapting shower and toilet facilities to increasingly frail occupants. Adaptability in the current thesis is extended to include the notion that housing should be designed so that solar collection is available in winter, glazing is able to be shaded in summer and natural ventilation is available without compromising occupant privacy or security. Not only should housing be able to adapt to climate but also the mechanisms for adaptation, such as the opening and closing of curtains, blinds, shutters or windows should be affordable and usable even if levels of personal competence fall.

- *Aesthetics* refers to a designed environment that is both delightful and helpful without appearing different or utilitarian.

Other researchers such as Coleman (1994) and Null and Cherry (1996) also make no specific mention of appropriate thermal conditions as part of the concept of universal design, but accessibility to appropriate thermal conditions by affordable means that are aesthetically acceptable appears to be an implicit part of universal design for housing for the aged. The four criteria of universal design mentioned above all support the idea of enabling older people to remain independent and stay in their chosen home.

The notion of universal design has typically not been adopted, even in housing that is purpose-built for the aged. This purpose-built housing has tended to become based on a prototype in terms of density, size and organisation. Howe (1992b) considered the design of dwellings in retirement villages and found they were based on the premise that most of the residents would be ambulatory and free of mental health problems. However, people are living longer and many residents now become increasingly frail, confined to wheelchairs or afflicted with memory impairments yet wish to remain in their retirement village dwelling in spite of their lower personal competence. As a consequence, owners are facing expensive building alterations in oreder to reduce environmental demand (Gunts 1994).

If the principles described in Australian Standard 4299 'Adaptable Housing' (AS 1995) were adopted in the design of housing, many aspects of accessibility, adaptability and affordability of changes to construction could be satisfied. But even this standard is silent in regards to the thermal environment. The only tenuous reference is to 'ease of reach'. This is specifically related to electrical controls and the like, but could be extended to mechanisms for climatic thermal control, such as ease of reach to curtain adjustors or window latches.

Older people's reduced ability to manage the physical environment impacts on design. As observed by Davison et al (1993) and Shapiro and Tate (1988), older people want to age in place, whether in a family home, retirement village or public housing. For this to occur, there is value in exploring energy-efficient design options for thermal comfort in all housing. However, in housing designed specifically for the aged, where some occupants will undoubtedly be frail and have limited movement and dexterity, any exploration of energy-efficient design must address the principles of universal design. Any energy-efficient design features intended to reduce dependency on mechanical space heating or cooling in housing for the aged should not make unacceptable demands on the competencies of those people as they move through the ageing cycle. Nor should they contribute to an untenable increase in environmental demand in the dwelling. Designers introducing energy efficient features should be cognisant of the importance of mental mapping for older people. If there are any unfamiliar demands placed on the older person as a result of energy-efficient design, there is a probability that the demand will be ignored, although there is no evidence to indicate at what point in the ageing cycle any such non-essential demand is ignored.

In the light of the above discussion and the government policy regarding ageing in place, appropriateness of energy efficient design has a number of implications on the entire housing stock. One implication is that all houses should be energy efficient. Another implication is that there is a need to familiarise people with energy-efficient design before they are old, so that they do not perceive energy efficient design as a new environmental demand that is beyond their capacity to manage. It is not intended that these two implications be pursued in this thesis as they are considered to be beyond the scope of the current study.

2.3.3 Personal competence related to thermal conditions

The concept of 'personal competence' is part of the Lawton's model (1989) of assessing satisfaction with the residential environment. 'Personal competence' in Lawton's model refers to the normatively evaluated biological, sensory, motor and cognitive levels of a person. In the current study, the ability of an ageing body to sense and adjust to thermal conditions in the home is of significance.

Normal physical losses related to ageing, such as the loss of bone density, the loss of muscle density, a loss of elasticity in body tissue and a thickening of blood vessels (Burnet 1974), affect sensory losses. As conduction of stimuli through the nerves becomes slower (Blank 1988), older bodies become less able to adjust to changes in temperature (Havenith 2001), whether they are high or low temperatures. According to Kenney and Havenith (1993) this reduced ability to adjust to changes in temperature may be due not only to ageing *per se* but to decreased aerobic fitness, altered anthropometric characteristics and body composition.

Health deterioration[1] further exacerbates physical and sensory losses associated with ageing whilst medication used to alleviate symptoms of some chronic diseases is known to lower core body temperature (Marion, Mcgann & Camp 1991). The presence of drugs and mental illness may also reduce older people's sensitivity to thermal conditions (World Health Organisation 1982; Collins 1986) so older people come to accept conditions to which they have become accustomed over many years.

However Taylor, Allsopp and Parkes (1995) suggest that it is unclear whether par-

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[1] Health statistics for older Australians (ABS 1996b) indicate that 90% of people over 64 years of age had experienced a recent illness and 99% reported at least one long-term health condition. The most common illnesses were hypertension (arterial disease resulting in high blood pressure) and heart disease while the most common disabilities were sight and hearing loss and arthritis, with arthritis affecting half of all older people.

ticular vulnerabilities of the aged to extremes in environmental temperature is the result of an impairment of the body's automatic response mechanisms, a failure to detect thermal discomfort and to initiate appropriate behavioural responses, or a combination of these factors. Gunby (1994) claims that the lack of data recording how people's response to heat and cold progressively changes with age needs to be addressed. He suggests there would be value in a longitudinal study which examined the response of a group of people as they aged. This is beyond the scope of the current study.

2.3.3.1 Environmental cold

The body's ability to adapt to environmental cold reduces with age (Hardy 1981; Wagner & Horvath 1985). A number of factors are involved. The action of thyroid hormones, which affect heat production, reduce with age so exposure to cold, particularly for the old-old, can produce musculoskeletal[1], neurological[2] and mental changes. All these changes can increase the risk of falling (Lloyd 1986), so exposure to cold is particularly dangerous for the elderly.

Blood pressure and blood chemistry also change in cold conditions. A seven-year study by Donaldson, Robinson and Allaway (1997) of the blood pressure and haematology[3] of more than 38,000 men aged between 50 and 69 years of age, found that mortality rates increased significantly when the outdoor temperature fell. The research showed that in the range of 0°C to 20°C short-term exposure to falling temperatures, encountered during everyday activities, were sufficient to cause changes in haematological and cardiovascular parameters which increased mortality rates in winter.

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[1] Musculoskeletal is related to the framework of muscles and bones.

[2] Neurological is related to the nervous system.

[3] Haematology is the study of the nature, function and diseases of the blood.

A number of researchers refer to 18°C as a transition point for cold-related stress. Bustad (1980) refers to the risk of clinical hypothermia[1] at 18°C for the elderly as they are less sensitive to the sensation of cold on the skin than other age groups. Collins (1986) suggests that below 18°C, three indoor temperature ranges can increase health risks:

- Between 16°C and 18°C - increasing risk of respiratory disease;
- Between 12°C and 16°C - cardiovascular strain[2] due to cold;
- Between 6°C and 12°C - falling thermoregulation and risk of hypothermia.

At 18°C older people may begin to shiver, if physically inactive and inappropriately dressed, as an involuntary mechanism to increase heat production (Sprintz 1997). According to Keatinge, Donaldson et al (1997), the risk of mortality from cold stress is higher in regions with mild winters, such as Athens, than in colder regions such as Finland. These researchers analysed death occurances for people over 50 years old to determine the percentage increases in deaths per day per 1°C fall in outdoor temperature below 18°C. The results showed that high rates of cold-related mortality were associated with regions of higher mean winter outdoor temperatures, low living room temperatures, limited indoor heating, wearing of inappropriate clothing and low activity levels. Keatinge et al (1997) suggest that in countries with mild winters, where the need for cold-avoidance is less obvious, excess winter mortality could be reduced substantially by increasing indoor temperatures and advising older people to wear warmer clothing and keep active in cold weather, particularly when outdoors. This research is particularly relevant to design of housing for the aged in Perth, because of the mild winters where the minimum mean daily winter temperature is 8°C and night-time winter temperatures never fall below 0°C (Bureau of Meteorology 1998).

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[1] Hypothermia is a drop in deep body temperature, low peripheral blood flow and a failure of blood vessels to constrict in response to cold.

[2] Statistics (ABS 1996b) show that heart disease is one of the most common illnesses of the aged.

A large-scale study in Great Britain by Fox et al (1973) examining the relationship between the body temperature of the elderly and their thermal environment at home in winter, made two findings particularly relevant to the current study. One finding is that there is a lack of awareness of cold by some older people. The other is that there is a significant disparity between body temperature, replies concerning general body warmth and preference for greater warmth. With approximately 80% of respondents claiming to be comfortable or warm at the particular temperature in their home, virtually all respondents also answered that they would have chosen to be warmer when asked about their preference for warmth.

2.3.3.2 Environmental heat

The body's ability to adapt to environmental heat also reduces with age. When the skin temperature is high, blood supply to the skin is increased and the rate of heat loss by convection and radiation is increased. However with greater blood flow to the skin, there is some reduction to blood flow to internal organs such as the kidneys. There is also a rise in general blood circulation which is reflected in a higher heart rate (Givoni, 1969). These two physiological responses in hot weather, namely reduced blood flow to internal organs and a rise in blood circulation, can create potential stresses for older people as any increase in heart rate for the elderly may exacerbate hypertension and heart disease, two common diseases of the elderly (Australian Institute of Health and Welfare 1998).

As the elderly have a retarded vasodilation[1] reflex, this prevents effective heat transfer of (deep) body heat with resultant greater heat storage (Pandolf 1991; Sagawa, Shiraki et al. 1988). If the indoor temperature reaches the same temperature as skin temperature[2] then the body is not able to rapidly dissipate the heat produced and the problem of rising deep body temperature is compounded.

A factor that may slow the cooling of an elderly body is the reduction of effectiveness of the hypothalamus gland, which regulates sweat secretion. With less sweat

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[1] Vasodilation is the dilation of blood vessels by the action of nerves.

[2] The approximate maximum desirable skin temperature is 34°C (Auliciems & Szokolay 1997).

secretion, a slower rate of evaporative cooling to balance metabolic heat production can occur (Vassallo, Gera & Allen 1995). A review of the literature shows that there is no universal agreement in relation to the function of the sweat glands related to ageing. For example, Sagawa et al. (1988) study of the sweating responses of a small sample of aged men and young men found no significant difference in the on-set of sweating between the two groups. Notably though, participants in this study were young-old men.

In older adults there is evidence that they have a reduced physiological sensitivity of the thirst mechanism, so the elderly are more susceptible to dehydration and a resulting increase in deep body temperature in hot weather (Pandolf 1991). As dehydration causes increased circulatory strain, indicated by increased heart rates and body temperature, older people may become more easily stressed in hot conditions (Collins & Exton-Smith 1983).

The numerous studies described by Pandolf (1991) that looked at the thermoregulatory system of older people in hot climates generally used subjects who were healthy men and women less than 75 years old. It may be that for old and old-old people having more body deterioration than the young-old, there are even greater physiological response problems and thus potentially high levels of stress.

In temperate climates, where hot weather is sporadic, there is little evidence to establish at what temperatures the elderly display heat stress. However studies show that the elderly are particularly vulnerable during heat waves. A description of a record number of heat-related deaths in Chicago, USA during a heat wave[1] (Donoghue etal. 1995) found that 51% of those who died were aged 75 years or over and the median age of the victims was 75 years. A report to the US Department of Health and Human Services by Wainwright, Buchanan and Mainzer (1994) also established that the elderly are particularly susceptible to hyperthermia during heat waves. Skinner and Kuleshov (2001) also report this phenomenon in Sydney where hot weather can be severe but occurs irregularly. During unusually hot weather mortality rises sharply.

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[1] Temperatures over a five-day period were unusually high with maximum daily temperatures varying from 33.9°C to 40.0°C.

Vassallo, Gera and Allen (1995), in a study of hyperthermia in elderly residents living in an institution in Malta[1], concluded that there was a direct relationship between increased age and susceptibility to death from heat. The study also concluded that there was an increase in hyperthermia with a decrease in physical mobility and that women were more likely to be affected by hyperthermia than men.

In an extensive study of the relationship between air-conditioning in the home and mortality in hot weather in the United States, Rogot, Sorlie and Backlund (1992) established a clear benefit of both central air-conditioning and room air-conditioning in small dwellings[2] as a way to reduce mortality during hot weather. They concluded that the percentage of time spent at home indoors was a critical factor in their results. Women, older people and the unemployed showed the greatest reduction in relative risk from heat-related causes when air-conditioning was available.

2.3.3.3 Significance of understanding older people's response to temperature

The physiological changes in older people, referred to in this section, point to the value of exploring the design of housing for older people which could minimise the potential thermal stress in both cold and hot conditions. The physiological changes also raise the question as to how much of the energy use by the aged is a result of inappropriate response to indoor thermal conditions. In a climate such as Perth, with its mild winter, it could be that cold-avoidance strategies for the aged are particularly important.

2.4 Energy use in housing

This section explores attitudes towards energy use in the home, how older people respond to thermal conditions and how this response relates to their actual energy use in the home.

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[1] In Malta summer average temperatures are similar to summer temperatures in Perth, although humidity is higher in Malta (Malta weather station, 2001 [Online] December 4 Available: http://www.aboutmalta.com/weather/climate.shtml

[2] Small dwellings in this study have between one and three rooms.

2.4.1 General

Space heating and cooling, which is of particular interest in this study, accounts for about 39% of energy consumption, the largest energy use in residential buildings (Australian Greenhouse Office 1999a). Experience in Europe (Edwards 1996) has shown that for a marked reduction in space heating and cooling in housing to occur, houses need to be designed to be energy efficient and incentives or penalties must also be considered in order to change people's behaviour patterns. The European experience has not been widely adopted in Australia. Instead, the Australian Government has been calling for voluntary action to conserve energy and improve efficiency in the use of energy in buildings. Yet this voluntary route is not leading to a reduction in energy consumption (ABCB 2001). Consequently building regulations have been introduced recently in Australia to require a minimum level of energy efficiency in housing (ABCB 1996).

The price of energy has also not been used as an incentive to reduce energy use in buildings in Australia. Australia's electricity prices are amongst the lowest in the world. For example, residential electricity prices are one third of those in Japan and half of those in most of Europe (Uranium Information Centre 2001). Privatisation of Australia's electricity and gas industries in the 1990s has seen a fall in the real usage charges to consumers (Quiggin 1999). However Dobney (2001) predicts that electricity prices will rise in Australia in the near future by between 15% and 20%, although there appears to be a high level of uncertainty about future electricity prices (Harman 2002).

As suggested by environmental psychologists, it may be that the price of energy is not particularly influential on energy use in the developed world. Gardner and Stern (1996), take the view that in the developed world, domestic energy use is only influenced by price in the short term. Their evidence shows that approximately one year after a price rise, there is no residual effect of the price rise on domestic energy use. They suggest that changes in behaviour and attitude may provide a key to reducing energy consumption in the day to day running of houses, as life-style decisions made by millions of people could ultimately reduce levels of energy consumption.

In Australia though, there seems to be a reluctance to address home occupant behaviour. Mullaly (1998) suggests that this reluctance is largely the result of a lack of quantitative data demonstrating the effectiveness of changing attitudes towards home energy conservation. However two studies, one by Sonderegger (1978) who examined a housing estate in New Jersey, United States and another by Verhallen and van Raaij (1981) who studied housing in Holy North, Netherlands, have shown that 18% and 26% respectively of variance in household energy use could be attributed to household user behaviour.

A study of householders of various ages in Melbourne looked at a different aspect of energy conserving behaviour. Crossley's (1981) study of 47 Melbourne householders' attitudes to energy conservation identified a conspicuous gap between intentions and actions in relation to energy conservation. Crossley's research indicated that although the majority of householders were supportive of conserving energy, they perceived significant barriers to energy-conserving behaviour. In regard to their housing, five categories of barriers were identified from comments made by respondents about their non-adoption of energy-conserving behaviour. These barriers arose out of:

- personal predisposition, including both beliefs and knowledge about conserving energy;
- the living situation, including biological and physiological needs of the respondents, together with the life-style, physical and social living arrangements and household characteristics of the respondents;
- economic costs including capital costs of energy efficient equipment and lack of control over choice of equipment in rented premises;
- social costs including inconvenience, impracticality, discomfort and ugliness;
- inadequate information including, lack of awareness, lack of motivation to obtain information, reliability of information particularly on the more technical aspects of energy-conserving practices.

Some of these barriers can be considered as difficult-to-quantify costs to the individual. These costs that require changes in behaviour, additional effort or some risk taking, are rarely included in cost considerations for improving energy efficiency in housing. Morrill (1994) refers to these diverse and difficult-to-quantify costs as *transaction costs*. He suggests that, unless public strategies to improve energy efficiency in buildings integrate transaction costs with new technology, the success of such strategies will remain limited. In a commercial situation, many transaction costs can be given a dollar value based on the time invested by salaried staff in adapting to new equipment or new ways of carrying out their work. In a domestic situation, transaction costs may be seen in terms other than dollar value, such as improved conditions or an intangible 'feel good' factor. Lutzenhiser (1993) points out that in the domestic situation when the social, cultural and class implications that are associated with the acquisition of energy consuming items are added to required altered behaviour, a general inconvenience factor and a learning factor, transaction costs become almost impossible to quantify but cannot be ignored.

Twenty years on, the barriers of economic costs and inadequate information referred to by Crossley still exist. Energy consumption statistics from the residential sector show that there has been no reduction in energy consumption per person (Wilson, Trieu & Bowen 1993)[1]. Limited effort has been made to inform the public about the need for energy savings. The cost of renewable energy to the residential consumer in Perth, Western Australia is 22% higher than non-renewable energy[2], if it is available at all and energy efficient white goods are generally more expensive than less efficient equipment (Australian Greenhouse Office 1999a).

2.4.2 Energy use by elderly at home

The elderly who can afford mechanical heating and cooling have high energy usage. In a study by the author (Karol 1997) of energy consumption in three non-

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[1] Average annual energy consumption per person in the period 1973/74 to 1981/82 was 18.16 GJ and in the period 1982/83 to 1990/91 was 18.38 GJ.

[2] The cost of renewable and non-renewable energy is indicated on energy bills in June 2003.

government retirement villages in Perth, the energy consumption per dwelling occupant was higher than the equivalent energy consumption in dwellings in a typical suburban subdivision in Perth. This was the result of high usage of energy for mechanical heating and cooling in the retirement village dwellings. Likewise Yamasaki and Tominaga (1997), in a study of ageing householders in Japan report that fuel and light expenses per person are higher and are growing at a higher rate in the ageing households than in other households.

One reason for high energy use for heating is attributed to the amount of time spent in the home. American research shows that the amount of discretionary time spent inside the home increases with age and those over 65 years old spend eighty to ninety percent of their day at home (American Association of Retired Persons 1990). The behaviour of older people in Australia is similar to that of older people in the United States with, on average, older people spending twenty-one hours out of the day in their home (ABS 1987b).

Other reasons given for high energy use per person for older people in the United States are that they are likely to live in older homes without insulation and that they set their thermostats higher (American Demographics Desk Reference 1993). A reason suggested for the higher thermostat temperatures is that older people are likely to remain in one position for some time (Belser & Weber, 1995). Also, as discussed previously, their blood circulation system may be compromised so they have an increased susceptibility to cold. In Japan, additional reasons are suggested by Yamasaki and Tominaga (1997) for high energy use by older people: larger houses occupied by fewer people, more energy-consuming equipment and a desire to eliminate temperature variations between different rooms in the home. The less affluent elderly either spend a high proportion of their income on heating or subject themselves to thermal stress.

In an Australian study, Davison et al. (1993) found that when the old and old-old talk about heating their homes in winter in Melbourne, the less affluent ones talk about a 'winter lifestyle' which is determined by the location of available heating. Some people move into one or two rooms where there is a heater which they use regularly, while others (particularly those who are private renters) are very conscious of energy expenditure and may go to bed early rather than turn on a heater.

Other studies have found that for the less affluent, the psychological importance of heating and cooling has particular significance. In a study entitled 'Energy inputs and household behaviour in France' Monnier indicated that in public housing, where households had little social mobility, the feeling of warmth took on a symbolic significance[1] and as a result, energy use was relatively high (cited by Heijs & Stringer 1988). Yamasaki and Tominaga (1997) also found that for low-income groups in the elderly population in Japan, the need to feel warm was a priority, and energy consumption was growing in these households at a higher rate than in other households.

However for the elderly poor, the need for mechanical heating and cooling creates an unaffordable financial burden. This financial burden can be seen in United States data from the 1990 Consumer Expenditure Survey conducted by the Bureau of the Census which indicated that, as a proportion of total expenditure, the over-65 year-old householders spent more on home heating than any other age group (Schwenk 1993). Some elderly poor spent more than 40% of their income on heating (Grogan, Valente & Chapman, 1991).

Another consequence of the need for mechanical heating and cooling is that many low-income, elderly poor economize on energy use for heating, increasing the at-risk population for temperature related deaths (Slater 1988). Macey and Schneider (1993) found in their study identifying elderly at highest risk of mortality from excessive heat and cold, that the urban poor, who were often malnourished, needed proactive intervention to minimize their risk levels. Such things as budget assistance, utility subsidies, weather proofing of older houses and adequate heating installations in rental properties were needed. In Britain, to address the issue of expense, the Government has a scheme of cold weather payments to all pensioners to reduce the possibility of someone dying of hypothermia because they cannot afford to heat their

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[1] The inverse could also be true. In hot climates the feeling of coolness may take on a symbolic significance of well-being leading to high use of air-conditioning, although no evidence of this was discovered.

homes. When the outdoor temperature is 0°C or less for more than seven consecutive days, pensioners receive £5 (this is more than 10% of a single pensioner's weekly income) for each week of cold weather (Kane, 1991). Despite this attempt to address fuel poverty, Britain has the worst record in the European Union for cold-related winter deaths. This is mainly attributed to old housing stock with poor insulation (Smith 2001).

In Western Australia the only financial assistance for mechanical heating and cooling is a concession on electricity bills for the elderly. There is no concession on gas charges. The concession on energy bills, for those receiving the age pension, is a rebate on the electricity supply charge[1]. There is no reduction on the rate paid for energy consumed and the rebate is not related to type or size of dwelling.

With privatization of the energy market, it is predicted that energy prices will rise in Western Australia[2]. Whether some State Government response becomes necessary to a potential increase in morbidity and mortality of the elderly, resulting from large energy price rises and reduced affordability of space heating and cooling, is yet to be established.

2.5 Summary

In Australia the number of small, medium density dwellings being constructed is increasing. As a significant number of these dwellings are being occupied by those over 55 years of age, the dwellings will need to adequately meet the needs of people who may be physically and financially vulnerable, particularly in old-old age. The principles of universal design incorporate design criteria that are especially relevant to small, medium density housing.

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[1] The rebate is approximately $95 per annum in 2003 as indicated on energy bills in June 2003.

[2] Based on experience in the eastern states of Australia, privatisation of the electricity market ultimately leads to increase in the cost of energy to the consumer. In Victoria there is an increase of 20% in electricity prices predicted in 2003 (Dobney 2001).

As ageing reduces the ability of the body to thermo-regulate and even to accurately sense the thermal conditions, the readily available provision of appropriate thermal conditions is important for the well-being of the elderly. The elderly who can afford to use domestic space heating and cooling do so and contribute significantly to Australia's greenhouse gas emissions. However some older people do not have the financial resources to use space heating and cooling to improve their thermal environment. This study suggests that energy-efficient design could be utilised in small, medium density housing, particularly in housing for the elderly, provided that design elements do not create unacceptable environmental demands on the occupants.

3. Appropriate thermal conditions and energy efficient design

3.1 Preamble

In Chapter 2 the needs of older people in relation to their physical and sensory decline were considered. It was concluded that if small, medium density housing is to provide appropriate housing for the aged it must respect the physical and financial limitations of older people. This raises the question as to whether energy-efficient design, that can reduce thermal and financial stress on occupants of small, medium density housing as well as reducing energy consumption in housing, can also be designed to be appropriate for the aged.

In the first part of this chapter the idea of small, medium density housing being 'appropriate' is further pursued by considering the temperatures determined as appropriate in non-air-conditioned buildings in a temperate climate (section 3.2). The second part of the chapter prepares a framework for the study of that part of the hypothesis relating to benchmarks for energy efficient design in small, medium density housing (section 3.3). The needs of older people, as discussed in Chapter 2, are overlaid on this framework for energy efficient design.

3.2 Indoor thermal considerations

As the current study involves an exploration of indoor thermal conditions in housing for the aged, there is a need to establish a temperature range that is considered acceptable to the occupants of such housing. Since the 1970's researchers such as Humphreys (1978), Auliciems (1981) and Givoni (1992) have referred to the complexity of precisely establishing the meaning of an 'acceptable' temperature in different cultural situations and in a variety of climates. Other researchers (Coldicutt, Williamson & Penney 1991) refer to thermal acceptability as being clearly context-dependent, so for example the thermal conditions people accept in different seasons inside their homes are quite different from what is acceptable in an air-conditioned work place. In the current study the meaning of acceptable is considered in the context of non-air-conditioned housing in Perth. It is important to distinguish this context-dependent use of the term 'acceptable' from the use of the term in ISO 7730 (1994) that defines 'acceptable' as being independent of context. In the current study quantitative values for thermal acceptability are established by considering de Dear and Schiller Brager's (1998) adaptive approach to thermal comfort and Humphreys and Nicol's (2000) consideration of optimum comfort in non-air-conditioned buildings.

3.2.1 Preamble

When Aristotle in 350 B.C. proposed his doctrine of the five senses - sight, hearing, smell, taste and touch - he made no reference to thermal sensation, as it was not associated with any identifiable sense organ (Gagge, Stolwijk & Hardy 1967). Research has only partly succeeded in explaining the complex condition of mind that is called human thermal comfort and why this condition of mind changes in different societies, at different times in history and with different technological and economic conditions. The complexity of the idea of human thermal comfort may also explain why there is an on-going debate by researchers (Oseland & Humphreys 1994; Brager & de Dear 2001) as to the range of temperatures that are acceptable to building occupants.

3.2.2 Concept of thermal comfort

Human thermal comfort is described in air-conditioning standards[1] as a subjective evaluation of thermal conditions where at least 80% of the population will consider the thermal conditions as being 'neutral' or 'comfortable'[2]. According to Shove (1995), the temperatures determined by air-conditioning standards have come to be expected in most building types in the industrialized world. Such expectations do

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[1] Thermal comfort standards for designers of air-conditioning systems include ASHRAE (1992) and ISO (1994).

[2] 'Neutral' or 'comfortable' are intended to demonstrate that a building occupant does not want the thermal conditions to be cooler or warmer than the conditions they are experiencing.

not accommodate non-air-conditioned buildings and imply an inferior quality of building if temperatures range outside the temperatures determined by air-conditioning standards.

The standards take a psycho-physiological approach to thermal comfort, based on a human heat-balance model as expressed by Fanger (1972) and McIntyre (1980). The heat-balance model reflects the results of controlled climate chamber experiments, in Denmark and the United States, that show that the majority of people indicate they are comfortable if a balance is kept between the rate of heat production by the body and the rate of heat losses by the body to the environment.

According to Oseland and Humphreys (1994) the model based on climate chamber experiments has brought about the notion that there is a fixed, narrow temperature range at which people rate their thermal sensation as neutral or comfortable. A narrow temperature range may be appropriate in optimizing human productivity in air-conditioned buildings, but a narrow temperature range disregards geographic location, climate, thermal expectations of building occupants, energy consumption of heating and cooling appliances or people's physical differences. Auliciems and Szokolay (1997) and Nicol and Humphreys (2001) indicate there is a growing consensus that this heat-balance model is unnecessarily restrictive.

3.2.3 Variables affecting thermal comfort

In this section, six interrelated factors that contribute to an assessment of human thermal comfort[1] are considered. According to Auliciems and Szokolay (1997) there are four environmental factors - indoor temperature, thermal radiation, humidity and air speed (see section 3.2.3.1) and two building occupant factors - personal activity and clothing levels (see section 3.2.3.2). In addition there are thermal comfort indices that provide a means of establishing comfort limits or a means to determine the optimum balance between all the quantifiable factors contributing to thermal comfort (ibid)(see section 3.2.3.3).

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[1] The definition of thermal comfort in ASHRAE (1992) refers to a subjective evaluation of satisfaction with thermal conditions on a 7-point thermal sensation scale.

3.2.3.1 Environmental factors of thermal comfort

Air temperature

The appreciation of indoor thermal conditions by humans is primarily based on a measure of dry-bulb air temperature as perceived by convection exchange. Researchers such as Bedford (1936), Drysdale (1950), Fanger (1972) and McIntyre (1980) acknowledge that the determination of convective heat dissipation, as measured by dry-bulb temperature, is the most important single measure in all studies of the thermal sensations of human subjects unless conditions are very hot and humid. According to Oseland and Humphreys (1994), in tropical conditions when the humidity of the air determines the evaporative capacity of the air and hence the cooling efficiency of sweating, another environmental factor, humidity, become equally as important as dry-bulb temperature.

Humidity

Humidity affects the quantity of water evaporating from the nose and respiratory surfaces and diffusing through the skin. By decreasing the humidity of the environment, a person's total evaporation rate and associated energy loss through evaporation is increased. As lower humidity results in a lowering of the skin temperature, a person feels cooler at the same temperature in a drier environment than in a humid environment (Berglund 1998). However, only at high temperatures does excessive humidity have adverse effects on feelings of comfort (Givoni 1992). Researchers such as McIntyre (1973) and Fanger (1972) have concluded that large changes in relative humidity in the range of 20% to 75% at average room temperatures, before the onset of human sweating, do not have a significant influence on feelings of warmth.

Thermal radiation

McIntyre (1980) in his work on radiation transfer between the human body and the environment, makes it clear that in many indoor situations, where surrounding surfaces are at a temperature which is similar to the dry-bulb air temperature, radiation is not a major determinant of thermal comfort. This is supported by Auliciems and Szokolay (1997) who suggest that, in a heated space, thermal comfort is not affected if mean radiant temperatures are between 2 K lower and 2 K higher than dry-bulb temperature. Radiation such as that coming from an unprotected window however can be a particular cause of discomfort, especially when ambient conditions are near the upper or lower limits of comfort.

If radiant panels are proposed for heating or cooling in a house, designers should be aware of the practical limitations of such devices. Oseland and Humphreys (1994) point out if radiant panels are small, a detailed knowledge of the location, orientation and posture of the person being heated or cooled and the potential discomfort from localised differential temperatures over the body surface must be addressed. In addition, the limited distance over which radiant panels are effective must be recognized. This limitation will be discussed in section 3.3.2.2, in relation to radiation from a Trombe-Michel external wall used as a solar collector.

Air movement

Air movement increases the convective heat exchange of the human body with the surrounding air. The higher the velocity of the air movement and the greater the air turbulence, the greater the evaporative rate at the skin surface and the greater the convection heat loss of the body or clothing surface (Fanger et al. 1988). Air flow also increases the heat loss of materials through convection. A pertinent aspect of the current thesis relates to how much air movement is desirable in summer to raise the acceptable maximum summer temperature in a temperate climate.

Over the years researchers have provided various suggestions related to air movement. Auliciems and Szokolay (1997) suggest that the human reaction to air movement depends on air temperature, the velocity of the air movement and individual preference. In hot conditions, Auliciems and Szokolay refer to a velocity of up to 1.5 metres per second (m/s) as acceptable. However, as suggested by Fountain (1995), because of individual preference, it is difficult to predict with accuracy how much air movement in summer leads to physical discomfort despite the cooling effects. Macfarlane (1958) indicated that thermal comfort zone temperatures could be raised by 0.55 K for each increment of 0.15 m/s of airflow past the skin, up to a maximum temperature of 33°C.

Givoni (1998) suggests that in non-air-conditioned buildings, indoor air speeds of between 1.5 m/s to 2 m/s (a very light breeze), are acceptable and could raise the upper limit of thermal comfort by up to 6 K above the ASHRAE upper limit. Wooley's (1999) recommendation regarding the cooling effect of air movement in non-air-conditioned buildings in hot dry conditions is that an air speed of 1 m/s will have a cooling effect of approximately 3 K provided that the air temperature is below a maximum of approximately 33°C.

In air-conditioned buildings ASHRAE (1992) specifies the upper limit for air movement as 0.8 m/s, on the basis that loose papers would be disturbed above this limit and that cold, mechanically-cooled air streams would be uncomfortable to building occupants. Air movement of 0.8 m/s is considered to raise the maximum comfort temperature in summer by 3 K above the ASHRAE (1992) upper limit of comfort at normal levels of relative humidity.

3.2.3.2 Building occupant factors of thermal comfort

Activity level and clothing insulation have a direct impact on determining acceptable thermal conditions. The amount of heat produced by the body depends on the level of activity and is reflected in the metabolic rate. The metabolic rate also depends, but to a lesser extent, on the basal metabolic rate which has been shown to decrease in the old-old (Ausman & Russell 1991). In ASHRAE (1992) metabolic rates for typical levels of activities are expressed in a unit called the 'met' and, for domestic activities, vary from approximately 1.0 met ($58 W/m^2$) for a person quietly seated to approximately 2.0 met ($116 W/m^2$) for a person doing active domestic work.

The metabolic rate depends to some extent on body shape and body fat. As heat production is related to body mass but heat dissipation depends on body surface area, a rounded body shape would have a lesser heat exchange with the environment than a thin body and have a higher level of body insulation (Auliciems & Szokolay 1997). This opens up the question as to how accurately the 'met' represents the heat loss and heat gain of the elderly. According to Wagner and Horvath (1985), the elderly who volunteer for environmental research are generally healthy young-old adults. The average Western young-old adult is at their peak in terms of body fat content (Linder

1991), but as they move into old age the body fat content declines sharply (Brown 1990). The changes in body heat production and dissipation could well have an effect on the range of temperatures considered to be comfortable by the old or the old-old, although no quantitative guidance could be located in this matter.

Clothing is a factor affecting heat dissipation, due to its insulating value. ASHRAE (1992) provides generally accepted typical insulation values for the resistance to sensible heat transfer for clothing. These values are expressed in 'clo', where 1.0 clo provides a thermal resistance of 0.155 m^2K/W. A man's business suit, when worn with cotton underwear, has 1.0 clo insulating value.

In addition to clothing, the furniture on which a person sits or lies contributes to body insulation. McCullough, Olsen and Hong (1994) provide a quantitative assessment of chair insulation based on a climate chamber experiment. These researchers indicate that the insulation value of an office chair can vary from 0.1 clo to 0.3 clo, depending on the amount of chair surface area in contact with the body and the style of clothing worn. No data could be traced in relation to insulation levels of furniture typically used by older people in their homes such as armchairs or beds. Bed insulation in particular may influence the determination of a maximum comfort temperature in summer for the aged at home. In the current study, an assumption is made that when calculating an acceptable maximum summer temperature, the sum of the insulation value of clothing worn to bed and the mattress insulation will not exceed any stipulated limit for clothing insulation. The research required to confirm the above assumption and establish the thermal insulation and evaporative resistance of mattresses is beyond the scope of the current study.

3.2.3.3 The psychrometric chart and indices of thermal comfort

The psychrometric chart, together with indices of thermal comfort, is fundamental to the process of designing for thermal comfort. The psychrometric chart graphically represents the various attributes of the mixture of air and water vapour in the atmosphere at different temperatures. It is typically used to determine the changes required to sensible heat and latent heat of the outdoor air being drawn into a building, in order to create acceptable indoor thermal conditions (Auliciems & Szokolay 1997).

However in the current study the psychrometric chart shown in Figure 3-1 is used to determine a widely used thermal comfort index, effective temperature (ET*).

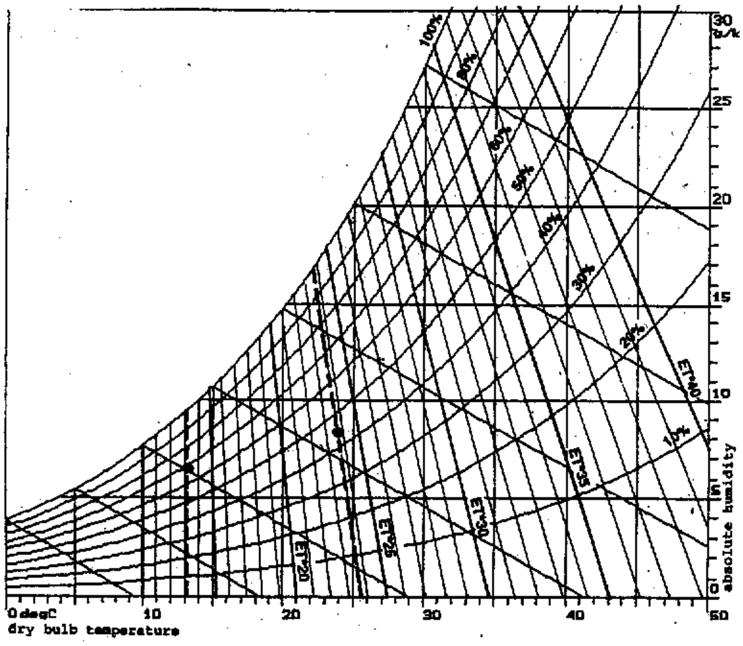

Figure 3-1 *Psychrometric chart showing DBT, WBT, RH and AH with ET* lines superimposed (Auliciems & Szokolay 1997 p. 60)*

Auliciems and Szokolay (1997, p.36) define ET* as

> *"the temperature (DBT) of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question".*

As ET* is a measure used to describe the human response to the combined effects of radiation, convection, evaporation and dry-bulb temperature for a particular metabolic rate and clothing insulation level, it is used by de Dear and Schiller Brager (1998) in their adaptive approach to thermal comfort (see section 3.2.5). As shown in Figure 3-1, lines of constant ET*, as established (Rohles, Hayter & Milliken 1975), have been superimposed on the psychrometric chart and can thus be readily quantified in the current thesis.

3.2.4 Acceptable thermal conditions for the aged

As demonstrated in a number of studies related to thermal comfort of the elderly carried out prior to the 1990s and referred to below, the elderly seem to be thermally comfortable in the same temperature range as the rest of the population. However more recent research indicates that there may be some differences between thermal comfort for the aged and for the general population. This difference may be related to a greater recognition that those traditionally volunteering for environmental awareness research were probably above average in health well-being and health consciousness and that elderly people who volunteered were usually young-old rather than old or old-old (Wagner & Horvath 1985).

Although the subjects of Rohles' (1969) study were not young-old, that study was a postal survey involving the notation of a comfortable temperature. In Rohles' study 64 elderly subjects (over 70 years of age and with a mean age of 75 years) in Kansas, United States were required to indicate their preference for a particular listed temperature by noting whether that temperature was comfortable, too hot or too cold. The temperature that was judged comfortable by the largest percentage of subjects was 75.1° F (23.9°C). On the basis of research by the author that examined thermal conditions in 30 retirement dwellings in Perth in 1996, this method of asking the elderly about the temperature may not be accurate. The author found, during interviews with the occupants of the retirement villages, that the perception of temperature of those interviewed was very inaccurate. When asked to indicate what the interviewees believed the indoor temperature to be at the time of the interview, some responses varied by more than 10 K from the actual temperature.

Based on climate chamber experiments, Fanger (1972) expressed the opinion that older people did not require higher temperatures for comfort, although he recognized that the basal metabolic rate declines with age. He claimed that a lower basal metabolic rate was compensated for by a lower rate of insensible evaporation. Other researchers, Griffiths and McIntyre (1973), confirmed experimentally that the ambient temperature required in winter by older women was no higher than that of the general population. However according to Vassallo, Gera and Allen (1995), older women are more susceptible than younger women to heat stroke at higher temperatures.

Cena, Spotila and Avery (1986) discovered, on the basis of their field surveys in New York and Ontario, that there was no effect of age on the preferred indoor comfort temperature. The mean dry bulb temperature of the dwellings in that winter study was 20.7°C and the elderly were generally thermally comfortable. However Cena, Spotila and Avery conclude from their study that the elderly are lowering ambient temperatures in their homes, for reasons relating to the expense of fuel and the societal pressures to reduce heating costs, without increasing their clothing insulation. Similar findings related to the expense of fuel have arisen in British studies. Kane (1991) and Fox et al (1973) found that the elderly poor in Britain lower indoor temperatures in winter to reduce expenses on heating.

Another interpretation of the acceptance of low temperatures by the elderly is identified in a more recent study. In a study comparing the preferred room temperature of young and aged men, Taylor, Allsopp and Parkes (1995) suggest that the elderly accept greater fluctuations in temperature extremes than the young, suggesting that their threshold of discomfort at low temperatures may be wider as a result of previous thermal history. This lower threshold of discomfort could also be explained however, by a slower response by older people than by the general population to external stimuli in general, as well as to temperature change. According to McIntyre (1978), the onset of discomfort as a result of temperature changes is not sudden and reactions depend very much on what else is occupying the person, the individual's expectations and their personality. This slowness of response to temperature change may contribute to older people failing to increase their clothing insulation or their activity level to compensate for lower ambient temperatures.

A slightly different observation was made in a Japanese study. Tsuzuki-Hayakawa et al's (1996) field study of housing conditions for the elderly in a village north of Tokyo showed that elderly subjects were more aware of the cold in their old age than in their youth but dealt with the cold winter conditions by increasing the amount of clothing worn, although this did not help with low temperatures in toilets, which were a particular concern.

Another field study[1] in Japan by Kashiwa et al (1996) monitored indoor temperatures of dwellings occupied by elderly people in summer and winter and the occupants were interviewed. During the interviews, occupants were asked to rate their indoor environment in relation to thermal sensations, sunshine, brightness, ventilation, spaciousness and noise. Although thermal comfort was not a major source of complaint by the elderly (lack of space, lack of sunshine penetration and excessive noise were the main complaints), the average temperatures of the overwhelming majority of accommodation was unsatisfactory. Average indoor air temperature in summer was 28.9°C. In winter, the average living room temperature was approximately 16°C and the average toilet temperature was approximately 11°C. These thermal conditions reflect Humphreys' (1981) observation that over time people accept the climatic conditions to which they become accustomed, whether the conditions are within a very narrow temperature range or are wide-ranging, and irrespective of whether the conditions may detrimentally affect their well-being.

Isaacs and Donn (1993);(1990), in two reports on seasonality in New Zealand mortality rates, present an apparent interaction between winter temperatures, mortality statistics, thermal performance of housing and house heating for those aged 65 and over. Their investigations shows a higher mortality rate in winter for those aged 65 and over than for the rest of the population. They also show that more than 30% of the lounge rooms in a study of 36 units for the elderly had minimum daily temperatures below 16°C. The study by Skinner and Kuleshov (2001) confirms that there is a regular peak in mortality in the over 65s even in mild winters such as that experienced in Sydney. The peak in mortality appears to be most closely associated with low outdoor temperatures (ibid).

Lloyd (1990) takes a slightly different position regarding temperature in the homes of older people. His position is that the body is more susceptible to variations in temperature than to a steady state low temperature, so for the elderly there is more risk in having one room much warmer (or cooler) than another. He maintains that

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[1] In winter 28 dwellings and 33 elderly occupants were involved and in summer 18 dwellings and 28 elderly occupants were involved.

bedrooms, bathrooms and living rooms should be maintained at similar temperatures.

When mortality statistics, indoor temperatures and increased health risks below 18°C (see section 2.3.3) are considered together, the link between the health of the aged and the thermal performance of their housing becomes persuasive.

3.2.5 Thermal comfort based on adaptive approach

The hypothesis articulated by Auliciems (1981), regarding the indoor-outdoor climatic interactions with thermal perceptions, provides a starting point for considering thermal comfort in non-air-conditioned small, medium density housing for the aged. Auliciems' hypothesis, referred to as an 'adaptive model of comfort', suggests that building occupants adapt their thermal expectations and preferences on the basis of prevailing outdoor and indoor temperatures, as well as on the basis of social and cultural norms.

Subsequent studies related to human adaptation to thermal conditions, such as those by de Dear and Schiller Brager (1998) and Humphreys and Nicol (2000), developed Auliciems' (1981) hypothesis and suggested that a holistic approach to the indoor environment is more appropriate in satisfying thermal comfort, air quality and low energy needs than the traditional approach reflected in thermal comfort standards. In addition to taking into account outdoor meteorological conditions, both these studies indicate that there are two broad categories of adaptation namely, behavioural adaptations when people, through their actions, play an active role in maintaining their thermal comfort, and psychological adaptation, where expectations and reactions are reconsidered. Non-air-conditioned, small, medium density housing for the aged allows for thermal adaptation by the occupants in regard to behavioural adjustments (such as changing clothing, resting and turning on a fan on a hot day, sitting in the sun in winter) and to psychological adaptation to some extent, as occupants may not have a history of living in small, medium density housing which is not the common form of housing in suburban Australia.

De Dear and Schiller Brager's (1998) adaptive theory of thermal comfort was based on a quality-controlled database from thermal comfort field experiments worldwide. Approximately 21,000 observations from 160 buildings were included in the data base. The field experiments showed that comfort depends on how people adapt to their climatic and cultural environment, as well as on the standard environmental and personal factors that influence perceptions of thermal comfort. The statistical analysis of data from the field studies indicated that, within certain limits, people adapt their thermal comfort expectations to their climatic and cultural environment. This adaptive approach showed that the temperature ranges for thermal comfort can be extended beyond the limits established in AHRAE (1992).

To establish an optimum temperature (T_n) using Equation 1 below, developed by de Dear and Schiller Brager (1998), calculations are first performed on meteorological air and humidity measurements to determine mean monthly dry-bulb temperature and relative humidity. The dry-bulb temperature and relative humidity can be plotted on the psychrometric chart shown in Figure 3-1 and mean monthly outdoor effective temperature (ET*) can be established.

$$T_n = 18.9 + 0.255 \times ET^* \qquad \text{Equation 1}$$

Using the same data base used by de Dear and Schiller Brager (1998), 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 (T_c) depends on mean outdoor temperature (T_o) rather than ET*. They suggest that Equation 2 below is an appropriate means of determining the comfort temperature.

$$T_c = 13.5 + 0.54T_o \qquad \text{Equation 2}$$

The limitations for acceptable temperatures using either of the above equations are applicable to the current study, as the limitations are for:

- sedentary people wearing clothing of their choice;
- people engaged in light activity;
- slight air movement; and
- climatic zones where the mean temperature ranges from 10°C to 33°C.

Nevertheless, it is recognized that debates about exactly how much outdoor climate, cultural expectations, financial considerations and energy implications may influence thermal comfort (particularly in non-air-conditioned buildings) still continue, as can be seen in papers presented by eminent researchers at a conference exploring possible thermal comfort standards in the 21st century. Papers by Fanger and Toftum (2001), Nicol and Humphreys (2001), Parsons (2001) and Brager and de Dear (2001) each questioned some aspect of the changing balance between occupant expectations of indoor temperatures and the sustainability of those expectations.

In the current thesis, Equation 1 is used to establish the optimum comfort temperature as Equation 1 provides a more conservative[1] result for Perth than is obtained by using Equation 2 (see T_n and T_c in Table 3-1).

	Mean temp. (°C) (T_o)	**Monthly mean RH (%)**	**ET* (°C)**	**T_n (°C) (Eq 1)**	**T_c (°C) (Eq 2)**	**Summer max./winter min.(°C)(Eq 1)**	**Summer max./winter min. (°C)(Eq 2)**
Jan. mean	23.8	45.5	23.7	24.9	26.4	27.4	28.9
July mean	13.2	69.5	13.2	22.3	20.6	19.8	18.1

Table 3-1 *Acceptable summer and winter design day temperatures using the adaptive approach*

To determine the maximum and minimum acceptable temperatures, it was necessary to establish an acceptable temperature range around the optimum temperature. This range can be taken as T_n -3.5 to T_n +3.5°C for 80% acceptability, or T_n -2.5 to T_n +2.5°C for 90% acceptability (Auliciems & 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. If these opportunities are minimal, the acceptable range of temperatures may be limited to +2 K or –2 K around T_n. In private housing in general, occupants do have the opportunity to change their clothes, levels of activity and rate of air movement, although for the old-old, this may cause some difficulty. Balcomb (1987) suggests that a diurnal temperature swing that is greater than 10°F (5.6°C) is gener-

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[1] Conservative is used to refer to a lower optimum comfort temperature in summer and a higher optimum comfort temperature in winter.

ally considered uncomfortable. As a result of these observations the 90% acceptability rate was applied to the optimum comfort temperature (T_c), calculated using Equation 1. The maximum summer and minimum winter temperatures are shown in Table 1.

Both Equations 1 and 2 fail to address the issue of the time for which a space may be occupied. Forwood (1995a) suggests time is an important parameter when considering the adaptive approach to thermal comfort. He argues that in defining acceptable temperature ranges, people will consider temperatures in excess of the upper range of the thermal comfort zone as acceptable, over a limited time period. However, in housing for the aged this argument may not be appropriate, as older Australians spend approximately twenty-one hours of the day in their homes (ABS 1987b) and all activities undertaken by the frail aged are time consuming.

3.2.6 Acceptable temperatures

As previously indicated there are no universal thermal conditions that are promoted as being acceptable for the aged, whether in air-conditioned buildings or non-air-conditioned buildings. The International Standards Organisation recognises the lack of information specifically related to thermal comfort of disabled, aged and other special groups occupying air-conditioned buildings. As a result, a working group (ISO WD 14415) is evaluating the special thermal needs of these three identified groups of people (Parsons 1995).

In addition to the temperature limits discussed in section 2.3.3.1 as inducing cold-related stress, there are some recommendations for temperature limits for the aged. These are summarized below.

- ASHRAE (1992) includes a note that the lower limits of the acceptable ranges of temperature determined in accordance with the Standard should be avoided for certain undefined elderly people. The generally recommended lower limit for an acceptable thermal environment, for people who are sedentary for more than one hour, is a temperature of not less than 18°C.

- The World Health Organisation (1984) recommends a minimum dry-bulb temperature of 18°C for rooms occupied by the young, old and disabled.

- The Architectural Institute of Japan recommends that minimum winter temperatures in living rooms should be 21°C and in toilets 22°C, and in summer, the maximum living room temperatures should be 27°C and in toilets, 29°C (cited in Kashiwa et al 1996).

In the current study, an acceptable temperature range has been established for public housing for the aged in Perth, based on the adaptive approach of de Dear and Schiller Brager (1998). Table 3-2 shows a summary of this acceptable range, together with three other sets of suggested temperature limits for energy-efficient buildings in a temperate climate. The maximum summer temperature is for still air conditions.

	Summer maximum (°C)		**Winter minimum (°C)**	
	Day	**Night**[1]	**Day**	**Night**
Baverstock & Paolino (1986) - Perth	28	-	18	-
Givoni (1992)[2]	27	-	18	-
Ballinger, di Franco & Prasad (1993) – Sydney[3]	27	24	18	12
de Dear & Schiller Brager (1998) - Perth[4]	27.4		19.8	

Table 3-2 *Maximum and minimum comfort temperatures applicable to non-air-conditioned buildings*

The minimum winter temperature of 19.8°C, determined using the adaptive approach to thermal comfort, is approximately 1K less than the recommendation of the Architectural Institute of Japan but approximately 2K higher than the World Health Organisation recommendation, the temperature at which the elderly may be subjected to health risks (Collins 1986). The temperature of 19.8°C is also approximately 2K higher than the general comfort limits suggested for energy efficient buildings. The

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[1] Night is defined as between 10pm and 7am (Ballinger, di Franco & Prasad 1993).

[2] Givoni (1992) refers to 27°C as the summer maximum temperature when humidity is low and there is no air movement.

[3] Comfort temperatures provided for Sydney may accommodate a slightly lower mean dry-bulb temperature and higher humidity levels in summer than in Perth (Drysdale 1975). However Sydney and Perth are designated in the same climatic zone in the ABCB (1996).

[4] Refer to section 3.2.5 for computations determining the maximum and minimum temperatures using the adaptive approach.

minimum temperature of 19.8°C seems appropriate in the light of the discussion in section 2.3.3.1 related to the vulnerability of the elderly to cold, particularly in climates having a mild winter.

The summer maximum temperature of 27.4°C in still air, determined using the adaptive approach to thermal comfort, does not appear to be in conflict with any of the identified research related to acceptable temperatures for the aged.

3.3 Energy efficient design in a temperate climate

Researchers (Balcomb 1984; Ballinger, Prasad & Rudder 1992; Givoni 1994) agree that in a temperate climate there are basic principles of design that can be applied to houses to make them energy efficient. These principles of design can significantly reduce the need for mechanical heating and cooling. According to researchers who have designed energy efficient housing in Perth (Baverstock & Paolino 1986, p.7),

"with the exception of relatively short periods of extreme climatic conditions, efficient solar homes built in Perth have maintained a temperature range of 18 to 25 °C in winter and between 20 to 28°C in summer with no auxiliary heating and cooling systems (apart from a wood fired cooking stove and ceiling fans)".

In this section, the basic principles of design that utilise solar energy and natural ventilation to make housing energy efficient are explored, including building orientation, thermal mass, control of heat transfer through the building envelope, zoning of indoor activities and ventilation for cooling.

3.3.1 Overview

Two thousand years ago the Roman architect Marcus Vitruvius Pollio advised in "The Ten books of Architecture",

"*if our designs for private houses are to be correct, we must at the outset take note of the countries and climates in which they are built.*" (Vitruvius 1960, p. 72).

For centuries this advice was heeded and rules of thumb were developed on the ways to maximise indoor thermal comfort in particular climatic and social settings. These rules of thumb were passed from one generation to the next (Rudofsky 1965) but were gradually modified with new technology and changes in social structure. By the middle of the twentieth century the impact of mechanical space heating and cooling was so strong that modern housing design could afford to ignore climatic conditions and not only satisfy general thermal comfort requirements but actually specify narrow bands for indoor temperature and humidity levels.

Olgyay (1963) in observing this growing separation between design of housing and the climatic region where a building was constructed, produced a definitive work on establishing what he called a 'bioclimatic' approach towards design. This bioclimatic approach revolved around establishing an indoor thermal comfort zone related to outdoor climatic conditions. The designer could then assess the usable prevailing climatic elements or those climatic elements to be avoided in order to provide indoor thermal comfort. Olgyay went on to describe different methods of treating design elements to improve indoor thermal conditions. In other words Olgyay elucidated on an approach towards energy efficient design.

However according to Balcomb (1998), in developed nations where energy has historically been cheap, mechanical equipment widely affordable and readily available and architectural style important, conventional wisdom such as that expressed by Vitruvius and Olgyay has not been heeded. It seems timely, with evident international concern about greenhouse gas emissions from fossil fuel burning equipment and the less affluent sector of Australia's population expanding, to reconsider the advice of Vitruvius and examine the principles of climate appropriate design.

To utilize the benefits of passive heating and cooling[1], architectural elements must be manipulated to enable the entry, collection, storage and distribution of warmth from solar radiation in cold weather and provide protection from solar radiation in hot weather. The building envelope is the primary element to be manipulated, as it provides a filtration system, excluding undesirable climatic features and admitting desirable climatic features. Inside a building, ceilings, walls and floors are secondary

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[1] The terms 'passive heating' and 'passive cooling' indicates that mechanical equipment is not the primary source of indoor space heating and cooling. Rather, a building is designed to utilise the positive aspects of the climate.

elements that require manipulation, depending on the strategy for heating and cooling a house (Vale & Vale 2000).

In a temperate climate, any of the following three traditionally accepted building envelope design possibilities can be adopted to provide passive heating (Balcomb 1987):

- Glazing is oriented towards the equator, to allow maximum solar radiation to enter and be absorbed by various room surfaces. These surfaces re-radiate the absorbed heat at some later time. This direct solar gain is the primary form of passive heating in Perth, and is used extensively in energy efficient housing as recorded in the Australian journal 'Solar Progress' and in Parnell and Cole's (1983) study of the construction and performance of solar designed houses in Australia.
- Solar radiation is absorbed by a dark-coloured external wall that has a high thermal mass and a glass curtain wall in front[1]. The building interior is heated from the internal face of the mass external wall, by both long-wave radiation and natural convection (Givoni 1998). This form of passive heating has been used in Perth, in combination with direct solar gain in a house called 'Unibuild Venus 3' (Parnell & Cole 1983, p.198) shown in Figure 3-2.
- Solar radiation warms air in a glazed solarium attached to the house or in a roof space. The glazing is oriented towards the equator. The heated air is directed into adjoining rooms.

For passive cooling in the summer months, it is recommended that the building envelope be designed so that all windows are protected from direct solar radiation and conductive heat gains are minimized by insulating the external fabric of the building

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[1] This is frequently referred to as a Trombe-Michel wall. Developed by Felix Trombe and Jacques Michel in France, the system can operate either with or without vents in the mass wall. If vents are provided at the top and bottom of the wall, the overall efficiency of the wall can be improved by up to 10%. This improvement depends on vents being opened and closed at appropriate times. They must be tightly closed at night in winter and during the day in summer and open during the day in winter and during the night in summer (Givoni 1998). In a vented wall accumulated dust must be removed from the inner surface of the glazing and the outer surface of the wall.

Figure 3-2 *Direct and indirect solar gain in an example in Perth (Parnell & Cole 1983, p.198)*

(Ballinger, Prasad & Rudder 1997). In addition to manipulating the construction of the building envelope, when the outdoor temperature is lower than the indoor temperature, as is generally the case at night, the building envelope should be able to be opened to allow the warm air to escape outside. The warm air is replaced by cooler outside air which cools the interior mass of the building. During the day, the cooled mass reduces the rate of rise in indoor temperature (Givoni 1992). This combination, of the building envelope resisting heat transfer during the day and encouraging heat transfer at night, is a viable option for passive cooling in Perth, provided that building occupants are willing and able to open the building at night.

The effectiveness of these heating and cooling strategies are dependent on the design of the building. There are common features of the design of successful energy-efficient houses in a temperate climate. These common features are discussed in the following section, together with an indication of where these features may be in conflict with particular livability issues in public housing for the aged.

3.3.2 Features of energy efficient design

Literature related to energy efficient design in Australia by Ballinger (1993a; 1993b), Cole (1997) and Reardon (2001) refer to interrelated building design factors which, in a temperate climate such as that of Perth, require manipulation to achieve passive solar heating and passive cooling of buildings. These factors can be considered under the following five headings:

- building orientation for solar gain;
- thermal mass for storage of heat;
- building envelope to control heat transfer;
- internal zoning of activities; and
- ventilation for cooling.

Each of these building design factors are discussed below and are used to evaluate the dwellings that make up the multiple - case study in the current thesis. Some aspects of the five building design factors create conflicting requirements in heating and cooling seasons. As highlighted by Balcomb in his discussion of passive solar heating, conflicts between requirements for heating and cooling must be determined by taking into account the more severe season and the consequences of thermal discomfort in extreme temperatures. In addition to the five building design factors mentioned, landscaping can have a dramatic effect on indoor thermal conditions. However, in the context of public housing, landscaping cannot be relied on to influence indoor thermal conditions and is not included as a controlling element in the current thesis.

3.3.2.1 Orientation

Orientation, particularly of glazing and solar collectors, is a crucial element in energy-efficient design. In a temperate climate, the seasonal change in the path of the sun enables solar radiation to be readily used to warm a house in winter and to be prevented from entry during summer. Solar charts are available (Phillips 1996) which provide information to designers regarding the angle and time the sun will strike a particular surface of a building at different months of the year in a particular location. These charts, when used together with climatic data, enable a building to be designed to allow direct solar radiation to shine on a designated surface in the cold periods and be protected from solar radiation in the hot periods.

For two main reasons, the best aspect for seasonal control of sunshine is obtained on that side of the building facing the equator[1]. Firstly, in a temperate climate in winter the solar heat gain received on the north side is about two and one-half times that on the east and west sides. In summer the situation is reversed with east and west sides exposed to higher solar heat gain (Spencer 1976; European Commission Directorate General XV11 1999).

A second reason for maximizing building exposure to the sun on the north side is the design of external shading devices. It is easier to control solar radiation, without blocking outdoor views and natural light, when the sun is higher in the sky, rather than attempting to block the low altitude sun on east and west sides (Phillips 1996).

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[1] In this thesis a northerly orientation refers to the side facing the equator.

In temperate climates, deviations of up to 15° west and 20° east of true north[1] are acceptable to retain the benefits of a northerly aspect (Cole 1997). However researchers in the United States (Lebens 1980; Balcomb 1987) indicate that greater variations[2] may be satisfactory, as performance for heating falls by only about 3%, although summer overheating in the afternoons may be an issue. Researchers preparing the design brief for the Olympic Co-ordination Authority for the Sydney 2000 Olympic athletes' 'green' village at Newington suggest that for Sydney's latitude (33°52'S)[3], 20° west and 30° east of true north provides acceptable northerly orientation (Prasad & Veale 1998). All these studies indicate significant flexibility in orientating buildings, to achieve adequate solar gain in winter while still addressing the real problem of summer afternoon overheating.

In medium density public housing for the aged, complications arise in determining how best to utilise direct solar radiation. Some older people are highly sensitive to glare from direct sunlight (Rubin et al. 1997) and others are more prone to falling when floor surfaces have a high contrast in light levels, such as a patch of sunlight surrounded by shade (Ivers, Cumming & Mitchell 1998). These frailties result in some occupants keeping curtains drawn to avoid direct sunlight and thus significantly reducing the benefits of direct solar gain for passive heating.

Another possible reason for keeping curtains drawn on northerly windows is a concern with privacy. As indicated in the study for the design of the Sydney 2000 Olympic 'green' village in Newington (Prasad & Veale 1998), where the size of each residential block of land is smaller than the average, there was a possibility of northerly windows close to public thoroughfares being permanently shaded by residents who were trying to retain the same high standards of privacy experienced in typical Australian suburban housing. The same approach towards privacy was found to apply in medium density housing for the aged.

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[1] True north is shown on drawings prepared by land surveyors. It is approximately 3.5°E of magnetic north in Perth (Phillips 1996).

[2] Variations of up to 30° east or west of true south (read north in Australia) are indicated.

[3] Sydney's latitude is similar to Perth's latitude of 31°55'S.

A third possible reason for keeping curtains drawn on the north side in small dwellings is a concern with deterioration of furnishings exposed to direct sunlight. Furniture is inevitably located close to glazing in dwellings having a small floor area, so direct solar radiation is likely to strike furnishings causing them to deteriorate more rapidly as a result of ultra-violet radiation.

3.3.2.2 Thermal mass

Another crucial element of energy efficient design is thermal mass that is exposed to the indoor air (Givoni 1998). Thermal mass enables a building material to store heat or coolness. In energy-efficient design in a temperate climate, the thermal mass can provide both a heat source in winter and a heat sink in summer. This assists in stabilising indoor temperatures, provides a time-lag[1] in the equalisation of outdoor and indoor temperatures and can reduce the overall temperature fluctuations indoors (Balcomb, 1984).

Thermal mass is a function of the material's specific heat and density. The higher the product of specific heat and density, the greater the amount of heat that can be stored in a unit volume of the material. Materials like water, concrete and brick, which all have high heat storage capacities, are the most suitable for storing large amounts of heat energy within a relatively small volume (Baggs & Mortensen 1995).

In addition to considering the thermal storage capacity of a material, indoor mass distribution including surface area, mass location, mass thickness and colour all affect indoor diurnal thermal performance and must be taken into account. For passive heating and cooling, it is generally desirable to distribute the thermal mass throughout a dwelling, as only a limited thickness of thermal mass effectively participates in the diurnal heat gain/heat loss cycle.

Passive heating

For passive heating, all thermal mass in rooms that receive direct solar radiation con-

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[1] Time-lag is the time delay between maximum outdoor temperature and maximum indoor temperature over a 24-hour period.

tributes to thermal storage in that room, whether the thermal mass receives direct sunlight, or is within direct line of sight of an area receiving direct solar radiation (Balcomb 1987). Researchers claim that for direct solar radiation to most effectively participate in the daily storage and release of thermal energy, a thickness of between 100 to 225 millimetres of thermal mass (Lebens 1980; Balcomb 1987) is desirable, although Winter (1998) claims that thermal mass of just 50 millimetres thickness is also effective in storing direct solar radiation. For indirect solar radiation, a maximum useful thickness is 150 millimetres (Lebens 1980).

Givoni (1994) recommends that for effective heating from direct solar gain, the area of thermal mass, accessible to indoor air within the space receiving the solar radiation, relative to the area of sun-facing windows, requires a ratio of at least 6 to 1, regardless of the thickness of the mass. Although only an area approximately equal to the glazing area receives direct solar radiation, the relatively high area of thermal mass reinforces the importance placed by Lebens (1980) and Balcomb (1987) on the role of reflected solar radiation when considering direct solar gain as a passive heating strategy. If the mass to glass surface area ratio is low, control of indoor temperature swings becomes difficult. Solar energy overheats the room air during sunny winter periods but as the solar energy has not been stored in thermal mass, there is insufficient capacity for night heating.

The colour of surfaces plays a role in the effectiveness of direct solar radiation for heating. According to Balcomb (1987) in his analysis of the effect of thermal mass in passive solar buildings, thermal mass should be light in colour if more than half the surfaces receiving direct solar radiation are massive. A light colour will diffuse light and heat and increase the contribution of the thermal mass from reflected solar radiation. Notably though, light colours produce high levels of glare. As indicated previously, glare may be a major drawback in housing for the aged, as some older people are sensitive to glare (Rubin et al 1997). Balcomb (1987) goes on to suggest that if only one surface is massive it should be dark in colour to absorb the maximum amount of direct solar radiation. In addition, floors having a high thermal mass should be dark in colour in all circumstances to provide heat storage at a low level.

Passive cooling

For passive cooling purposes it is recognised that there is a functional relationship between the volume of air in a space and the surface area of thermal mass accessible to the air (Givoni 1994). The wider the distribution of thermal mass, the more efficiently the thermal mass can provide a heat sink for the space. Baggs and Mortensen (1995) indicate that for Perth, 80 kilograms of mass[1] is required per cubic metre of air to provide optimum energy savings for cooling. To use thermal mass effectively for passive cooling, Givoni's studies (1994) show that the maximum indoor surface temperature of the thermal mass during the day must remain at least 2 K below maximum comfort temperature to allow heat flow from the indoor air to the thermal mass to be maintained. For the thermal mass to be able to continue to work as a heat sink during the day, it must be able to discharge the stored heat at night. Night cooling of thermal mass is a conventional way of passive cooling in a temperate climate, as discussed in section 3.2.2.5.

Location

Baggs and Mortensen (1995) suggest that a slab-on-ground is the most economical and effective means of locating mass in a building. If the slab is not insulated with carpet, in summer it can distribute stored heat into the ground, and in winter it can minimise heat losses by utilising the stabilising effect of the thermal mass of the earth below the slab. However, in dwellings having a small floor area, the effective heat capacity of floors may be far less than postulated (ibid). In these dwellings, only a small fraction of the floor area may actually be exposed to penetrating solar radiation or accessible to the air mass within the occupied space (Pryor 1984; Givoni 1998). This could be the case in public housing for the aged, where a concrete floor may not be available to direct or reflected solar radiation, due to much of the floor area being covered with furniture or rugs. In addition, in dwellings for the aged, car-

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[1] The mass referred to is concrete having a density of 2400kg/m3 and 150 mm. thick. This equates to approximately 1m^2 of 150mm thick concrete for each 4.5m^3 of air. For brickwork, having a density of 1700kg/ m^3, approximately 113 kilograms of mass is required per cubic metre of air in the space. This equates to approximately 1m^2 of 100mm thick brickwork for each 1.5^3 of air (Baggs & Mortenson 1995).

pets are prevalent as they are warmer under foot, considered easier to clean and safer, reducing possible slips and falls. It may be that a greater dependence on thermal mass located in internal walls is more effective in these types of dwellings.

It is possible that undesirable aspects of a climate can be exaggerated if mass is inappropriately used. One such example occurs in summer when an unshaded external mass wall stores the heat of the sun and, because of the time taken for heat to flow through the mass, radiates this heat indoors at night. A winter example involves the use of thermal mass in a room that is dependant on intermittent mechanical heating for comfort, because it does not receive any direct solar radiation. In this case, thermal mass should be insulated from the room, otherwise large amounts of heat are absorbed by the thermal mass each time the heating is turned on (Ballinger 1993a). However in the latter situation, if thermal mass is insulated from a room, it is no longer available to act as a heat sink in summer.

Building envelope

Thermal mass that is part of a building envelope can combine in one building element the functions of solar energy collection, heat storage and heat transfer to the building interior (Winter 1998). The thickness and density of a thermal mass external wall largely determine the time lag between peak solar absorption and heat delivery on the inside. According to Givoni (1998), for each 100mm of thickness of concrete wall, there is a time lag of two to two and one-half hours, depending on the particular density of the concrete. Baggs, Baggs and Baggs (1991) similarly found that a 250 millimetre concrete wall provides a time lag of 6.9 hours.

A Trombe-Michel wall, as referred to in section 3.3.1, is thermal mass incorporated in the building envelope whilst effectively increasing solar collection. An unvented Trombe-Michel wall is a north-facing wall that is high in mass, high in conductivity and dark in colour, with glazing placed 20 to 50mm in front of it. The air space between the glass and the wall surface is sealed so that solar radiation that penetrates the glazing is mostly absorbed by the mass wall. The heat is conducted through the wall to the inside surface of the wall from where, by long-wave radiation and natural convection, the room is warmed. As heating from this wall is felt only for a limited distance of about one and one-half times the height of the wall (Givoni 1998), it is particularly suitable for public housing for the aged, where the spaces are small.

When Charters, MacDonald and Akbarzadeh (1984), compared the thermal performances of two energy efficient houses, which were identical except for the addition of a vented Trombe-Michel wall in one, they found that the Trombe-Michel wall added approximately two hours to the time lag of the house, as well as increasing maximum and mean indoor temperatures in winter. Research by Lebens (1980) showed that a 200 millimetres solid concrete wall with double-glazing on the outside (an unvented Trombe-Michel wall) provided a time lag of nearly seven hours, similar to a 250 millimetres concrete wall.

There is limited evidence of Trombe-Michel walls being used in Perth. Parnell and Cole (1983) describe a simple external mass-wall system constructed in Perth in a pre-fabricated house named 'Unibuild Venus 3' as shown in Figure 3-2. The prefabricated house uses a mass wall system of two, 125 millimetres thick pre-cast concrete panels fixed back-to-back with 10 millimetres of cement grouting. The outer face of the concrete panels is painted matt black, the wall is covered by a layer of glass 50mm from its surface, and the cavity between the wall and the glass is sealed around the edges with rubber gaskets. According to Parnell and Cole (1983) this wall, together with a similar area of northerly glazing for direct solar gain, provides adequate heating for the house to maintain an indoor winter temperature of 20°C, with a two-day carry-over period when there is no sun.

Charters, MacDonald and Akbarzadeh (1984) claim that a Trombe-Michel wall has inherent advantages over direct solar gain: it improves indoor comfort conditions particularly in the evening, it avoids the problem of glare, reduces the ultra-violet degradation effects on furnishings and fabrics, and requires no direct operational involvement by the building occupant. These are all very desirable attributes in housing for the aged.

The appropriateness of a Trombe-Michel wall in a temperate climate is directly linked to the provision for shading of the wall in summer. Researchers (Givoni 1998; Ballinger 1993a) discussing mass external walls, emphasise that in climates where buildings tend to overheat in summer, it is vital that solar collecting walls be shaded in summer, both from direct solar radiation and from reflected and diffuse radiation. These external mass walls must be shaded in the same way that glazing requires shading in summer. Summer shading of the building envelope is discussed in section 3.3.2.3.

3.3.2.3 Building envelope

A building's thermal performance is also linked to the level of insulation, the shape and the colour of the building envelope. Each of these three factors have a slightly different impact on thermal performance, with the insulation, in conjunction with indoor thermal mass, being the most influential in modifying the effect of outdoor climate and affecting the time between external and internal maximum temperatures. Shape (or form) can have an impact on a building's thermal performance because of the relationship between the surface area of external walls and floor area. The colour of materials exposed to solar radiation enhances the reflective or absorptive properties of the materials and thus the resulting heat transfer. The three factors are considered below.

Insulation level

The construction of the external envelope of a building, particularly its insulation properties, influences the effectiveness of passive heating and cooling. In temperate climates in those Australian states where building regulations do not mandate minimum levels of insulation, the current construction of typical housing include a combination of timber or steel framed roofs, generally un-insulated, and clad with concrete or terra-cotta roof tiles or metal sheets. Walls are generally of un-insulated brick veneer or cavity brickwork and windows are single glazed. The floor is a concrete slab, usually directly on the ground, or a timber framed floor raised above ground level, again usually un-insulated.

The particular combination of these construction elements, as well as the air tightness of the dwelling (Liddament 1996), determine how quickly a dwelling that is heated in winter looses that heat to the outside and in summer, how quickly heat penetrates into a cool dwelling – in other words the time-lag between the external maximum temperature and internal maximum temperature (Ballinger, Prasad & Rudder 1992). The time-lag of a typical Australian brick veneer house in a temperate climate is usually approximately two hours (Ballinger 1993a).

Insulation of the building envelope is an inherent part of the design of energy-efficient housing in Australian temperate zones. According to Energy Victoria (1996), insulated buildings will always be warmer in winter and cooler in summer than un-insulated buildings, provided that in summer, heat gain is minimized and any excessive heat stored indoors during the day is able to be discharged rapidly at night.

Roof space insulation is critically important, as the roof of a dwelling is generally the largest single exposed surface that permits heat gain and heat loss. A layer of reflective insulation under the roof cladding reduces over-heating in summer but is less effective in winter due to reflective insulation having a greater resistance to radiant energy flow downwards (as occurs in summer) than to conductive energy flow upwards from inside, which occurs in winter. According to Givoni (1994), a layer of resistive or bulk insulation directly above the ceiling and with an air gap above, is more effective than reflective insulation in both summer and winter, as it minimizes both indoor heat loss in cold weather and indoor heat gain in hot weather. However, this insulation does reduce possible conductive heat losses to the night sky in summer. Baverstock and Paolino (1986) recommend that in Perth insulation having a minimum resistance value of R2.0 be installed in the roof cavity. Building regulations (ABCB 1996) that will come into operation in Western Australia in mid 2003, specify for roofs in Perth a minimum total resistance value of R2.7 for heat flow moving upwards, slightly higher than the recommendation of Baverstock and Paolino (1986).

Typical external wall construction in energy efficient houses are either reverse brick veneer[1], cavity brick walls or mass walls, such as rammed earth, that have a high volumetric heat capacity. In reverse brick veneer construction and cavity brick wall construction, Lim and Williamson (1999) and Baverstock and Paolino (1986) rec-

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[1] Reverse brick veneer refers to lightweight framed construction that is on the outside of a masonry internal wall.

ommend the installation of R1.5 wall insulation in Perth, to reduce heat flow through the building envelope. Massive walls like rammed earth can be effective without the need for insulation but only in a temperate climate that does not have long periods of cold weather (CSIRO 2000a). The designated climatic zone for Perth (ABCB 1996) requires a minimum total thermal resistance value through the walls of R1.4, slightly lower than the recommendation of Baverstock and Paolino (1986).

Typical floor construction in energy efficient houses in Perth is a concrete slab on the ground. According to Baggs and Mortensen (1995) in temperate climates insulation of the floor slab is not considered necessary. Insulation below a concrete floor slab would create a barrier between the stabilising effect of the earth below the slab. Insulation on top of the floor slab (such as carpet) would isolate the slab from direct solar gain in winter and reduce its ability to act as a heat sink in summer. Thus building regulations (ABCB 1996) do not require insulation beneath a floor in Perth.

Glazing can have a significant effect on the total insulation level of a building envelope, depending on its orientation as discussed in section 3.2.2.1, but also depending on its area and on the type of glass installed. If passive heating in energy-efficient design depends on direct solar radiation, the north-facing wall must incorporate a substantial area of glass. This northerly area of glazing needs to be sufficient to allow heat build-up during the day to balance heat losses at night. However, too much glass can, in winter, cause overheating during the day and large heat losses at night, and also large heat gains during the day in summer (Balcomb 1987). Baverstock and Paolino (1986) provide rules-of-thumb for the desirable area of glass for houses of between 100 and 500 square metres. For a 100 square metre house, north-facing glazing should be approximately 18% of the floor area and the percentage of glass area to wall area on the north side should be just over 50% (ibid). The current thesis will determine whether an extrapolation of these percentages to buildings of small floor area that are typical of public housing for the aged, are applicable, by examining the results of the multiple - case study.

The transfer of heat through glass can be significantly reduced by using treated glass or double glazing rather than single clear glass (Pupilli 1993). The main thermal disadvantage of treated glass is that in winter, when sun penetration is desirable, heat gain is reduced. However, improved summer performance may more than compensate for that loss, as indicated in a simulation by Lim and Williamson (1999) of a passive solar house design in Perth. In that simulation double-glazing reduced the combined annual heating and cooling loads of a standard passive solar designed house by around 30%, from approximately 10 kWh/m2 to approximately 7 kWh/m2. Although these figures show that double glazing does reduce total energy loads, the reduction is from a relatively low load base and primarily related to cooling load reduction. This may be of particular relevance in housing for the aged if other passive cooling strategies are inadequate in lowering indoor temperatures. However, the cheapest double-glazed sealed unit is approximately three times the cost of 4mm thick clear float-glass (Rawlinsons 2003) and in public housing for the aged may not be considered cost effective. This will be further discussed in relation to the multiple - case study.

The thermal performance of glazing in summer depends on the type of shading provided to the glazing. External shading devices frequently form an integral part of the building envelope, with roof eaves being the most common but least flexible form of external shading in Australia.

Any fixed external shading device on the northern side can be designed to totally shade glazing from midsummer sun but still allow at least part of the glazing to be exposed to midwinter sun, the extent of exposure depending on the height of the glazing. Fixed shading on the northern side does have the inherent disadvantage of being unable to adjust to the lack of synchronization between extreme solar positions and extremes of temperature (Lebens, 1980; Balcomb, 1984). This means that if fixed shading devices are designed to exclude the sun during the hottest period (up to 10 weeks after the sun reaches its highest altitude), they will also exclude the sun when the temperature may still be uncomfortably cool (10 weeks before the sun reaches its highest altitude).

Moveable external shading devices can be designed to respond most effectively to thermal needs. The drawback to moveable external shading, even in their simplest form such as manually-adjusted canvas shades or timber shutters, is the expense to install and maintain the shades or shutters and a requirement that occupants adjust the shading device on a daily basis. Results from the National Evaluation of Energy Efficient Houses (NEEHA) study (Samuels et al. 1993) showed this last drawback is generally unacceptable. In that study, occupants of energy efficient houses rejected the notion of personal intervention in regulating thermal performance of their houses through adjustment of flexible shading devices. The expectation was that the house design should automatically take shading requirements into account. This expectation is also applicable to housing for the aged where environmental demand needs to be minimized.

Interior protection of glazing can also be used to control heat gain or heat loss, although this is less effective than external window treatments or treated glass. The most successful interior window treatments are heavy, insulated curtains which wrap around the sides of the window, are fitted with a curtain pelmet at the top and reach floor level or a projecting ledge at the bottom. This has the desired effect of restricting the movement of air trapped between the glass and the curtain. The restricted air becomes a layer of insulation. With curtains closed on a summer's day, the trapped layer of air is hot, and on a winter's night the trapped layer of air is cold (Ballinger 1993a). As this window insulation largely depends on the action of the building occupant, it is not a reliable method of insulation as shown in the study by Samuels et al. (1993). That study indicated that building occupants are generally poorly informed about how to best utilize curtains as window insulation and furthermore are not committed to maximizing indoor thermal comfort. When interviewed on 19th May 2000, Mr J. Thorogood, Manager Construction, Ministry of Housing confirmed that the policy in public housing in Perth is not to install curtain pelmets and there is also no mechanism to control the type of curtains installed by public housing tenants.

Shape

Building form emerges as the result of complex interactions between function, technical considerations, aesthetics and sometimes, environmental considerations. If environmental considerations are to be successfully incorporated into the building form, according to the European Commission Directorate General XV11(1999), heating and cooling strategies must be meshed into considerations of the building envelope at an early stage.

Where mechanical heating and cooling is used, the optimum shape of a building is one that looses the minimum amount of heat in winter and gains the minimum amount of heat in summer. For a given floor area, the greater the external wall area the greater the heat transmission gains and losses (Ballinger 1993a). However, for a building depending on passive heating and cooling, the form must respond to the particular strategies adopted for heating and cooling as introduced in section 3.2.1. Researchers (Olgyay 1963; Balcomb 1984; Givoni 1992) considering principles for energy-efficient design in a temperate climate recommend that non-air-conditioned buildings be approximately twice as long as they are wide, with the long axis oriented east-west to take advantage of maximum solar penetration on the north side. This building proportion reduces the need for rooms to have east or west facing windows. The elongated building form also facilitates effective cross ventilation for summer cooling, although external wall area is not minimized (Aynsley 1996).

However, in small, semi-detached dwellings[1], this conventional wisdom regarding building proportions may be irrelevant because in buildings having a small floor area, the entire dwelling operates as one thermal zone. In this case the most relevant requirements are that each dwelling has sufficient north-facing exposure for solar gain for heating and has minimum east and west glazing to avoid solar gain in summer.

Colour

Light colours reflect heat and light, and dark colours absorb heat and light. Cole (1997) highlights the effect of the choice of colour on the performance of a building envelope in energy efficient design. A light colour can enhance the solar effectiveness of a roof or wall in summer by increasing reflection. On the other hand, light-coloured surfaces such as paved areas or shading devices around window openings can also increase the amount of radiant energy reflected through window openings. This is beneficial in winter but can create additional indoor heating loads in summer. Dark colours provide the advantage of enhancing the absorption of solar energy of

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[1] This type of dwelling has three external walls and one wall is attached to an adjoining dwelling. This style of development is typical of public housing for the aged in Perth.

external high thermal mass surfaces in winter. However, dark areas of thermal mass must be protected from solar radiation in hot weather to avoid undesirable heat absorption and re-radiation.

3.3.2.4 Zoning of internal spaces

In family homes, the prevailing wisdom of researchers (Reardon 2001; Cole, 1997) indicates that the internal planning of spaces which have long periods of daytime use in winter should be on the northern side, while spaces used infrequently should be on the south. This has been commonly interpreted as living spaces on the north side being separated from bedroom and utility spaces on the south side. This arrangement enables those rooms requiring the greatest amount of heating to be passively heated by the sun during the day in winter.

However, in a temperate climate, conflict can arise between occupants' needs and designers' preconceptions. There is evidence from the NEEHA research project[1] that building occupants prefer to have winter and spring sun penetration in bedrooms as well as living areas. This implies that non-south-facing bedrooms are desirable (Samuels et al. 1993) although in summer, these rooms will not be as cool as on the south side. This research finding is particularly relevant in housing for the aged, where bedrooms may be occupied for longer periods of time than in other types of housing so sun penetration may be even more desirable. Also, in housing designed for the aged, where temperature variations between spaces is undesirable from a physiological point of view (Lloyd 1990), the conventional wisdom related to zoning of spaces is not applicable.

Another aspect of zoning relates to the grouping together of heat-producing appliances. Particularly in small dwellings, any heat generated within a house by domestic appliances like ovens, refrigerators and freezers effects the entire dwelling. Thus in summer it is desirable to remove the heat as it is produced, for example with ex-

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[1] The NEEHA project was a post-occupancy evaluation of 146 households in four Australian cities. The aim was to determine the relationships between "thermal comfort, lifestyle quality/amenity and both design characteristics and energy consumption" (Samuels et al 1993 p.6).

haust ventilation over cookers and behind refrigerators. By using a set of dampers with an exhaust system, the heated air can be expelled in summer whereas in winter the heated air can be retained indoors.

3.3.2.5 Ventilation

One of the simplest strategies cited by Givoni (1998) and Parnell and Cole (1983) for improving comfort during summer in a temperate climate is to ventilate a building when outdoor temperatures are lower than indoor temperatures. The ventilation may be either natural ventilation or enhanced with the use an exhaust fan. This strategy is commonly referred to as night cooling and has been utilised in solar-efficient houses in Perth. Givoni (1998) describes night cooling ventilation as a system which cools the internal mass of a building by convection from the inside, thus bypassing the thermal resistance of the building envelope. During the daytime the building is closed, to prevent it being heated by the outdoor air. If this procedure is carried out, the indoor temperature can be lowered at night to within 2 to 3 K of the outdoor overnight minimum, and most of the stored heat from the day can be dissipated (Szokolay 1995).

According to Givoni (1994) night cooling ventilation systems are most effective in climates having a large diurnal temperature range (at least 15 K) and low humidity levels. Minimum summer temperatures at night should be no higher than approximately 20°C and summer day maximum temperatures should be approximately 36°C. Provided these climatic conditions are met, the expected maximum indoor temperature can be maintained 6 to 8 K below the outdoor maximum temperature. Also, the indoor temperature range would be expected to be 45% to 55% of the outdoor temperature range (Givoni 1992). These indoor temperatures depend on the heat storage capacity of the thermal mass, along with the distribution and the exposed area of the thermal mass in the building (Givoni 1998).

Although Perth has a summer mean diurnal temperature range of approximately 13 K (Bureau of Meteorology 1998), which is slightly less than desirable, night cooling is effective for most of the summer period in houses designed to be energy efficient (Baverstock & Paolino 1986). During extended, very hot weather or periods of unusually high humidity, indoor thermal conditions may exceed comfort levels, but this does not imply that night cooling should be discounted as an effective cooling strategy for Perth (Parnell & Cole 1983).

Night cooling systems that are not fan-assisted depend on winds blowing regularly and at the appropriate times. Maping of wind data in Perth indicates that southerly and south-westerly winds are the most frequent in summer in the afternoon and easterly and north-easterly are the most frequent on summer mornings (Sturman & Tapper 1996). However cooling winds are not totally reliable and the building design requirements for natural ventilation can be rather onerous.

In order to maximize the use of prevailing winds for night cooling, openings on the windward and leeward sides of a dwelling must be of sufficient size to enable approximately 30 air changes per hour through the dwelling (Givoni 1999). The required area of openings to achieve this rate of ventilation depends on the wind velocities. Although mean summer wind velocities in Perth are approximately 4.8 metres per second (Szokolay 1982), they become weaker in the evening. If, for example, a 2 metres per second breeze was blowing, then at least 0.5 square metres opening on both the windward and leeward sides of the dwelling would be required in a dwelling of 50 square metres floor area to accommodate 30 air changes per hour, as confirmed by Mr. D. Stevens, a mechanical consulting engineer. In housing for the aged, concerns about personal security could make the option of night cooling untenable.

Aynsley (1996) refers to an additional design implication when depending on natural ventilation for night cooling. He reports that, for effective ventilation, air outlets should be larger than air inlets and, ideally, opposite the air inlet. Where internal openings form part of a cross-ventilation system, those openings, as well as the air inlet and air outlet, must be able to remain open when ventilation is required. Liddament (1996) refers to a further design implication when natural ventilation is used for cooling. He suggests that the practical limits of penetration of a natural ventilation system is approximately two and one-half times the ceiling height.

Ideally the design of the ventilation opening on the windward side should also act as a 'wind catcher'. For example, friction-stayed casement windows provide the greatest possibility for directional control of wind while sliding windows and double-hung windows are much less effective, as only half the window area can be opened and no adjustment is possible according to wind direction (Aynsley 1996). Louvre type windows are most effective in assisting to direct incoming air to a particular level in a room and also allow most of the window area to be opened. The current study shows that the most usual type of window installed in housing for the aged is an aluminium sliding window. There could be an opportunity to improve natural ventilation in housing for the aged by installing another type of window, provided that opening and closing of such windows did not make unacceptable demands on the physical limitations of older people.

As already discussed in regard to the performance of shading devices, the success of natural ventilation design strategies depends on building occupant behaviour as well as on building design. Occupants must be willing and able to participate in the operation of the building. For building occupants this could create practical problems, including the need to open and close windows at prescribed times, issues of security, intolerance of noise from adjacent open windows, the dislike of too strong wind, or air temperature falling below an acceptable temperature, even in summer (Givoni 1994). These practical issues may limit the amount and duration of natural ventilation accepted by people at night.

Mechanical exhaust ventilation, with openings that do not pose a security threat and require minimal involvement from a building occupant, is one way of dealing with some of these practical problems of natural ventilation for night cooling. The option of mechanical ventilation was considered in the current study and is discussed in section 6.4.2.2.

3.3.3 Barriers to energy efficient design

Despite the extensive knowledge of design elements that contribute to energy-efficient design, as observed by Shove (1995), all over the industrialized world the marketplace of the construction industry conspires against widespread adoption of climatically sensitive, site specific housing design. That is because the design of energy-efficient buildings

> "*is a complex process, a subtle complexity consisting of consciously designing to take advantage of environmental energies and natural processes. Design decisions must factor in considerations of cost, aesthetics, use of the various spaces in the building, natural lighting, security, code restrictions and privacy as well as thermal performance....*" (Balcomb 1984, p. xvi).

The common perception by researchers such as Wilson, Trieu and Bowen (1993) and Wittman (1998) is that the perceived complexity of energy efficient buildings has deterred a significant pursuit of energy efficient architecture. According to Kam (1999) the conservatism of the construction industry and its consumers has resulted in thermal comfort being addressed through the installation of a substantial air-conditioning system to meet any likely demands. Such air-conditioning systems are not generally questioned by purchasers of real estate, partly because real estate agents do not use energy consumption as part of marketing (Lim 1999) and partly because in Australia there is a lack of definitive information related to either the anticipated temperatures in a house when space heating and cooling is not provided, or to the possible energy savings when it is provided (Kam 1999).

3.3.4 Benchmark for energy efficient design in Perth

As discussed in section 3.2.2, the general principles of energy-efficient design in Australia are well established and are able to be quantified. Baverstock and Paolino (1986) have quantified the common design parameters in a manual "Low energy buildings in Australia - A design manual for architects and builders". This manual, derived from computer analysis, provides a reputable[1] benchmark for energy-efficient design. The manual provides design parameters for optimising the thermal performance of dwellings in both summer and winter in various locations around Australia. These design parameters apply to houses having a floor area between 100

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[1] The manual continues to be acknowledged as a guide to energy-efficient design by Australian researches such as Reardon (2001), Ballinger, Prasad and Rudder (1992) and Baggs and Mortensen (1995).

square metres and 500 square metres, and a plan form where north and south walls are between one and one-half and two times as long as east and west walls.

The scope of design parameters include:

- area of glass for solar collection;
- volume of thermal mass for storage of heat;
- insulation level for control of heat transfer through the building envelope;
- options for improving the thermal performance in winter so mechanical heating can be eliminated; and
- fan sizes to improve natural night ventilation in summer.

Based on Baverstock and Paolino's design parameters for Perth, a series of regression analyses (see Appendix 1) were undertaken in the current study to provide a starting point in determining various design parameters for housing having a smaller floor area[1] than that used by Baverstock and Paolino in their calculations. To determine the probability of the results of the regression analyses being acceptable, both linear and quadratic functions were considered. Adopting a level of significance of 0.1[2], the results showed that either linear or quadratic functions could be adopted. As the quadratic function produced a more conservative result, this function was used in this thesis.

Required areas of northerly wall, total glazing, northerly glazing, east and west glazing and Trombe-Michel wall have been extrapolated for semi-detached dwellings with three external facades, one of which faces north and a floor area of 65 square metres and 50 square metres as shown in Table 3-3. The façade facing north incor

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[1] The floor areas chosen are the approximate floor areas of one and two-bedroom dwellings that are typical of public housing for the aged.

[2] Although this probability is higher than the 0.05 frequently adopted, it is considered that a 90% possibility of the regression being accurate is appropriate for this situation.

porates glazing for direct solar gain and the option of improving thermal performance through supplementary heating in the form of a Trombe-Michel wall.

Floor area (m^2)	**Total north wall area (m^2) [% of floor area]**	**North glazing area (m^2) [% of floor area]**	**East & west glazing area (m^2)**	**Total glazing area (m^2) [% of floor area]**	**Option for improving thermal performance with Trombe-Michel wall area (m^2)**
100	37.0 [37]	18.4 [18]	2.0	24.9 [25]	6
65	32.0 [49]	16.2 [25]	1.5	21.3 [33]	3.7
50	30.0 [60]	15.2 [30]	1.3	19.7 [39]	2.7

Table 3-3 *Recommended areas of solar collection for small semi-detached dwellings in Perth (based on Baverstock & Paolino 1986)*

Further design parameters for the dwellings of small floor area have also been extrapolated and are presented in Table 3-4. These design parameters are volume of thermal mass, total insulation level of the roof and walls (no insulation is recommended for a concrete slab on ground) and fan size for night cooling ventilation. Table 3-3 and Table 3-4 provide a reference point for the discussion of benchmarks for energy efficient design in the current thesis.

Floor area (m^2)	**Thermal mass (m^3) (primary windows facing north)**		**Total R value of insulation**		**Night ventilation exhaust fan (l/s)**
	Concrete	Brick	Roof	Walls	
100	10	20	2.0	1.5	1850
65	5	15	2.0	1.5	1400
50	3	13	2.0	1.5	1200

Table 3-4 *Recommended volume of thermal mass, insulation levels and fan size for night cooling for small dwellings in Perth (based on Baverstock & Paolino 1986)*

If Givoni's (1994) recommendations for area of thermal mass relative to northerly glazing for passive heating and Baggs and Mortensen's (1995) area of masonry walls relative to volume of indoor air for passive cooling (see section 3.2.2.2) are computed for dwellings of 65 and 50 square metres, using the northerly window area from Table 3-3, this will provide a further benchmark for assessing the energy efficiency of the dwellings in the multiple-case study of this thesis. These desirable areas of thermal mass are shown in Table 3-5.

Floor area (m^2)	**Volume[1] (m^3)**	**Minimum desirable area of available thermal mass for passive heating based on area of northerly windows from Table 3-3 (m^2) (Givoni 1994)**	**Minimum desirable area of 100 mm thick masonry walls for passive cooling based on volume of indoor air (m^2) (Baggs & Mortensen 1995)**
65	156	97	104
50	120	91	80

Table 3-5 *Desirable areas of thermal mass for passive heating and cooling*

3.3.5 Significance of understanding traditionally accepted energy efficient design features

The traditionally accepted energy-efficient design features of building orientation for solar gain, thermal mass for storage of heat, insulation of the building envelope for control of heat transfer, internal zoning for locating activities and ventilation for cooling have been discussed in order to be able to:

- assess how the design of existing small, medium density dwellings utilise these design features;
- identify those design features that do not conflict with older peoples' needs in small, medium density housing for the aged; and
- extend quantitative design parameters for energy efficient housing so that they can be applied to small, medium density dwellings.

3.4 Summary

There appears to be a fortuitous confluence between the acceptable temperature limits for thermal comfort in non-air-conditioned buildings and the achievable temperature range in a temperate climate for buildings designed to be energy efficient. To achieve acceptable indoor temperatures using energy efficient design, building designers must utilize the five features of energy-efficient design – orientation, thermal mass, building envelope design, zoning and ventilation. In addition, building occupants must be prepared to adapt their behaviour in a variety of ways, including the

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[1] Volume is based on the typical 2.4 metres ceiling height in public housing for the aged.

use of curtains and blinds, operable windows, fans, the choice of clothing and activity levels, to suit the particular season.

However some aspects of a housing design may conflict with the occupants' frailties, so energy-efficient housing for the aged must be designed to acknowledge these frailties. Based on Baverstock and Paolino's (1986) benchmark for energy-efficient house design in Perth, an adjusted set of benchmarks for energy-efficient design for small dwellings in Perth will be tested.

In relation to establishing an 'acceptable' indoor temperature through energy-efficient design, Brager and de Dear (2001) suggest that enough is still not known about all the factors that make up the state of thermal comfort. Nevertheless, for naturally ventilated homes in Perth, the equation developed by de Dear and Schiller Brager (1998) presents a useful benchmark against which acceptable thermal conditions can be established for small, medium density dwellings in Perth.

The complexities of applying the theory of energy efficient design in the construction of small, medium density housing for the aged is evident in the literature considered. In the research hypothesis, a specific gap has been identified in relation to how energy-efficient design in small, medium density dwellings can address the need for appropriateness for the aged. The theory of energy-efficient design and the adaptive approach to thermal comfort suggests that this gap can be addressed through a quantitative study. A method for carrying out this quantitative study is developed in the following chapter.

4. Research methods

4.1 Preamble

From the matters raised in Chapters 2 and 3, it appears that there are significant areas of complexity in intertwining issues of energy efficient design and housing of small floor area, particularly housing for the aged. The current research narrows the focus of study to particular aspects of the relationship between energy efficient design and appropriateness in small, medium density housing for the aged. In this chapter the research questions are first restated (section 4.2) and then the tools of study are discussed. The first tool provides a method of analysing conditions in existing small, medium density housing for the aged (discussed in section 4.3). The second tool enables an exploration of the notion of appropriateness of energy efficient design in typical small, medium density housing including housing for the aged (discussed in section 4.4).

4.2 Restatement of purpose & research questions

The purpose of the study is to examine the current benchmarks for energy efficient design and determine whether they are appropriate, or can be made to be appropriate, when applied to small, medium density housing in a temperate climate including housing for the aged. The two research questions developed to address the purpose are listed below.

1. Does existing small, medium density housing for the aged in Perth:

    (a) satisfy the principles of energy efficient design; and/or

    (b) provide acceptable indoor temperatures?

2. Are current benchmarks for energy efficient design appropriate:

    (a) for small, medium density housing; and

    (b) particularly for small, medium density housing for the aged?

4.3 Analysing existing conditions

To determine a research approach towards the post-occupancy evaluation of thermal conditions and design of small, medium density housing for the aged, social science research strategies such as surveys, experiments and case studies were considered. In their examination of these three research strategies, Hammersley, Gomm and Foster (2000) provide a comparison between the features of social surveys, experiments and case studies. From this comparison it was concluded that the experimental approach and the social survey approach were not appropriate ways of carrying out a post-occupancy evaluation for the following reasons.

- The experimental approach was not considered feasible as it would involve some direct control over some of the important variables, rather than an observation of the naturally occurring situation in housing for the aged. This would not provide the type of information sought.

- The social survey was not a preferred option for the following three reasons. Firstly, the area of interest was not a statistically random sample of small, medium density housing, but rather public housing for the aged. Secondly, the advice from the management of public housing for the aged[1] indicated that the participation rate of this aged cohort in surveys was low and finally, Davison et al. (1993) suggests that older people themselves are the ideal source of information about their housing but they are less inclined to respond to surveys than to face to face, less structured forms of data collection.

The case study approach seemed more appropriate as it identifies a form of inquiry that implies an examination of a limited number of cases, chosen for their particular attributes, rather than specifically for statistical correctness. Relatively detailed information can be collected about each case and the information can be wide ranging

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[1] When interviewed on 6 October 1999, Mr. J. Thorogood, Construction Manager, Ministry of Housing, provided this advice, based on the organisation's experience of gathering information from public housing tenants.

in comparison to surveys. Also, there is no attempt by the researcher to influence the situation, as occurs in experiments.

4.3.1 Case study methodology

Case study methodology appeared to be an appropriate research tool to carry out a post-occupancy evaluation to study the thermal conditions in and design of small, medium density housing for the aged. It was envisaged that, through case study research, there was an opportunity to quantify data as well as "*for adding to existing experience and humanistic understanding*" (Stake 2000, p.24) in this specific area of housing. To set up a valid case study, Yin's (1994) three tests of validity were considered - 'construct validity', 'external validity' and 'reliability' of results.

'Construct validity' requires the identification and collection of the correct set of measures for the factors being studied and avoidance of subjective judgements in the collection of data. In the current study, the collection of data related to indoor temperatures, building design and construction and energy bills. These measures are identified as appropriate in addressing the research questions and are not coloured by subjective bias. More anecdotal data was also able to be collected through the use of a structured interview that included consideration of occupants' behavioural patterns[1].

'External validity' involves establishing whether the findings of a study can be generalized beyond an immediate case, on the basis of a developed theory. The areas of validation revolve around statistical processes and analytic generalizations.

Statistical processes are used to determine mean indoor temperatures and mean gas and electricity consumption in approximately 60 dwellings in order to be able to make statistical generalisations about conditions in small, medium density dwellings[2] for the aged in Perth. To determine key factors for energy-efficient design in small

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[1] Occupant behavioural patterns were self-reported, and thus were not considered to be entirely objective.

[2] Small dwellings refer to dwellings having a floor area between approximately 50 and 65 square metres.

dwellings, four typical dwellings were examined in detail. The construction and design of each dwelling was analysed and compared to benchmark requirements for energy efficient design. Further, the influence of occupant behaviour in each dwelling was assessed. This provided the basis for analytical generalization that could be validated by considering other dwellings.

'Reliability' of results requires that procedures of the study be documented in sufficient detail that a future investigator could conduct the same case study. The rest of this chapter provides details for future investigators to repeat the case study and describes in detail how the validity tests have been addressed.

4.3.2 Parameters of the multiple - case study

The starting point for the multiple - case study was to identify a building typology (medium density housing for the aged), typical examples of the typology and an appropriate design brief for the particular building typology.

4.3.2.1 Public housing

Medium density public housing developments[1] for the aged are the most common form of medium density housing for the aged currently being constructed in Perth, with hundreds of these dwellings being constructed in Perth annually (Holding 2001). The design brief for public housing for the aged in Perth includes requirements for energy-efficient design. This appeared to contrast with the design of private sector retirement accommodation in Perth, where there is no apparent pursuit of energy-efficient design, as ascertained by the author in an unpublished study of perceptions of thermal comfort in 30 dwellings in three retirement villages in Perth in summer and winter in 1996.

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[1] A development in the context of this study refers to a cluster of one and two bedroom dwellings located on a single site. The dwellings are self contained and of similar design within a particular development. Throughout this study, these developments are referred to numerically from 1 to 7.

The following two extracts from the public housing design brief (Ministry of Housing 1999) indicate the general intent of the public housing authority in regard to energy efficiency. The current design brief requires that:

" *3.09 Orientation*

(i) Sun: (of primary importance): The main axis of the dwelling should be, where possible, within 15° of the east-west axis. Windows of habitable rooms preferably should not be placed on the western and eastern elevations unless fully shaded.

(ii) Wind: (of secondary importance): Windows and door openings should, where possible, be oriented to maximise the potential for cross ventilation of rooms by prevailing breezes.

(iv) All designs should be able to confirm best orientation for lowest energy use" (p.7).

"4.02 Generally

(iv) Natural lighting: Natural light should be maximised (without direct sunlight). Natural lighting should be available to all rooms to allow their use during the daylight hours without artificial lights.

(v) Natural ventilation: The position and size of window openings should permit cross ventilation. Artificial ventilation is to be used for internal bathroom and toilets but designers should be vigilant to avoid rooms without natural light or ventilation.

(vi) Solar design: Passive solar design techniques (particularly the shading of walls and especially windows) should be maximised. Non habitable rooms eg. storage areas etc., should be used as thermal buffer. Windows facing east-west should be shaded or protected by a verandah, permanent canopy or hood of minimum 900 mm overhang in conjunction with aesthetics of street

> *elevation. All designs shall achieve an optimum energy effectiveness through orientation, shading, ventilation and insulation"* (p. 13).

However there is inconsistency in the provisions. For example, on the one hand the provisions call for passive solar design techniques to be used to minimize the use of energy. On the other hand, the provisions state that windows to habitable rooms on the eastern and western elevations must be permanently shaded. Knowing that in typical designs for housing for the aged windows are generally provided only on two opposite elevations, if east and west windows are permanently shaded there will be no possibility of collecting solar radiation in winter.

Nevertheless it appears that the intent of these guidelines is to develop energy efficient dwellings. The first research question in the current thesis arose from this stated intent in the guidelines. Further reasons for examining public housing for the aged rather than private retirement villages include the large number of such existing dwellings[1], the knowledge that the construction of public housing for the aged is an ongoing commitment and the similarity of the limited disposable income of the tenants. The limited disposable income may result in a hesitancy in using space heating and cooling and also in few occupants having air-conditioning, so the thermal performance of the building itself can be more readily assessed.

However, it cannot be assumed that a common attitude or sense of responsibility towards energy consumption exists amongst Ministry of Housing[2] tenants or that attitudes are related to disposable income. As shown in studies discussed in Chapters 2 and 3, some elderly poor lower indoor ambient temperatures to economise on energy use (Kane 1991; Cena, Spotila & Avery 1986) while for others, the need to feel

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[1] At a meeting on 29th August 2001, Mr. R. Holding, Data Manager, Corporate Development, Department of Housing & Works, Western Australia, advised that the Department has been constructing housing developments specifically for the aged since 1959, and people over 55 years old now make up approximately 26% of public housing tenants. The number of aged persons dwellings constructed annually has fluctuated in the past decade with 795 aged persons units being constructed in 1991/92, 229 dwellings in 1996/97, the lowest number for the decade, and in 1999/2000, 391 aged persons dwelling units being constructed.

[2] In 1998, the public housing authority was known as the Ministry of Housing. In 2001 the name was changed to Department of Housing and Works.

warm despite the expense is a priority (Schwenk 1993; Yamasaki & Tominaga 1997). Some general indications of approach to energy usage will be established based on responses to the questionnaire.

4.3.2.2 Climatic limitation

The focus of the multiple - case study was narrowed to the small geographic and climatic zone of Perth, Western Australia[1]. The geographic limitation provides ample scope for replication of this study and the climatic limitation is essential to enable possible generalization of the results from computer simulations of the energy-efficient designs. Perth's key climatic features are provided in Table 4-1. It is recognised that the climatic data can vary depending on the microclimate of the particular monitoring station. In this case the mean outdoor temperatures are based on long-term mean values of weather data measured by the Bureau of Meteorology (1999)[2].

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Mean daily max temp. (°C)	29.7	30.0	28.0	24.6	20.9	18.3	17.4	18.0	19.5	21.4	24.6	27.4
Mean daily min temp. (°C)	17.9	18.1	16.8	14.3	11.7	10.1	9.0	9.2	10.3	11.7	14.0	16.3
Mean 9am DBT (°C)	23.6	23.3	21.5	18.6	15.2	13.1	12.1	13.0	15.0	17.2	20.1	22.4
Mean 9am RH (%)	50	53	57	65	74	80	81	77	70	62	55	52
Mean 3pm DBT (°C)	27.9	28.3	26.5	23.4	19.8	17.3	16.4	17.0	18.3	20.0	23.0	25.6
Mean 3pm RH (%)	41	40	42	48	53	60	59	56	53	50	46	44
Mean 3pm wind speed (km/hr)	20.2	18.7	17.2	14.8	13.4	14.4	14.9	15.7	17.5	19.5	20.7	21.1
Mean daily sunshine (hrs)	10.7	10.2	9.0	7.3	6.0	5.0	5.4	6.4	7.4	8.8	9.9	10.7

Table 4-1 *Climatic averages for Perth (Bureau of Meteorology 1999)*

The seasonal climatic characteristics of Perth are warm to hot summers with medium to low humidity and cool to mild winters, as can be seen from mean values in Table 4-1. Table 4-1 also highlights some characteristics of Perth's climate that are rele-

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[1] Perth's latitude is 31°55'S, longitude 115°52'E and elevation 24.9 metres. Based on Koeppen's global classification of climate, Perth has a warm climate with a hot, dry summer (Sturman & Tapper 1996).

[2] Data is from the Perth Regional Office number 009034 in East Perth taken between 1876 and 1992.

vant to energy-efficient design. The data shows that the average highest monthly temperature occurs approximately two months after the summer solstice and average lowest monthly temperature occurs approximately one month after the winter solstice. In energy efficient design, this lack of symmetry around the solstices particularly influences the design of fixed shading devices associated with solar collectors.

If northerly solar collectors are to be shaded until the end of the hot period (end of March), they will also be shaded in mid-September, when it is still cool. With fixed shading devices some compromise much be reached between solar collection when it is cool and solar protection from undesirable heat. Based on the high mean temperatures occurring in February, in the current study the compromise adopted for energy efficient design is that northerly solar collectors should be fully shaded until the end of February. Consequently they will also be shaded in mid-October.

From November to March the average amount of sunshine received is over nine hours per day with little variability. If the amount of sunshine is taken in conjunction with the very high intensity direct solar radiation on unshaded east and west walls during the summer (Spencer 1976), there should be no compromise for glazing on these two orientations. That glazing should be fully shaded from early November until the end of March.

Mean diurnal temperature range in the hottest summer months is approximately 12 K. This indicates an opportunity to use cool night air to lower the temperature of indoor thermal mass. However, between December and March there are, on average, nine days when the minimum temperature does not fall below 22°C and twenty-five days when the minimum temperature does not fall below 20°C[1]. On such days, dependence on cool night air to lower the temperature of indoor thermal mass to an acceptable level may not be realistic.

During the hottest summer months, the mean relative humidity at 3pm is just over 40%. In terms of affecting the cooling efficiency of sweating, relative humidity is

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[1] This data was provided on 23 May 2002 by Mr B. Kowald, technical officer in the Climate Consultancy Division of BoM in Perth.

not usually an issue in Perth, although there are exceptional summer days of high humidity.

Western Australia is renowned for the strength and regularity of afternoon sea breezes in coastal areas as indicated in Table 4-1. Although the strength of these winds may sometimes be unwelcome, as their speed frequently exceeds 8.9 m/s (Bureau of Meteorology 1995), they increase the heat loss of the building envelope through convection, can raise the upper limit of thermal comfort and, when outdoor temperatures fall, can increase the heat loss of indoor thermal mass through natural ventilation.

During July, the coldest winter month, there is an average of five hours of daily sunshine in Perth, although there is a high daily variability, due to June and July typically being the wettest months. Thus in energy-efficient design, it is particularly important that solar energy during winter can be collected and stored for indoor heating.

4.3.3 Data collection and analysis

The data sought included information regarding the design and construction of dwellings, indoor temperatures in dwellings, occupants' consumption of electricity and gas and occupants' behaviour in relation to adjusting building elements to respond to climate.

Based on consultation with both the administration and operations managers of the public housing authority, housing developments from around the Perth metropolitan area were considered for selection. The final selection of developments to be examined was based on perceived differences between the developments in terms of location, design, apparent adherence to energy efficiency principles and advice from the operations managers as to the likely co-operation of the tenants.

Data was collected from a number of sources. The Ministry of Housing provided site plans, floor plans and elevations of the developments. Thermal conditions in individual dwellings were measured with computerised data loggers. Semi-structured interviews were carried out with dwelling occupants and particular features of the occupied dwellings were observed during the interviews. Records of annual energy consumption in the monitored dwellings were obtained from the energy providers.

4.3.3.1 Sample selection

Seven housing developments were selected from the database of the Ministry of Housing. The selection criteria were that the developments should be relatively new, thus designed to a common design brief.

Most importantly, the selection of the developments was based on an apparent adherence or non-adherence to the traditional accepted approach to energy-efficient design regarding window orientation to the north and the long axis of the building running east to west. In three developments nearly all dwellings have significant areas of glazing facing approximately north and the longer axis of the building running east-west. One of these three developments received an award from the Housing Industry Association in 1994, with a commendation for the approach taken towards energy efficiency in the design. In the other four developments, orientation is more arbitrary and the direction of the longer axis of individual dwellings varies.

Another selection criteria was that the developments should be constructed in a range of suburban locations on the sand plain of Perth, thus varying in proximity from the tempering influence of the Indian Ocean. Each of the seven developments is located in a different municipality as shown in Figure 4-1. Consequently each development is at a different distance from the Indian Ocean to the west of Perth. The distance between the northern most development (Development 2) and the southern most development (Development 1) is approximately 45 kilometres.

The third selection criterion was that the developments should be the work of different designers. This would provide some insight into how designers were responding to the energy efficiency requirements of the design brief.

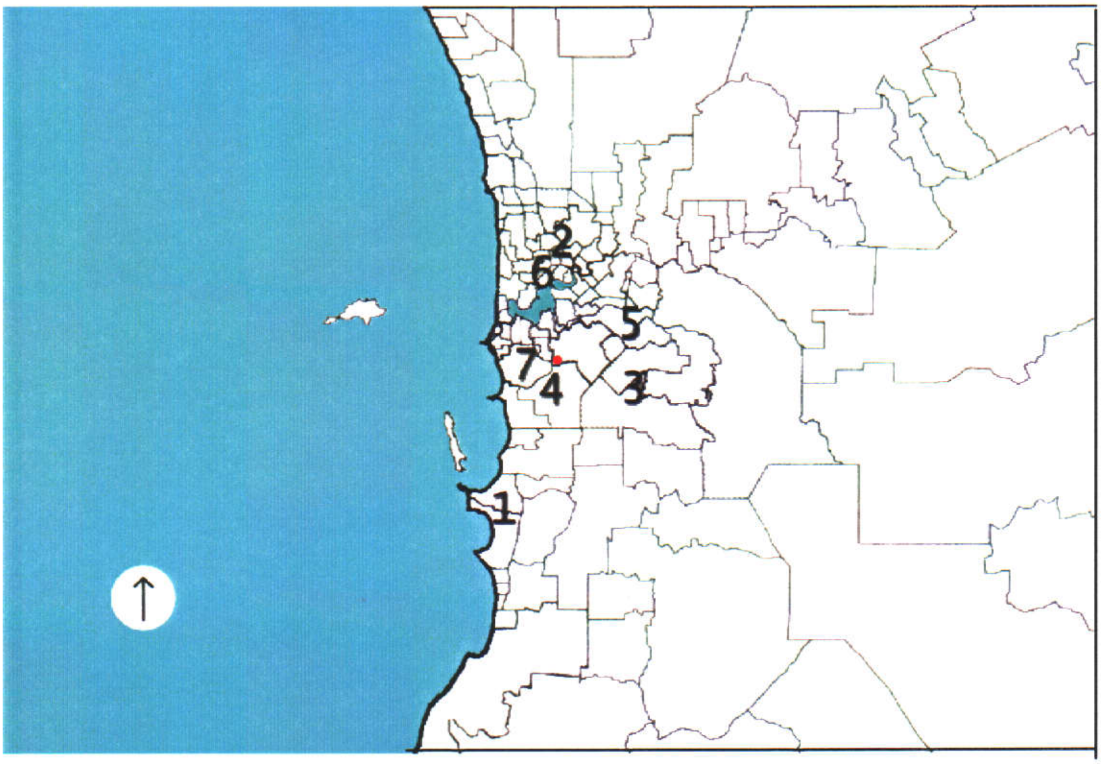

Figure 4-1 *Locations of the seven aged-persons developments in Perth (UBD Perth Street Directory 1999, Key map)*

Developments

The housing developments vary in size from sixty-two dwellings to eight dwellings, with a combination of one and two-bedroom dwellings in each development. A tabulation of the total numbers of dwellings in the seven developments, the numbers monitored in summer and winter and their adherence to a traditionally accepted approach to energy efficient design is presented in Table 4-2.

Development	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Total dwellings	14	25	62	16	9	17	8
Dwellings monitored in summer	10	15	7	8	6	8	6
Dwellings monitored in winter	3	4	3	3	3	4	2
Total dwellings with sig. northerly glazing	14	5	22	6	9	17	5
Total dwellings with long axis east- west & north glazing	14	5	0	0	9	15	0

Table 4-2 *Size and monitoring pattern of developments*

Site plans and typical floor plans for each development are shown in Appendix 2. An example of one of the developments is shown in Figure 4-2. In addition to showing the relationships of the dwellings to each other and their orientation, the site plan indicates the private open space allocated to each dwelling.

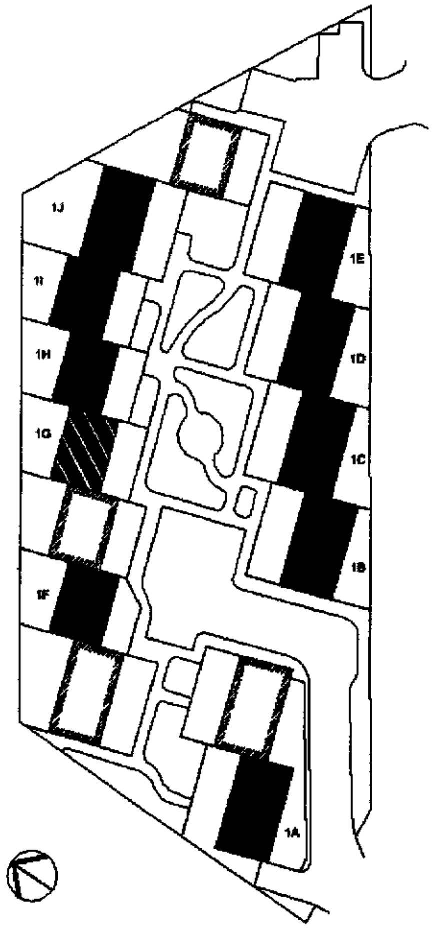

Figure 4-2 *Site plan - Development 1*

All the dwellings that are shown black on the site plan were monitored in summer. A limited number of these same dwellings were also monitored in winter.

Dwellings

In January 1999 a sample of residents from each of the seven developments were recruited with the assistance of staff from the Ministry of Housing. The operations managers in charge of different developments identified and approached tenants whom they thought may be willing and able to participate in the current study. Consequently, the numbers of dwellings monitored in summer reflect to a large extent the way the particular operations manager advised tenants about the current study. All residents who indicated a desire to participate in the current study were accepted.

The residents were advised that they would be interviewed and their dwellings would be monitored in summer and in winter. The dwellings of these residents are referred to by an alphanumeric, with the number referring to the development and the letter referring to the particular dwelling.

The dwellings are all single level. They are either free-standing dwellings, semi-detached dwellings with one common wall, terrace dwellings with two common walls or, in one development where part of the site is sloping, semi-detached dwellings constructed one above another but with each dwelling having access directly from ground level. A private courtyard space is provided, generally adjacent to each living area. Internal planning combines a living area with the kitchen area so heat generated from the refrigerator and cooking activities directly affect the temperature in the entire dwelling. Bedrooms generally opened directly from the living area.

Two standard floor plans are commonly used for dwellings in each development, a one-bedroom design and a two-bedroom design. These are located on a particular site in various arrangements as indicated on the site plans. A typical floor plan of a dwelling monitored in both summer and winter is shown for each of the seven developments in Appendix 3 (designated with a white hatch on black on the site plan). These are Dwellings 1G, 2D, 3D, 4A, 5D, 6E, 7D. Figure 4-3 shows one of the typical plans.

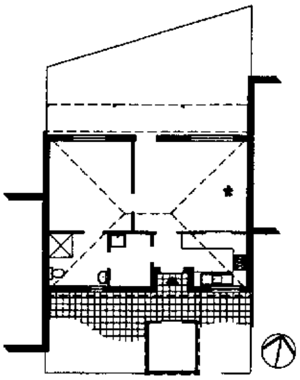

Figure 4-3 *Typical floor plan - Dwelling 1G*

Sixty dwellings were monitored in summer and twenty-two dwellings were monitored in winter (see Table 4-2). Not all dwellings were monitored in winter for two primary reasons. Firstly, many of the original volunteers were either not interested or not available to participate in the winter study and secondly, a preliminary analysis of the results from the summer survey showed the repetitive nature of the results within developments. The particular dwellings revisited in winter were chosen on the basis of the willingness of the volunteer to again participate, the inclusion of both one bedroom and two-bedroom dwellings from each development and, if possible, the inclusion of dwellings with different window orientations in the four non-north oriented developments.

The general construction details of the dwellings were recorded. The construction was typical of domestic construction in Perth as can be seen in the key elements of construction listed below.

- All dwellings had an uninsulated concrete slab floor covered with a vinyl floor finish, except for a small area of ceramic tile floor finish in bathroom areas. Some occupants had fitted carpet over the vinyl floor in the living area and bedrooms.

- External walls were generally uninsulated cavity brick walls, plastered internally, although in two developments some external walls were of either steel or timber frame with sheet cladding both externally and internally. One development had some external walls of reverse brick veneer construction. No fixed air vents were built into any external walls.

- Glazing was single pane glass in aluminium frames with security screens fitted to all operable windows and doors. Each dwelling incorporated at least one skylight that was a translucent acrylic dome with an acrylic sheet at ceiling level. One development incorporated north facing translucent Alsynite roof sheeting in dwellings where north windows could not be provided.

- Internal walls were 90mm masonry with 12mm plaster each side.

- Roof structures were timber framed with pitched roofs and boxed eaves. The roofs were clad with either roofing tiles or steel decking.

- Ceilings were 10mm plasterboard with a minimum R2 ceiling insulation
- All dwellings had gas hot water services and gas room heaters installed prior to being made available for rental.

The dwellings varied in floor area from 47 square metres to 65 square metres. The relationships between floor area, external wall area and glazing area also varied between developments as can be seen in Table 4-3 for a typical dwelling in each development.

Development	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Dwelling number	**1G**	**2D**	**3D**	**4A**	**5D**	**6E**	**7D**
Floor area (m^2)	49	59	63	47	47	63	47
External wall area (m^2)	40	73	38	35	34	43	39
Glazing area including skylights (m^2)	7.8	14.8	10.6	10.2	19.7	17.0	12.8

Table 4-3 *Floor area, external wall area & glazing area, in square metres, of typical dwellings in each development*

4.3.3.2 Data collection

One objective of the field work was to establish representative values for indoor air temperature that could be compared with those levels of indoor temperature considered to be acceptable, as discussed in Chapter 3. Another objective was to ascertain a mean value of gas and electricity consumed in the different developments. A third objective was to record how older people's behaviour in relation to the designed shell of the building influenced indoor temperatures. These three objectives were addressed by measuring temperatures in the chosen dwellings, obtaining energy accounts for the monitored dwellings, interviewing an occupant in each dwelling and noting those physical characteristics of the dwelling that were not included in the available drawings.

Measurement of indoor temperatures

Both summer and winter conditions were taken into account as variations in outdoor dry-bulb temperatures frequently exceed the upper limit of comfort in summer and lower limit of comfort in winter. Dwellings in each development were monitored for at least five days in summer and five days in winter so that a design day could be identified within the monitoring period.

The dry-bulb air temperature in the living area of each dwelling was monitored. This procedure follows that of a number of other researchers like Marshall (1958), Rohles (1969), Pryor (1984) and Vale and Vale (2000) who considered that in climates where humidity is not high[1] in summer, dry bulb air temperature was a sufficient indicator of thermal conditions in an occupied house.

As the dwellings examined in this study are all small in area and doors between rooms are generally open, there is little difference in temperature between different spaces in the dwelling. This similarity of temperature between spaces in small, medium density dwellings was established in a study of 30 dwellings in three non-government retirement villages. The dwellings, which were between 15% and 30% larger in floor area than the dwellings in the current study, were monitored simultaneously in the living room and bedroom. The mean temperature difference between the rooms was found to be approximately 0.2 K[2]. Thus, in the current study, only the air temperature of the living area was monitored.

The air temperature was monitored using the Gemini 'Tinytalk II' automatic data loggers with external sensing probes. These loggers are the size of a film canister and thus are unobtrusive. They have a sensor range of –40 to +50°C and an accuracy of plus or minus 0.2 K, which complies with the requirements of the standard ISO 7726 (1998). A calibration test of the data loggers to plus or minus 0.2 K was carried

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[1] Climatic data for Perth in summer shows that mean relative humidity in the hottest months in the afternoon is no more than 44% (see Table 4-1).

[2] This temperature difference was ascertained by the author in an unpublished study of perceptions of thermal comfort in 30 dwellings in three retirement villages in Perth in summer and winter in 1996.

out in summer and winter prior to placing them in the dwellings. Loggers that could not be calibrated to the required level were rejected.

The loggers were programmed to measure dry-bulb air temperature at 30-minute intervals in each dwelling. Data was retrieved by means of the management software that is run on a Windows-based host computer. As one data logger malfunctioned during the summer monitoring, due to a fault in the connection between the external sensing probe and the logger, that dwelling in Development 6 was excluded from the study.

Each data logger was placed in the living area, 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 varied in each dwelling, depending on the horizontal surface available and acceptable to the occupier. In each case the data logger was positioned away from direct sunlight or other obvious direct sources of heat or cold. Typical data logger positions are shown on the floor plans thus '*' in Appendix 2.

External air temperatures and relative humidity[1] were obtained online from the Bureau of Meteorology's site at Murdoch University for the same dates and same times as the indoor air temperatures were logged <http://wwwmet.murdoch.edu.au>. This Bureau of Meteorology site[2] is approximately 25 kilometres from the most distant monitored development. It is in a suburban area, thus unlikely to give rise to pronounced urban heat-island effects. Although it is recognised that the external temperature around each of the monitored dwellings may vary from that at this Bureau of Meteorology's monitoring station, the observations from that monitoring station were deemed representative for the purposes of this study.

For analysis, one day in each monitoring period for each development was chosen which most closely resembled Szokolay's (1982) 'design' conditions for Perth. In

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[1] The external temperatures and relative humidity for the periods of logging are recorded in Appendix 3:

[2] The location of the site is shown as a red dot on Figure 4-1 just north of Development 4.

the current study, the chosen days are referred to as 'design days'. Szokolay (1982) had adopted design day conditions from a major air-conditioning manufacturer's design manual. These design conditions refer in summer to a maximum dry bulb temperature of 36°C and a wet bulb temperature of 24°C and in winter, to a minimum dry bulb temperature of 9°C. 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 6 K higher than the mean maximum summer temperature. Consequently it may be more difficult to satisfy the more extreme summer conditions than winter conditions.

Acceptable maximum summer temperatures and acceptable minimum winter temperatures were calculated for the chosen design days using de Dear and Schiller Brager's (1998) adaptive theory of thermal comfort as previously discussed in section 3.2.5.

Interviews and questionnaire

Interactive semi-structured interviews were undertaken in the volunteers' dwellings in summer and winter. The primary interview was in summer and was based around a structured questionnaire shown in Appendix 4. The interview in winter was intended to confirm behaviour patterns using the same questionnaire. It also provided the opportunity to gather additional data that had not been envisaged at the first interview.

The questionnaire was intended to provide basic demographic data in addition to information about physical aspects of the dwelling that could influence the thermal performance of the dwelling. It was also intended to provide insight into the interaction of the occupant with the thermal performance of the dwelling. Nine questions were included relating to the occupant's behaviour that may affect indoor temperatures and their need for space heating or cooling. The interviewer recorded responses during the interview and sought elaboration of responses as required. Anecdotal remarks made during the interview were also recorded.

After concluding the questionnaire, the interviewer recorded details of the physical environment, which could potentially affect the energy efficiency of a dwelling, but was not evident from the plans of the development. This included details of the hot water service and refrigerator, amount of furniture and type of curtains. It was noted if a dwelling was sparsely furnished or particularly crowded with furniture. A record was made of those dwellings where carpets had been fitted over the vinyl floors. The resident's permission for obtaining copies of their energy bills for the previous twelve months from the reticulated gas provider, Alinta Gas, and the electricity authority, Western Power, was also obtained at the time of the primary interview.

During the second interview, in winter, occupants were again asked about their winter habits that may influence indoor temperatures, to check for consistency with summer responses. In winter, a timetable was left with the occupants for them to note if they were out of the house for more than two hours or if they were making extraordinary use of the stove or oven during the monitoring period. In hindsight this may also have been useful for the summer analysis.

Interview protocol

Following initial contact by the Ministry of Housing with each volunteer, appointments were made to carry out the interviews and leave the programmed data loggers. All volunteers were advised that their involvement with the study was entirely voluntary and they could choose to withdraw from the study at any time. A number of volunteers asked for a copy of the results of the monitoring in their dwelling. This was duly forwarded.

4.3.3.3 Data analysis - overview

The raw data collected, in the form of logged temperatures, responses to questionnaires, researcher's notes and observations, accounts from gas and electricity providers and plans of developments and dwellings, progressed through a number of stages of correlation before being recorded into permanent data sets for detailed analyses.

SPSS –PC[1] statistical software package was used to analyse the logged temperatures on the chosen design days in summer and winter, responses to questionnaires and gas and electricity consumption at each development. Data sets used in SPSS appear in Appendix 5.

Analysis of logged temperatures

The intent of the analysis was to determine if there is a significant difference between the mean indoor temperatures in the seven developments and between the dwellings in each development. Descriptive statistical tests were carried out to establish the mean values and the extreme values of monitored summer and winter indoor temperatures of dwellings in all the developments on the design days.

Data reduction

In order to facilitate the comparison of the hourly temperatures on the design days in summer between all 60 dwellings in the developments, factor analysis was used. The hourly monitored summer temperature data was subjected to a Principal Component Analysis (PCA). This PCA enabled four representative factors of the 24 hour temperature data to be extracted. These four factors were interpreted to relate to four bands of time within the 24 hours on the design day.

Test for significant temperature differences

Having established the four time bands, all dwellings monitored in summer in the seven developments were subjected to an analysis of variance (ANOVA) to determine in which bands the summer temperatures were significantly different between the seven developments.

Summer temperature differences between the dwellings within each development were also subjected to ANOVA but without resorting to using the reduced data. The full data sets were used in these analyses within a development to avoid violating the

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[1] SPSS version 9 for Windows was used for the majority of analysis. Subsequent versions, including version 11.5 were used for additional analysis.

statistical assumptions for analysis of variance, as the numbers of dwellings monitored in the individual developments were small, somewhere between six and fifteen dwellings.

Reduction of data was also considered inappropriate when the monitored winter temperatures were subjected to ANOVA to determine whether there was a significant difference between the thermal conditions in the various dwellings. This was for two reasons. As the number of dwellings monitored in winter were approximately one third of those monitored in summer, the size of the matrix of 24 hourly temperatures and number of dwellings could be managed. In addition it is questionable whether there are underlying common factors that accurately summarise hourly indoor winter temperatures when all dwellings are fitted with space heaters and the use of the heating is highly individualistic.

Analysis of responses to questionnaire

Chi-Square tests were used to determine if there is independence or relatedness between various aspects of occupant behaviour in the developments. Chi-Square tests were also used to determine if there are differences between the developments in the frequency of a particular occupant response. These results could then be considered in relationship to acceptable temperatures, the design of the dwellings and the occupants' behaviour.

Gas and electricity consumption

To establish the mean, minimum, maximum and standard deviation of energy consumption in the seven developments, descriptive statistical tests were used. Both annual energy consumption and winter energy consumption were analysed using t-tests. The consumption figures were based on the units of energy recorded on the accounts presented by the gas and electricity utilities. Electricity readings are provided every two months and gas readings every three months, with the readings not necessarily coinciding with the seasons. Consequently, in this thesis winter electricity consumption figures capture four months of data that include June, July and August whilst winter gas consumption figures capture six months of data which also include June, July and August. These consumption figures were converted to energy consumption per square metre of floor area. The energy data was also subjected to ANOVA to determine if there is any significant difference in energy consumption between the developments. The relationships between occupant behaviour and energy consumption were also examined using chi-square tests.

4.3.3.4 Data analysis – detailed examination

To carry out a detailed examination of a limited number of typical dwellings, two steps were taken, as summarised in Table 4-4. The detailed examination was based on monitored temperatures, interviews, direct observations, floor plans and computer simulations (see Appendix 6). The detailed examination included a study of the indoor temperatures in the buildings as constructed as well as computer simulations of the indoor temperatures in the dwellings.

	Consider	Action	Expected outcome
Step 1	all developments	* identify typical development that appears to be energy efficient * identify typical development that appears NOT to be energy efficient	* 2 representative dwellings from each type of development
Step 2	4 existing dwellings	* compare actual temps., computer simulated temps., acceptable temp. range & relate to occupants' behaviour * establish energy consumption to achieve acceptable temps.	* influence of design on temperature * influence of behaviour on temperature * comparison between actual energy consumption and energy consumption required to achieve acceptable temps.

Table 4-4 *Summary of detailed examination process*

Basis for selecting developments

The two developments chosen for detailed examination represent two ends of the design spectrum demonstrated in the seven developments in relation to energy-efficient design. Each development represents a particular approach towards energy efficiency.

Development 4 is representative of developments designed with a combination of north-south and east-west oriented glazing and little attention given to providing direct solar gain in winter. Development 5, on the other hand, is designed using the accepted passive solar design principles of orienting primary glazing in all dwellings in a northerly direction and designing buildings to have the longer dwelling axis running east-west. This development, as previously indicated, received a commendation from the Housing Industry Association in 1994 for the approach taken towards energy efficiency in grouped housing.

The construction of the buildings in Development 4 is typical of the medium red-brown coloured cavity brick walls and tile roofs in approximately half of the developments. The construction of the buildings in Development 5 represents a less traditional method of construction of the building envelope. It has a combination of light-coloured cavity brick walls and lightweight wall cladding, together with a metal deck roof.

Basis for selecting dwellings

The dwellings selected from Developments 4 and 5 are representative of the dwellings monitored and the occupants of these dwellings represent a range of tenants with a single female, a single male and a couple being included. The dwellings represent:

- the most common layout plan, namely a semi-detached one or two-bedroom dwelling;
- the majority of dwellings, as none have room air-conditioners installed; and
- a range of levels of energy consumption (from the lowest statistical quartile to the second highest statistical quartile).

One north-south and one east-west oriented dwelling was selected from Development 4. The east-west dwelling is representative of the majority of monitored dwellings in the current study that have little or no sun penetration into the living area in winter.

Plans of all the dwellings considered in detail are included in Chapter 5. A plan of one of the selected dwellings (Dwelling 4A) is shown in Figure 4-4. The plan shows that Dwelling 4A is a one-bedroom dwelling with its longer axis oriented 5° east of north and all glazing oriented north or south except for one skylight that is oriented west. The location of the data logger used to monitor the temperature in the dwelling is marked '*' on the plan.

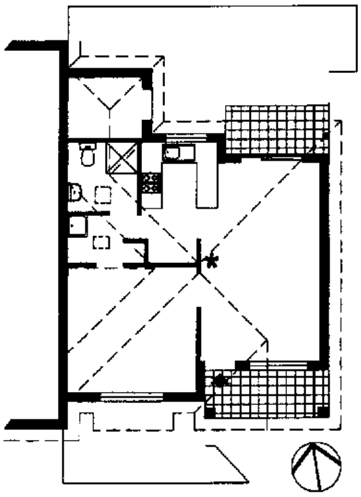

Figure 4-4 *Dwelling 4A floor plan*

Thermal conditions

One way of characterising the transient thermal response of a building is to compare the daily internal temperature fluctuations with the daily outdoor temperature range. Thermal conditions over the full monitoring period, including the design days, were examined. In addition, computer simulations of the thermal performance of the four dwellings as constructed were carried out. The simulated hourly indoor temperatures on design days in summer and winter in the four dwellings were analysed and compared with monitored temperatures.

The simulated hourly temperatures provided a thermal performance reference base for Dwellings 4A, 4B, 5D and 5E so that design modifications could be compared to this base performance. The base performance also provided a reference point to speculate on how the occupants' behaviour may have affected any discrepancies between actual thermal performance and simulated performance in these four dwellings. This would assist in addressing the appropriateness of the design for the occupant.

Evaluations of the relationships between monitored temperatures and the building design including orientation, size of glazing, area of external walls, eaves design, occupant behaviour related to opening and closing of windows and blinds and use of mechanical heating and cooling, were carried out for each of the four dwellings.

4.4 Appropriateness of energy efficient design

To explore the notion of appropriateness in energy efficient design the following dimensions of appropriateness, discussed in Chapters 2 and 3, were taken into account:

- providing minimum indoor temperatures in winter of 19.8°C;
- providing maximum indoor temperatures in summer of 27.4°C in still air;
- fitting the needs of physically vulnerable older people;
- fitting the site planning and form of typical small, medium density housing for the aged in suburban Australia; and
- meeting the needs of financially vulnerable people.

The method used for the exploration of appropriateness of temperature was to empirically test the thermal performance of hypothetical dwellings that were similar, where possible, to the design of typical monitored dwellings. Building elements that improved energy efficiency and were 'appropriate' were systematically tested in a hypothetical dwelling. Affordability was one of the criteria of appropriateness to be considered.

4.4.1 Modelling tool for empirical analysis

The tool used to assess the empirical thermal performance of the dwellings was the Nationwide House Energy Rating Scheme for Australian conditions, referred to as NatHERS[1]. The engine software for NatHERS is CHENATH. This engine software is an upgrade of the CHEETAH program that was developed by CSIRO to calculate

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[1] NatHERS Version 2.31 (dated January 2000) was used.

heating and cooling energy requirements for small buildings in Australian climatic conditions. As well as providing the engine software for NatHERS, most computer thermal modelling systems for residential buildings used presently in Australia such as FirstRate, QuickRate, BERS, QRate and ACTHERS are also based on CHENATH.

NatHERS has undergone continuous improvement and validation in the course of its development, including improvements related to the modelling of windows, the modelling of concrete floor slabs and the simultaneous heating and cooling in different zones of a building (Ballinger 1998a; 1998b). NatHERS is an appropriate tool to use in the current thesis as the intent of NatHERS was that it:

"*be used by building designers, architects and municipal authorities, to assess and compare the performance of building designs, and improve the energy efficiency of those designs*" (Symons, Li & Moller 1997, p.6).

NatHERS analyses heat flows to and from each thermal zone in a building. In the current thesis NatHERS was used to both calculate hourly temperatures in each dwelling, when no mechanical heating or cooling was provided, and to provide an indication of heating and sensible and latent cooling loads required to maintain acceptable thermal conditions.

To determine heating and cooling loads, temperature settings were configured so that during the day the temperatures in the living and bedroom areas remained between 19.8°C and 27.4°C[1]. In the bathrooms the minimum temperature was reduced to 18°C, as this was considered acceptable based on the World Health Organisation (1984) recommendation that the temperature in rooms occupied by old people should not be below 18°C.

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[1] These minimum and maximum temperatures are based on the minimum acceptable mean temperature for July and the maximum acceptable mean temperature for January respectively (see section 3.2.5).

The computed thermal loads were converted to approximate energy consumption, using efficiency factors of 0.7 for gas heating and 2.4 for refrigerated air-conditioning (Fay & Treloar 1999). This enabled comparisons to be made between theoretical energy consumption in typical dwellings and in energy efficient dwellings.

As with other simulation programs, dimensions of the dwelling configurations and construction materials are required to be inserted into the program. In addition, NatHERS requires that at least two thermal zones be defined. The concept of thermal zoning is related to the acceptance that moderate temperature differentials are to be expected within a house that is not centrally heated or cooled. In average family houses that are designed to respond to climatic changes, a warm north oriented zone and a cooler south oriented zone will occur (Samuels et al 1993). As discussed in section 4.3.2.2, in small dwellings the actual temperature differences between living areas and bedrooms is small thus in practice creating only one thermal zone. As two zones were required to be designated in order to utilise NatHERS as a simulation tool, the bathroom area was designated as one zone and the remainder of the dwelling formed the other zone. The store room area was not included in the simulations. An example of the defined zones is shown in Figure 4-5 for the plan of an existing monitored dwelling. The zone indicated with a vertical line hatch is the living/bedroom zone. All the temperatures referred to in regard to simulated performances of the dwellings refer to the temperatures in the living/bedroom zone of the particular dwelling.

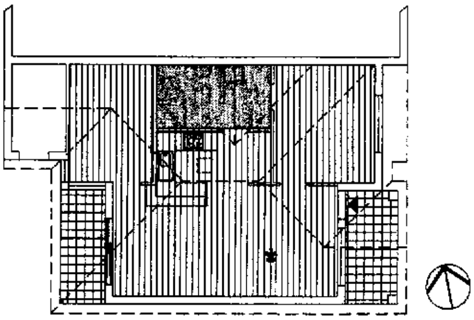

Figure 4-5 *Example of designation of two thermal zones for simulation purposes*

NatHERS incorporates nationally agreed criteria of occupational patterns based on studies conducted with project homes (Lee & McKinnon 1996). As these occupation patterns may not reflect heat gains in very small dwellings occupied by one or two older people, the internal sensible and latent heat gains were reduced at 8am and 7pm to the same level as indicated in NatHERS for the general morning (8 to 9am) and evening (7 to 10pm) peak periods. At the two peak times, 8am and 7pm, the heat gains in a family dwelling are substantially higher than at other times, whereas there is no evidence that such high peaks reflect the lifestyle of households of older people. Monitored temperatures in the current study did not reflect these peaks in indoor temperatures. Thus, in every temperature simulation carried out in the current thesis these two peak heat gains were reduced by amending the SCRATCH file generated with each simulation. However further research may be required to more accurately determine whether the magnitude of the heat gains in the peak periods in NatHERS represent internal heat gains in housing specifically for the aged.

The construction materials incorporated in the NatHERS library generally reflect the materials and construction systems actually used in the construction of the four dwellings. On those occasions when the desired width of a construction material in the NatHERS library was not prescribed, such as the thickness of brick walls, this was amended in the SCRATCH file for the particular simulation. However, in developing proposals for energy efficiency, an approximate modelling of one wall system that is not included in the NatHERS library was carried out. This was a Trombe-Michel wall shown in Figure 4-6.

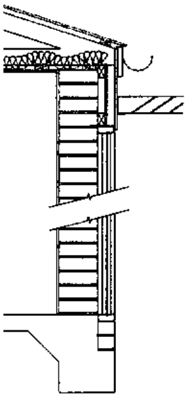

Figure 4-6 *Section through an un-vented Trombe-Michel wall*

In order to simulate the Trombe-Michel wall in NatHERS, Delsante (2002) suggested an approximate method of modelling. The air gap between the glass and the wall could be treated as an 'unconditioned zone' with no air infiltration and with a concrete floor having an area equal to the area of the Trombe-Michel wall. This 'unconditioned zone' would have a glass northerly-facing window wall of the required area and have no curtains. This 'unconditioned zone' could be modelled as a zone above the living zone and thus the floor of the unconditioned would form part of the ceiling of the living zone. Thermal radiation would be transferred through the ceiling rather than through a masonry wall. As a result of the unconditioned zone being above the living zone, a nominal stair well was required for simulation purposes. This stair well was given an area of 0.1m^2. It is recognized that this modelling of an un-vented Trombe-Michel wall is an approximation that enables the situation to be simulated using the library of construction materials within NatHERS.

There is an operational assumption of NatHERS that clearly does not accurately reflect the circumstances in these four dwellings. The standard infiltration rates were used, although it is clear that the impact on infiltration level of the entrance door, opening directly into the living area, is greater in these small buildings than in the basic living zone[1] used in NatHERS.

As Rossit (1993) makes clear, simulation programs such as NatHERS are simplified representations of real buildings and numerous assumptions are made to enable calculations to be done in a reasonable time. This program is however most useful in comparing the performances of dwellings. In the current study the results from NatHERS are used primarily to make comparisons between the thermal conditions in typical dwellings and in dwellings as modified to improve energy efficiency. Nevertheless, computed temperatures are compared with the acceptable temperature range.

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[1] In the basic living zone, NatHERS (2000) refers to a volume of 200 m^3. This is greater than the total volume of these small dwellings.

4.4.1.1 Weather data file

The weather data file for Perth incorporated in NatHERS includes two days in January (7th and 17th January) and a day in July (27th July), which have temperature patterns similar to the design days referred to by Szokolay (1982) and similar to the design days identified during the monitoring periods. The weather data file was amended on these three days so that the temperatures were the same as temperatures on the monitored days for Developments 4 and 5. Indoor hourly temperatures on these three design days were used for the purpose of comparing monitored temperatures and simulated temperatures in typical dwellings. Indoor hourly temperatures on two of these design days, 7th January and 27th July were used to determine temperatures in a typical dwelling that was progressively modified to improve energy efficiency.

4.4.2 Empirical analysis

The objective of the empirical analysis was to explore how energy efficient design elements could improve the theoretical thermal performance of typical[1] small, medium density housing. Each design element could be assessed for impact on indoor temperatures. Generally, the design elements were limited to those that were typical in developments monitored in the multiple - case study in the current thesis and considered to address appropriateness criteria for older people. The results could then be used to establish a benchmark for acceptable design features for small, energy-efficient housing in a temperate climate. The five steps taken to carry out the empirical analysis are shown in Table 4-5.

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[1] A two-bedroom dwelling from Development 4 was selected as a typical dwelling. This dwelling was considered typical for a number of reasons. It is not designed to be energy efficient as it has no northerly glazing, it represents the most common size of dwelling in the multiple - case study (approximately 65 m^2) and the materials of construction are commonly used in residential construction in Perth as well as being the most commonly used in the multiple - case study in this thesis – a concrete slab on ground covered with vinyl tiles, uninsulated cavity brick walls, single glazing in aluminium frames, plasterboard ceiling with R2.0 insulation and terra-cotta roofing tiles on a timber framed roof.

	Consider	Action	Expected outcome
Step 1	hypothetical dwelling (65m^2)	* computer simulation complying with benchmarks	* temps. to compare with acceptable temps.
Step 2	typical dwelling (65m^2)	* BCA compliance	* temps. to compare with acceptable temps.
Step 3	typical dwelling (65m^2)	* series of modifications & computer simulations to determine appropriate solution	* temps. to compare with acceptable temps.
Step 4	typical dwelling (65m^2)	* affordability of modification using discounted cash flow methodology	* energy consumption with & without modifications * payback period
Step 5	2 typical dwellings (50 m^2), (80m^2)	* apply appropriate solution modifications to other typical dwellings * computer simulation of temps	* temps to compare with acceptable temps

Table 4-5 *Summary of empirical testing process*

4.4.2.1 Computer simulations

Operational assumptions and adjustments

The following assumptions and adjustments were made in the NatHERS simulations:

- the dwellings were in a suburban terrain;
- the internal sensible and latent heat gains were reduced only at 0800 and 1900 hours, as discussed in section 4.4.1;
- closed weave, unlined curtains were assumed in all simulations;
- the solar pergola was assumed to cut out 100% of direct solar gain in summer (November, December, January and February) and 10% of direct solar gain in winter (May, June, July and August). Although the nominated months for control of solar gain do not strictly reflect the actual symmetry of the sun's movement around the solstices, it is not possible to include half a month of shading in the NatHERS pergola schedule. A 50% direct solar gain was nominally assumed for the other months;
- as only one type of skylight can be nominated, a double-glazed opal skylight was specified for all simulations although in the typical dwellings in the multiple -

case study, single-glazed skylights were provided in some bathrooms and laundries; and

- although the design of typical, medium density housing lends itself to cross ventilation, at least in living areas, for reasons of appropriateness based on evidence from the multiple - case study in the current thesis, the simulations were carried out without allowing for the potential cooling effect of natural cross ventilation.

Modelling dwelling to comply with benchmarks

To determine how the benchmark requirements (as presented in section 3.2.4) affected indoor temperatures in small, medium density dwellings, a hypothetical building was designed to comply with the benchmarks for area of north wall, area of northerly glazing, area of total glazing, volume of thermal mass in brickwork, wall and roof insulation and night ventilation. This building was simulated and temperatures compared with acceptable temperatures.

Modelling dwelling to comply with regulatory requirements for energy efficiency

To determine how the new regulatory requirements for energy efficiency in housing (ABCB 1996) would effect indoor temperatures in small, medium density housing in Perth, a typical dwelling was modified to comply with the BCA requirements. This building was simulated and temperatures compared with acceptable temperatures.

Modelling dwelling for energy efficiency

A series of design modifications were made to a typical dwelling. The modifications were kept within the current design vocabulary and the typical site layout was retained. This approach adopts one of the tenets of universal design, expressed by Demirbilek and Demirkan (1998), that universally designed environments should not stand out as being different.

The areas of modification were selected from the five criteria discussed in Chapter 3 for improving thermal performance through energy-efficient design. The modifications related to building orientation, area and properties of glazing, volume of thermal mass, the insulation of the building envelope and ventilation for night cooling.

It was recognised that a balance would be required between improved performance in summer and improved performance in winter, thus the temperatures resulting from each modification were considered in both summer and winter. Figure 4-7 describes diagrammatically the approach taken to exposure of glazing to solar radiation and ventilation during different months of the year. The period of solar exposure and solar shading are not ideal but take into account the limitations of fixed shading devices, chosen for affordability reasons[1]. A solar pergola provides shading symmetrically around the solstices, rather than around monthly mean temperatures as discussed in section 4.3.2.2. As natural ventilation was not considered to be 'appropriate' on the basis of the multiple - case study findings, the computer simulations generally assume there to be <u>no</u> cross-ventilation in the dwellings. However the effect of mechanical ventilation for night cooling was tested in one set of simulations.

Preliminary modifications

Preliminary modifications revolved around the design of the building envelope on the north[2] side of the dwelling. Design modifications considered included:

- adjustment to the area of northerly glazing[3]; and
- adjustments to eaves or other projections so that neither northerly windows nor the north wall itself was significantly shaded in mid-winter, but total shading from direct solar radiation was to be available on the north wall solar collectors during November, December, January and February.

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[1] Ideally solar shading should be automatically adjustable, without placing an on-going environmental demand on the occupant. However, as indicated by a manufacturer, automation of solar louvres can more than double the cost of the louvres thus are not suggested in the current thesis.

[2] Northerly orientation refers to between 30° east of north and 20° west of north (Prasad & Veale 1998).

[3] The area of northerly glazing to the living area was increased to the maximum typical size of glazing (2.1 x 2.1m^2 glazed sliding door). North oriented roof glazing as constructed in a number of dwellings in Development 6 was not included as an option. This was based on negative comments from some occupants regarding excessive heat gain in summer and uncomfortable glare, thus it was considered inappropriate.

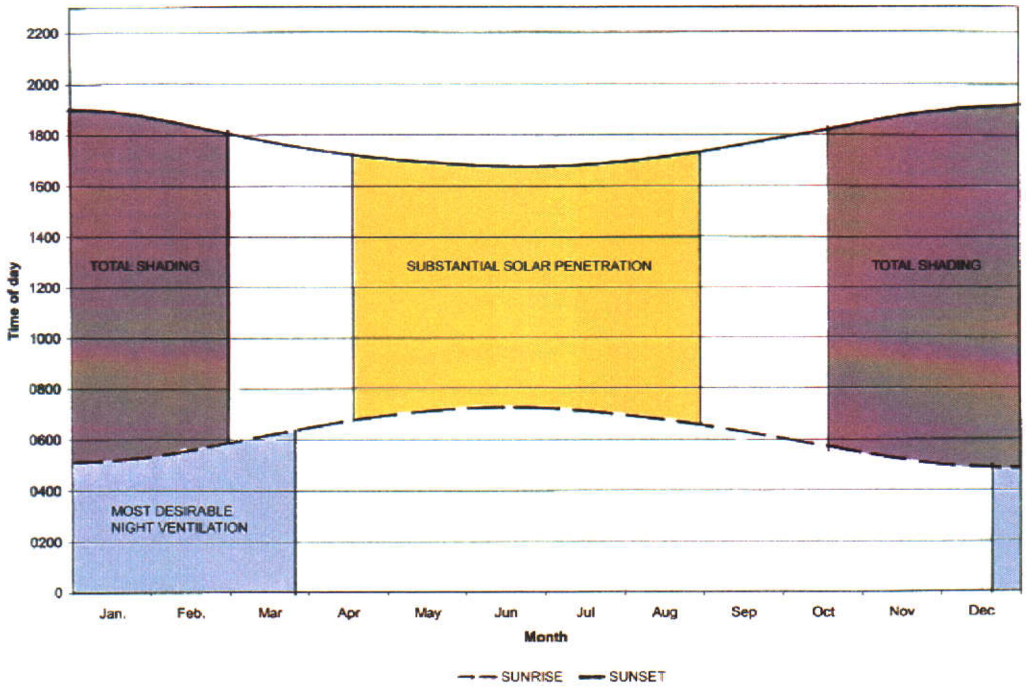

Figure 4-7 *Approach taken towards shading and ventilation in different months to assist in energy-efficient design*

Further modifications

On the basis of the simulated hourly temperatures resulting from the preliminary design modifications, other design decisions were made because of their potential thermal performance benefit.

To reduce reliance on direct solar gain for winter heating, an option for indirect solar heating was incorporated. The construction of the north wall was changed to an un-vented Trombe-Michel wall. An un-vented Trombe-Michel wall is particularly suitable for small, medium density housing for the aged as it is:

- suitable for heating buildings of small floor area;
- not dependant on occupant behaviour such as the opening and closing of curtains at appropriate times;
- not effected by the type of curtains installed by tenants;
- free of issues related to privacy of the occupants;
- not the cause of uncomfortable glare; and
- not the cause of deterioration of furnishings as a result of ultraviolet radiation.

In considering the possible area available for a Trombe-Michel wall, typical one and two-bedroom dwellings with their long axis running north-south, and thus a limited available area for indirect solar gain, were examined. In these 'worst cases', approximately 13% of the floor area could be made available for the construction of a Trombe-Michel wall if the area of glazing remained similar to the typical area of glazing provided. All other glazing was located on the opposite side (southerly side) of the dwelling, utilising the same pattern of glazing as in the majority of typical designs.

A further series of design decisions were tested, revolving around:

- insulation of the walls of the building envelope;

- volume of thermal mass of brick walls in the living area;
- the type of glazing used; and
- mechanical night cooling.

Two conditions of wall insulation were considered - cavity brick walls without insulation and with R1.0 insulation added to all external cavity brick walls (excluding the Trombe-Michel wall on the north side). The first condition represents the common wall construction used in Perth, whilst the second adopts the benchmark level[1] of wall insulation.

Two conditions of indoor thermal mass were considered – the area of internal masonry walls as designed in a typical dwelling and the addition of thermal mass by increasing the thickness of internal masonry walls <u>within</u> the living zone to 220 millimetres in the SCRATCH files in NatHERS. The increased thickness of these internal walls was considered to represent a viable possibility in adjusting the volume of thermal mass in brick walls in small, medium density dwellings and is compatible with the notion discussed in section 3.3.2.2 that only a limited thickness of thermal mass can play a role in the diurnal heat exchange between the thermal mass and the air in the room.

Two conditions of glazing were considered – single glazing and double-glazing. Single glazing represents the common window construction in Perth while double-glazing was included to address summer overheating.

Mechanical night cooling in summer, providing approximately 30 air changes per hour[2] when the temperature inside was higher than outside temperature, was also considered.

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[1] The benchmark level of total wall insulation for Perth is R1.5 (section 3.2.4). The R value of typical cavity brick wall construction is stated as 0.67 in the Building Code of Australia (ABCB 1996), thus R1.0 insulation is added to bring the total insulation level to approximately R1.5.

[2] 30 air changes per hour was based on the benchmark level of night cooling proposed by Baverstock and Paolino (1986).

By using this process of adding modifications to improve thermal conditions, the most influential combination of building modifications on thermal performance could be established in summer and winter. Key ratios such as north glazing area to floor area, total glazing area to floor area, Trombe-Michel wall area to floor area and volume of thermal mass in brick walls could then be calculated.

4.4.2.2 Affordability of modifications

It is recognized that the proposed modifications to typical small, medium density housing for the aged would add to the construction costs of these dwellings. The savings in the cost of heating and cooling equipment and savings in energy costs over the effective life of the dwelling may offset the additional costs.

The approach taken to determining the length of time taken to recoup additional costs through savings is the Net Present Value (NPV) method of discounted cash flow analysis. This methodology is used in preference to the Internal Rate of Return, Payback Period or Annual Return methods as the NPV method is consistent with the current practice in the construction industry (DoFA 1991). The specific advantages of the NPV method include that it is a consistent and rational method of dealing with the future, it is readily calculated and it creates the fewest opportunities for error.

The NPV method enables capital expenditure to be compared with savings that will arise at future time periods. The value of the savings can be compared with the costs in present dollar values. In order to use the Net Present Value (NPV) method of discounted cash flow, a discount rate must be established to convert future expenditure into present values. In the current study, a discount rate of 6% is adopted, based on recommended figures from the Department of Housing and Works (McFarlane 2002) and supported by Project Evaluation Guidelines from the WA Treasury Department (2001). Net present dollar values can then be calculated by determining the NPV factor using the formula

NPV factor = $1/(1 + i)^n$ where 'i' is the discount rate and 'n' is the time period in years.

Using this method, no account is taken of the potential improvements in the well-being of public housing tenants as a result of warmer indoor conditions in winter and cooler indoor conditions in summer. Nor is account taken of the contribution that energy-efficient design makes to Australia's initiatives on energy matters as agreed by the Coalition of Australian Governments in 2001.

Costs of building modifications for energy efficiency

Having established the design features required to optimise thermal conditions in a typical dwelling, unit rates of the building modifications were determined in conjunction with the Department of Housing & Works. The building modifications included a Trombe-Michel wall, a louvred pergola extending along the north side of the dwelling, additional wall insulation, additional thermal mass, double glazing and an exhaust fan for night cooling. Using the unit rates, the capital costs of the modifications to a typical two-bedroom dwelling were established.

Operational energy consumption

One of the desired results of energy-efficient design in housing for the aged is to reduce energy consumption for space heating and cooling and thus reduce domestic running costs for the building occupant whilst retaining appropriate indoor thermal conditions. When NatHERS is used in energy rating mode, the theoretical thermal loads[1] for space heating and cooling, when acceptable temperatures are maintained, can be determined for a typical dwelling as existing and as modified to be energy efficient.

These thermal loads will be converted to energy consumption using an efficiency factor of 0.7 for gas and 2.4 for air-conditioning (Fay & Treloar 1999). In this way, the cost of energy consumption for space heating and cooling can be determined.

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[1] The theoretical thermal loads are located in the Natrep.dt2 file where heating load, sensible cooling load and latent cooling load are listed in MJ.

Energy consumption compared to capital cost

Having determined the capital cost of proposed building modifications and the potential savings in energy consumption for heating and cooling, the capital costs can be compared with theoretical operational energy savings in consumption and savings in heating and cooling equipment over a period of time.

The domestic supply tariffs charged by Western Power and Alinta Gas, the supply authorities in Perth, are 12.75 cents per kWh for electricity and 5.88 cents per kWh for gas[1]. In carrying out the financial assessment in the current study it is assumed that the cost of energy in Western Australia will remain the same as it is today, as advice provided by Mr. F. Harman from the Murdoch University Energy Research Institute in July 2002 indicated that it is not possible to predict with any certainty how real costs of power generation and power supply may change in the future. However, it is assumed that the cost of heating and cooling equipment will rise in accordance with the Consumer Price Index (CPI). In the current study, a CPI increase of 3% per annum is assumed as this is close to the average CPI in Australia over the last decade (ABS 2001b).

4.4.2.3 Applicability of energy efficient design criteria to other dwellings

After determining the design criteria required to achieve acceptable temperatures in a typical dwelling and establishing whether the design elements are affordable, three other typical dwellings were modified in accordance with influential and affordable design features and key ratios. These three dwellings were simulated using NatHERS. Through this verification process it was intended that some appropriate design criteria could be established for energy efficiency in small, medium density housing for the aged.

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[1] These rates were current in September 2000.

4.5 Progression

Through the methods described in this chapter, the intention is to collect a set of data that describes the thermal conditions in typical, small, medium density housing. In the analysis of this data there will be a search for a strategy that can lead to affordable, energy efficient, small medium density housing for the aged, so that compared to current conditions, indoor temperature fluctuations are reduced and dwellings become cooler in summer and warmer in winter, whilst minimising requirements for mechanical heating and cooling.

The results obtained from the collection and analyses of these data are presented in the following two chapters. Chapter 5 presents results and analyses pertaining to the performance of existing dwellings including the thermal conditions, behaviour of occupants, features of the buildings and energy consumption. Chapter 6 presents results and analyses pertaining to the potential for appropriateness in energy efficient design in typical, small, medium density housing for the aged.

5. Current Conditions

5.1 Preamble

Sixty dwellings in seven public housing developments for the aged were examined in order to gain an understanding of their design and materials of construction, the indoor temperatures, the behaviour patterns of the occupants that affected indoor temperatures and the energy consumption. In this chapter the results of the examination are presented in the following five sections:

- an examination of the dwelling characteristics in the seven developments, considered in the light of the benchmarks for energy-efficient design for small buildings, as developed in section 3.2.4 (section 5.2);
- an analysis of the current thermal conditions in the seven developments in relation to the benchmarks for acceptable thermal conditions in Perth (section 5.3);
- an assessment of the occupants and their behaviour in the seven developments, particularly in regard to the non-quantifiable effort made to improve indoor thermal conditions (section 5.4);
- a review of energy consumption in the seven developments (section 5.5); and
- an integrated assessment of dwelling characteristics, thermal conditions, occupant behaviour and energy consumption in four dwellings (section 5.6).

5.2 Dwelling characteristics

The dwelling characteristics considered in this section relate to the building envelope in general and to the areas of glazing and volumes of thermal mass in particular.

5.2.1 Building envelope

Table 5-1 summarises the numbers of different types of dwellings[1] monitored in each development, the floor areas and the basic characteristics of the building envelopes.

Development		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**all**
Number of dwellings examined		10	15	7	8	6	8	6	60
Type of dwelling	**detached**	0	6	0	2	0	0	2	10 [17%]
	semi-detached	4	3	7	6	5	8	4	37 [62%]
	semi-detached & common floor/roof	0	6	0	0	0	0	0	6 [10%]
	terrace	6	0	0	0	1	0	0	7 [11%]
Floor area (m2)	**approx. 50**	4	6	4	4	3	3	3	27 [45%]
	approx. 65	6	9	3	4	3	5	3	33 [55%]
External wall construction	**cavity brick**	10	15	7	8	0	0	6	
	frame + cavity brick	0	0	0	0	6	0	0	
	reverse brick veneer+ cavity brick	0	0	0	0	0	8	0	
Roof cladding	**tiles**	0	15	7	8	0	0	0	
	metal deck	10	0	0	0	6	8	6	

Table 5-1 *Summary of numbers of dwellings in each development with particular characteristics*

The majority of dwellings monitored were semi-detached dwellings with each of the seven developments incorporating some semi-detached dwellings. One type of dwelling generally predominated in a particular development. Development 2 is the exception, where there are three types of dwellings (detached, semi-detached and semi-detached with common floors or roofs), all distributed in approximately equal numbers around the perimeter of a large suburban block, as shown in the site plan in Appendix 2.

The building envelopes in the various developments represent a typical variety of wall and roofing materials used in the construction of housing in Perth. In the current study, walls include uninsulated cavity brick, steel or timber framed construction

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[1] Types of dwellings are described in Chapter 4, section 4.3.2.1 in relation to the extent of walls and floors shared with adjoining dwellings.

clad with fibre cement sheets externally and plaster board sheets internally and insulated reverse brick veneer construction. Roof cladding is either clay tiles or metal deck sheeting. The materials are consistent within a particular development. For example, all dwellings in Development 4 have uninsulated cavity brick walls and clay roofing tiles, whilst all dwellings in Development 5 have a metal deck roof and walls of both uninsulated cavity brick and framed construction.

5.2.2 Solar collection and shading

As the potential for direct solar gain through northerly glazing[1] in winter and protection of glazing from direct sunlight in summer is critical in energy efficient design, an overview of these features is shown in Table 5-2 for the monitored dwellings in each of the seven developments. The table indicates the numbers of dwellings in which northerly glazing and total glazing areas are provided in accordance with areas determined in section 3.2.4 for rules-of-thumb for direct solar gain in winter. Table 5-2 also indicates whether any sunlight is permitted to enter[2] the living areas in winter and if the glazing in general is protected to minimise solar gain in summer.

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[1] North facing glazing in the current study is considered as glazing which is oriented between 30° east or 20° west of true north (Prasad & Veale 1998). Northerly glazing generally refers to glazed areas in north facing walls. In Development 6 however, those dwellings that have no external north facing walls are provided with translucent north facing roof sheeting protected by a solar pergola. This is also referred to as north facing glazing.

[2] Permitted to enter refers to solar access being available due to the design and construction of the dwelling.

Development Code	**1**	**2**	**3**	**4**	**5**	**6**	**7**	All
Glazing on northerly side and orientation of main dwelling axis within 15° of east west axis[1]	10	0	0	2	6	6	0	
Approx. Benchmark area of north facing glazing[2]	0	0	0	0	0	0	0	0
Approx. Benchmark area of total glazing[3]	0	0	0	0	5	0	0	5
Little or no winter sun in living area	10	12	7	8	2	2	8	47 [80%]
Dwellings with no sun penetration in mid-summer	10	4	1	1	0	2	0	18 [30%]
Insulated curtains to majority of glazing	0	0	2	1	0	0	1	4 [7%]

Table 5-2 *Overview of solar collection and shading in monitored dwellings in each development*

None of the monitored dwellings have sufficient northerly glazing for direct solar gain in accordance with the benchmark areas for northerly glazing computed in section 3.3.4. However in Development 5, five of the six monitored dwellings have a total glazing area that is approximately equal to the benchmark area of total glazing.

In all of the developments there is a lack of winter sun in living areas in <u>some</u> dwellings. This lack of winter sun can be attributed to a number of factors.

In some developments it is the result of shading of northerly windows with extended eaves or canopies. For example, a canopy[4] in Development 1, as shown in Figure 5-1, blocks a substantial amount of northerly winter sun as well as fully shading the glazing in summer.

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[1] The orientation requirement is an item in the guidelines for public housing for the aged (see section 4.3.1).

[2] Benchmark area of northerly glazing is 16.2 m^2 for a 65m^2 dwelling and is 15.2 m^2 for a 50m^2 dwelling (section 3.3.4).

[3] Benchmark area of total glazing is 21.3 m^2 for a 65m^2 dwelling and is 19.7 m^2 for a 50m^2 dwelling (section 3.3.4).

[4] The canopy was extended at the request of occupants who complained of overheating in summer.

Figure 5-1 *An extended canopy on all dwellings blocks both summer and winter sun from northerly windows (Development 1)*

Figure 5-2 *Extended eaves block significant winter sun from glazing (Development 2)*

Figure 5-3 *Shading of northerly windows by high boundary wall (Development 4)*

Figure 5-4 *Northerly windows always covered with blinds (Development 6)*

In other developments, for example in Development 2, the lack of winter sun into the majority of the monitored dwellings is largely a result of the orientation of glazing. Only two of the monitored dwellings in Development 2 have northerly glazing in the living areas. Some of the lack of winter sun can also be attributed to extended eaves that provide excessive shade to windows as shown in Figure 5-2.

In still other developments such as Development 4, the lack of winter sun is due to shading by other structures. In Development 4, there is shading of northerly windows in three dwellings from a high boundary wall (shown in Figure 5-3) on the north side of the dwellings. Also, there is shading of northerly windows in another three dwellings from carports that are located on the north side of the dwellings (refer to site plan in Appendix 2).

In some developments there is a lack of winter sun in living areas because the north facing windows are shaded by the action of occupants, rather than by building structures. During the interviews, some occupants in Developments 5 and 6 talked about a perceived invasion of visual privacy from the northerly windows, so these occupants chose to have those windows permanently covered with blinds or curtains, thus ignoring the possibility of direct solar gain. This situation can be seen in Figure 5-4 where there is a public pedestrian thoroughfare close to living room windows.

In regard to shading of glazing from summer sun, it is evident from Table 5-2 that, except in Development 1, some glazing areas in dwellings in each development are inadequately shaded. The design of external summer sun control to glazing in most developments is not related to the orientation of the glazing but rather to the requirement to design a standard floor plan. Consequently, the total exclusion of summer sun depends on the dwelling occupants either installing additional shading devices such as pergolas or shutters, or planting shrubs to provide shade. The shading to the roof glazing in Development 6 is a notable exception. In this case, the shading device has been designed to exclude summer sun but allow the entry of winter sun.

To further explore the consideration given to solar collection in the design of the developments, two typical dwellings are considered from each development. The chosen dwellings represent a common design within the particular development and also represent both one and two bedroom dwellings. Table 5-3 provides an indication of the total areas of glazing, areas of northerly glazing, the ratios between area of glazing and floor area and the benchmark areas of northerly glazing and total glazing.

Although Developments 1, 5 and 6 are designed with all dwellings having living room glazing oriented between N30°E and N20°W, acknowledging a fundamental energy-efficient design principle for solar gain, the areas of glazing in these developments vary widely. It is evident in Table 5-3 that dwellings in Development 5 have considerably more glazing area than any of the other dwellings. Consequently, the ratios of glazing to floor area are significantly higher in Development 5 than in any other development. This large glazing area reflects the perception of appropriate energy efficient design for housing in Perth and is consistent with the award-winning status of Development 5 as a project designed to be energy efficient.

Development		1	2	3	4	5	6	7
Floor area –FA		49	49	48	47	47	48	47
		60	59	63	63	63	63	63
Total glass area (including roof glazing) – TG	**1 BR**	7.8	10.0	10.4	10.2	19.7	12.9	12.8
	2 BR	9.2	14.8	11.6	11.8	25.1	17.0	13.4
Area of northerly glazing – NG	**1 BR**	5.2	0	0	5.0	12.6	6.0	0
	2 BR	6.6	0.7	5.4	0.2	13.7	8.8	5.2
TG/FA	**1 BR**	0.16	0.20	0.22	0.22	0.42	0.27	0.27
	2 BR	0.15	0.25	0.18	0.19	0.40	0.27	0.21
NG/FA	**1 BR**	0.11	-	-	0.11	0.27	0.13	-
	2 BR	0.11	0.01	0.09	-	0.22	0.14	0.08
Benchmark area of northerly glazing	**1 BR**	15.2	15.2	15.2	15.2	15.2	15.2	15.2
	2 BR	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Benchmark area of total glazing	**1 BR**	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	2 BR	21.3	21.3	21.3	21.3	21.3	21.3	21.3

Table 5-3 *Areas of glazing for solar collection in typical one & two-bedroom dwellings in sseven developments (all areas in square metres)*

To compare the total areas of glazing and areas of northerly glazing (in those dwellings where northerly glazing is provided), Figure 5-5 provides a graphic summary of the areas of glazing for one-bedroom dwellings from Developments 1,4 and 5 and two-bedroom dwellings from Developments 2, 3, 6 and 7. The areas of glazing are compared with the benchmark values for areas of glazing for energy-efficient design (see section 3.3.4). Only Dwelling 5D has total glazing areas similar to the benchmark values. Northerly glazing areas vary from 4% of the benchmark area to 83% of the benchmark area.

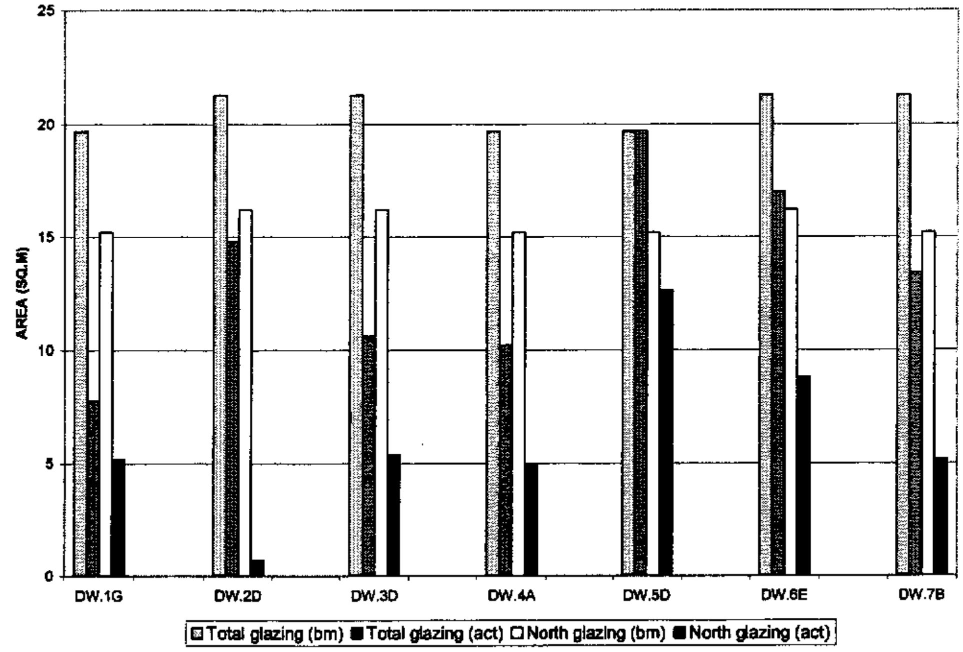

Figure 5-5 *Areas of glazing compared to benchmark areas of glazing for energy-efficient design*

5.2.3 Thermal mass

In all the developments considered in the current study, concrete floor slabs and masonry walls have the potential to provide thermal mass for heat storage. To explore the potential for heat storage in the thermal mass, the same typical dwelling from each development that was considered for solar collection (see section 5.2.2) was considered in relation to thermal mass.

Table 5-4 is a summary of volumes of thermal mass that are provided in the building structure. Only the volume of the internal leaf of a cavity brick wall has been included in the volume of brickwork. This conforms with the benchmark levels of thermal mass referred to by Baverstock and Paolino (1986). Where a solid wall rather than a cavity wall separates adjoining dwellings, the additional thickness is included in the volume of masonry. This is the case in only one development (Development 6) as, for acoustic reasons, the general policy of the public housing authority in Perth is to provide a cavity wall between adjoining dwellings (Thorogood 2000). Table 5-4 also includes the length of common wall between adjoining dwellings. This length may influence indoor temperatures, as the heat transfer through the common walls is less than the heat transfer through external walls.

Development		1	2	3	4	5	6	7
Floor area –FA	**1 BR**	49	49	48	47	47	48	47
	2 BR	60	59	63	63	63	63	63
Concrete (volume)	**1 BR**	4.9	4.9	4.8	4.7	4.7	4.8	4.7
	2 BR	6.0	5.9	6.3	6.3	6.3	6.3	6.3
Brick (volume)	**1 BR**	7.4	7.7	7.0	7.0	5.8	7.7	6.9
	2 BR	8.7	9.6	8.7	8.8	7.6	10.0	8.7
Benchmark concrete (vol)	**1 BR**	3	3	3	3	3	3	3
	2 BR	5	5	5	5	5	5	5
Benchmark brick (vol)	**1 BR**	13	13	13	13	13	13	13
	2 BR	15	15	15	15	15	15	15
Length of common wall (m)	**1 BR**	7.0	12.6	6.2	7.5	5.5	5.8	8.0
	2 BR	6.0	0	10.3	10.1	3.0	10.5	6.0

Table 5-4 *Floor area (m^2) and volume (m^3) of thermal mass in a typical dwelling in each development*

In small dwellings the average volume of brick is well below the benchmark volume of brick. If the volume of masonry walls were to be increased, the gross floor area of each dwelling would need to be increased, as indicated in Table 5-5.

	One-bedroom	**Two-bedroom**
Average vol. brick (m^3)	7.1	8.9
Additional length of 100mm thick masonry to achieve benchmark vol. (m)	25	37
Increase in gross floor area (m^2)	5%	6%

Table 5-5 *Implications of increasing volume of brick to benchmark levels*

A comparison of the volumes of thermal mass provided in a typical dwelling in each development and the benchmark volumes of thermal mass, developed in section 3.2.4, is shown in Figure 5-6.

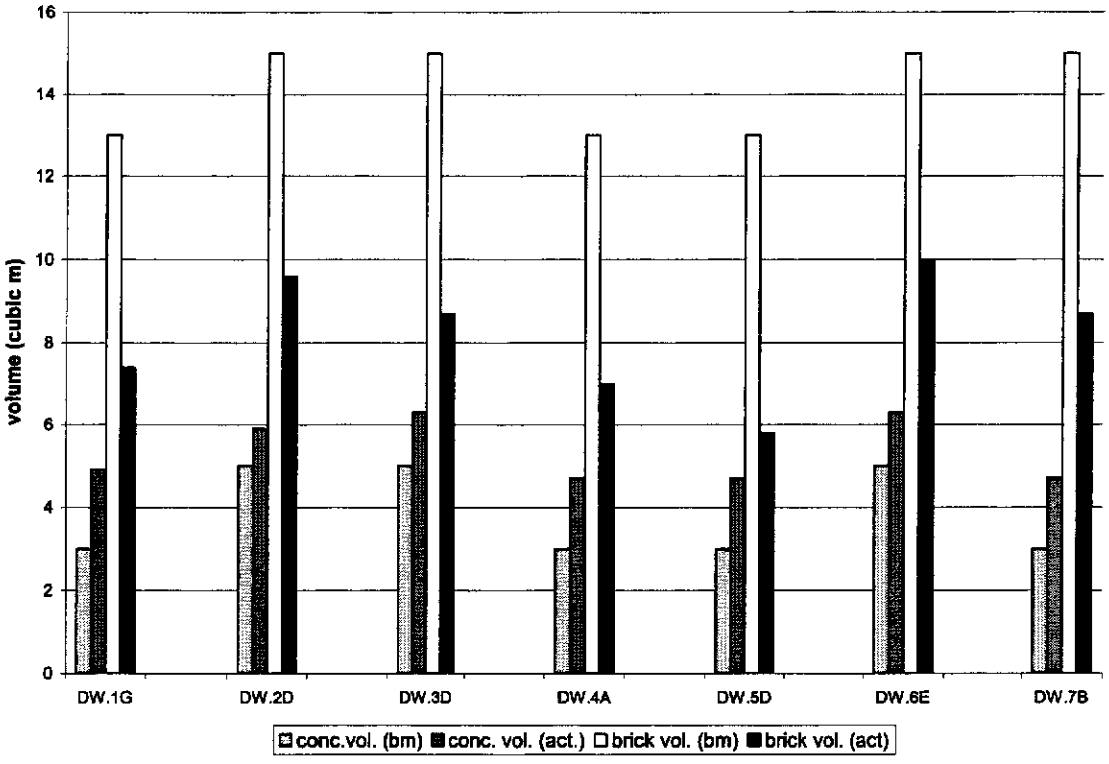

Figure 5-6 *Actual volumes of thermal mass compared to benchmark volumes for thermal mass*

As indicated in Table 5-4, the volume of thermal mass in the concrete floor slab is directly proportional to the floor area of the dwelling and exceeds the benchmark volumes of concrete. In spite of the actual volumes of concrete in each development being higher than the benchmark volumes of concrete, the effectiveness of the diurnal heat transfer process to and from the concrete floor slab depends on the accessibility of the concrete floor slab to the indoor volume of air. This accessibility may be compromised depending on the floor finish.

The standard floor finish in the dwellings provided by the public housing authority is vinyl tiles. However, 27% of dwellings in the current study have wall-to-wall carpet in the living area and the bedrooms. This does appear to have an effect on indoor temperatures. Using computer simulations[1], temperatures in a carpeted dwelling were compared to temperatures in a dwelling with a vinyl floor finish. The hourly temperatures on the design days show that summer indoor temperatures rise and winter indoor temperatures fall when the floor is carpeted. These computer simulations are discussed in detail in section 6.4.4. Other furnishings such as loose floor rugs and furniture could also reduce the effectiveness of the concrete floor slab in the diurnal heat transfer process. Thirteen percent of dwellings were assessed as having a substantial area of concrete floor slab insulated from the indoor space due to the quantity of furniture and rugs.

The accessibility of indoor masonry walls to the indoor volume of air is more consistent than the accessibility of thermal mass in the floors. However, as shown in Figure 5-6, the actual volumes of brickwork are below the benchmark volumes of brickwork in all seven developments. The volumes of brickwork vary from 45% (Development 5) to 67% (Development 6) of the benchmark volumes of brickwork, depending on the construction materials of the building envelope, the length of external walls, the thickness of common walls and the area of windows. As the specification for these dwellings requires that internal walls be of either clay or concrete blocks, the internal walls should be able to participate in the diurnal heat storage cycle. A limitation to this would occur if the internal walls were finished with plasterboard sheets which were not fully adhered to the masonry wall. This would create an insulating air gap between the thermal mass and the indoor volume or air. This occurrence was not able to be checked in the current study.

To summarise, in regard to building characteristics related to solar collection and thermal mass, none of the dwellings comply with all the benchmark proposals for northerly glazing, total glazing and thermal mass. Only dwellings in Development 5 having total glazing areas and northerly glazing areas approaching the benchmark

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[1] NatHERS was used to carry out computer simulations in the current study (see Appendix 7)

areas, whilst in the other developments, total glazing and northerly glazing areas vary widely from the benchmark areas. All dwellings have a greater volume of thermal mass in the concrete floor than established by the benchmarks, whilst the volumes of brickwork in internal walls are generally between approximately 55% and 65% of the benchmark volume of brickwork. There is no evidence that the floor area of the dwelling leads to any difference in the design of building elements, such as proportion of glazing or volume of thermal mass.

5.3 *Thermal conditions*

In this section the indoor temperatures in the seven developments are assessed and compared with the temperatures considered to be acceptable, as determined in section 3.2.6.

5.3.1 Outdoor conditions during monitoring period

Dwellings in each development were monitored for at least five days in summer and five days in winter. As the number of available data loggers was limited, different developments were monitored generally during different weeks in the summer period. In winter, as fewer dwellings were monitored, all the monitoring occurred during a single week. Details of outdoor hourly dry-bulb temperatures and relative humidity during the monitoring periods are included in Appendix 3.

Figure 5-7 summarises daily maximum, minimum and mean temperatures during the summer monitoring periods between 12th January and 17th February 1999. The day numbers on the horizontal axis relate to 1st January. Perth's typical summer climatic pattern of a number of hot days with relatively warm nights followed by a few cooler days and cool nights is clearly visible.

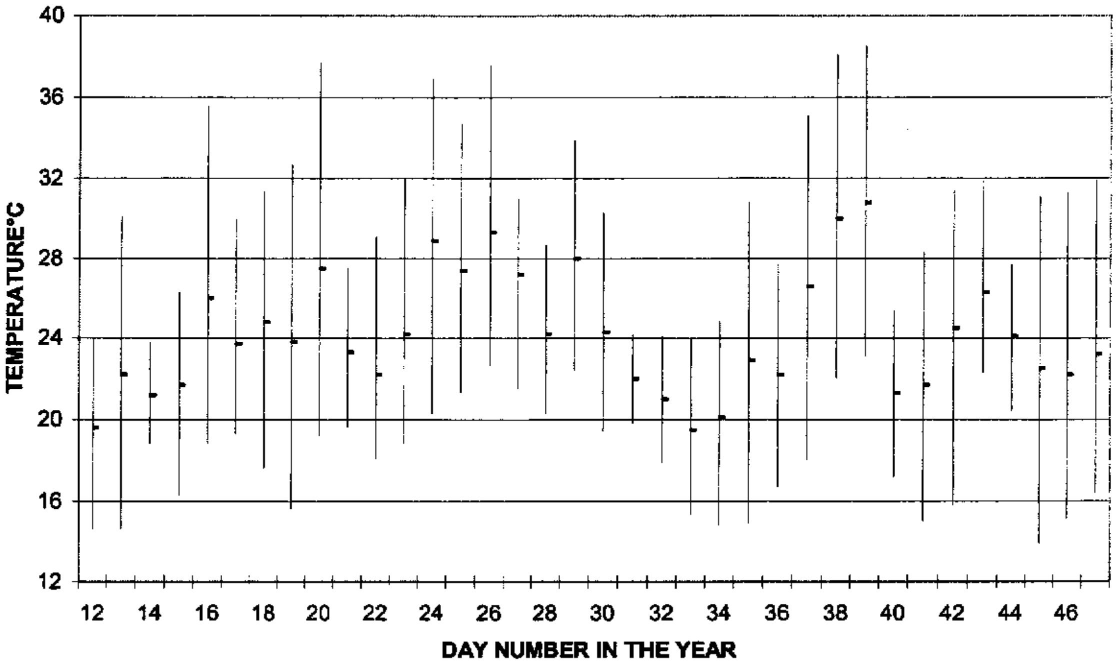

Figure 5-7 *Maximum, minimum and mean daily outdoor temperatures during summer monitoring period.*

Figure 5-8 summarises daily maximum, minimum and mean temperatures recorded during the winter monitoring period between 13th July and 21st July 1999. A comparison between Figure 5-7 and Figure 5-8 clearly shows that the outdoor diurnal temperature range in winter is far smaller than in summer.

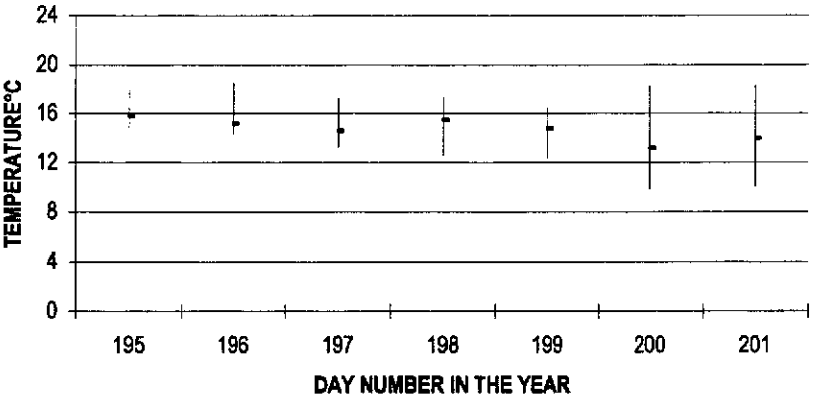

Figure 5-8 *Maximum, minimum and mean daily temperatures during winter monitoring period*

For the purpose of comparing monitored indoor temperatures between the seven developments, one day during each monitoring period was designated as the design day, a day when temperatures represented the more extreme likely temperatures rather than mean temperatures. Szokolay (1982) recommends 'design' conditions for Perth as 36°C maximum dry-bulb temperature and 24°C maximum wet-bulb temperature in summer and a minimum of 9°C dry-bulb temperature in winter.

Five days in summer (days in the year number 16, 20, 24, 29 and 43 shown in Figure 5-7) and one day in winter (day in the year number 200 from Figure 5-8) were selected as the design days in this study that were used for comparison of temperatures in the different developments. Hourly dry-bulb temperatures on these design days are shown in Figure 5-9.

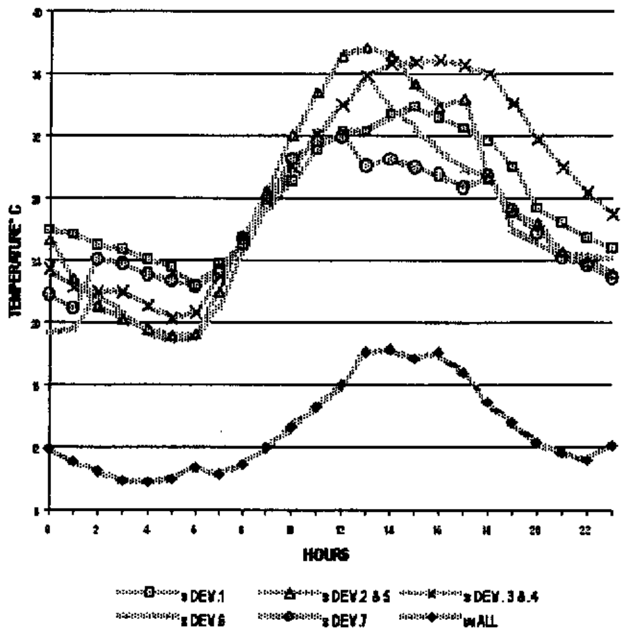

Figure 5-9 *Outdoor dry-bulb temperatures on designated design days in summer and winter used for comparison of temperatures in developments*

As indicated in Table 5-6, the summer design days when Developments 2, 3, 4, 5 and 6 were monitored had maximum dry-bulb temperatures similar to or slightly higher than 36°C, the design day maximum temperature referred to by Szokolay (1982). Wet-bulb temperatures were in all cases lower than Szokolay's design day condition of 24°C. On the summer design days when Developments 1 and 7 were monitored, maximum dry-bulb temperatures were between 2 K and 4 K lower and wet-bulb temperatures were again lower than Szokolay's design day condition. However, a relatively small diurnal temperature range on these two design days somewhat neutralised the effects of the lower maximum outdoor dry-bulb temperature.

Dev.	**Dry-bulb temperature °C**				**Relative humidity**		**Wet-bulb temperature °C**	
	Max.	**9am**	**3pm**	**Mean**	**9am**	**3pm**	**9am**	**3pm**
1	33.9	27.9	33.9	28.0	38	28.2	18.04	20.25
2 & 5	37.3	28.5	35.4	27.5	36.3	26.6	18.15	20.87
3 & 4	36.9	27.9	36.8	28.9	50.2	25.6	20.29	21.56
6	35.6	27.3	32.5	26.0	27.6	34.5	15.56	20.75
7	31.9	28.0	30.0	26.3	41.2	41.3	18.73	20.30

Table 5-6 *Outdoor thermal conditions on summer design days*

To determine if a significant difference could be identified between the five summer design days, an analysis of variance (ANOVA)[1] with multiple comparisons was carried out. No significant differences in temperatures were identified, $F(4,115) = 1.335$, $p>.05$.

5.3.2 Indoor monitoring

As mentioned previously (section 4.3.3.1), the temperatures in sixty dwellings were monitored in summer and in twenty-two dwellings in winter. The monitored temperatures are included in Appendix 3. What was of particular interest in the current study was how the dwellings performed on a design day. The thermal performance of the dwellings on identified design days was assessed, in comparison to the maximum acceptable temperature of 27.4°C in still air in summer and minimum acceptable temperature of 19.8°C in winter[2]. These monitored hourly indoor dry bulb temperatures on the design days in the seven developments are included in the data set in Appendix 5. It is evident that the logged temperatures varied widely between dwellings in a particular development, as well as between dwellings in different developments. To determine if there was any significant difference between the temperatures in one bedroom and two bedroom dwellings in summer or winter, independent sample t-tests were conducted. No significant differences in mean temperatures between one bedroom and two bedroom dwellings were identified in summer, $t(58)=-0.389$, $p>0.05$ nor in winter, $t(20)=-0.169$, $p>0.05$.

5.3.2.1 Summer

To assess if the indoor temperatures of dwellings monitored in summer displayed a normal distribution, a test of normality was undertaken through the EXPLORE pro

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[1] This analysis is shown in Appendix 5. All other statistical tests carried out are listed in Appendix 5 and are included in the CD accompanying this thesis.

[2] Computations for the acceptable temperatures are discussed in section 3.2.5.

cedure in SPSS. A summary of the results is shown in Table 5-7. A normal distribution is indicated with the Shapiro-Wilks Statistic W = .980 (60), p>0.05.

Mean temperature °C	27.930
95% lower bound confidence interval for mean °C	27.678
95% upper bound confidence interval for mean °C	28.182
Minimum temperature °C	25.4
Maximum temperature °C	29.9
Std. deviation	.9744

Table 5-7 *Test of normality for mean summer monitored temperatures*

To determine if there is a significant difference in temperature on the summer design day between dwellings within each development, an ANOVA with post hoc tests and multiple comparisons was undertaken. The hourly indoor temperatures were used as the dependant variable in the analysis. The results are shown in Table 5-8.

Develop.	**F**	**DF**	**p**	**Dwellings showing significant difference in multiple comparisons**
1	1.763	9,230	>.05	N.A.
2	4.176	14,345	<.05	None
3	4.507	6,161	<.05	3F (air conditioned) compared with 3C & 3D
4	11.201	7,184	<.05	4H (air conditioned) compared with 4D, 4F & 4G 4D (no night ventilation) compared with 4A, 4B, 4C, 4E & 4H
5	2.852	5,138	<.05	None
6	2.282	7,184	<.05	None
7	1.638	5,138	>.05	N.A.

Table 5-8 *Summary of significant differences in summer temperatures between dwellings within the developments*

Significant differences were indicated in Developments 2, 3, 4, 5 and 6 although the Scheffe test of multiple comparisons did not confirm this difference in Developments 2, 5 and 6. In Development 3 the difference was confirmed between the air-conditioned dwelling (Dwelling 3F) and Dwellings 3C and 3D, and in Development 4 between an air-conditioned dwelling (Dwelling 4H) and Dwellings 4D, 4F and 4G and between a dwelling where windows and doors were closed at sunset (Dwelling 4D) and Dwellings 4A, 4B, 4C, 4E and 4H.

As discussed in section 4.5.3, to facilitate the analysis of temperatures between dwellings in different developments, a Principal Component Analysis of the hourly data was first performed. This enabled four representative factors of the 24 hour temperature data to be extracted. These four factors were interpreted to relate to four common time bands - midnight to 8am, 9am to noon, 1pm to 7pm and 8pm to 11pm.

To determine if there is any significant difference in summer indoor temperatures on the design days between the seven developments, an ANOVA with post hoc analysis was undertaken. A significant temperature difference was identified between the developments in two of the four time bands: midnight to 8am, $\underline{F}(6,53)=5.341$, $\underline{p}<.05$ and 1pm to 7pm $\underline{F}(6,53)=2.479$, $\underline{p}<.05$. In carrying out the post hoc analysis within the time bands, to determine where the significant temperature differences lay between the developments, the Scheffe test showed that the only significant difference ($\underline{p}<.05$) was in the time band of midnight to 8am, between Development 6 and Development 3.

Table 5-9 provides a statistical summary of the average thermal conditions in each development on the monitored design days in summer. Maximum indoor temperatures in all dwellings except one[1] exceeded the acceptable maximum temperature.

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[1] On the design day, the only dwelling where the indoor temperature did not exceed 27.4°C was Dwelling 4H. An air-conditioner was regularly used in this dwelling.

	Dev. 1	Dev. 2	Dev. 3	Dev. 4	Dev. 5	Dev. 6	Dev. 7
Indoor mean	28.2	28.2	28.9	27.4	27.5	27.1	28.0
Indoor mean night[1]	26.7	26.7	27.1	25.9	25.5	25.2	26.5
Indoor mean day[2]	26.2	26.3	26.5	25.5	25.0	24.7	26.1
Mean diurnal range	6.0	6.2	7.6	5.6	8.1	6.5	5.5
Range of maximum	29.2-33.3	28.3-34.5	32.3-34.0	27.0-33.0	29.6-34.2	29.0-32.3	29.2-31.9
Range of minimum	24.3-26.8	22.7-26.8	24.3-27.4	23.3-26.8	22.7-24.3	22.7-25.3	24.9-25.5
Outdoor minimum	22.4	19.2	20.3	20.3	20.3	18.8	20.3
Acceptable maximum	27.4	27.4	27.4	27.4	27.4	27.4	27.4

Table 5-9 *Statistical summary of monitored dry-bulb temperatures (°C) in the seven developments on the five design days in summer*

As indicated in Table 5-9, the indoor mean temperatures at night[3] in Developments 1, 2 and 3 are at least 1.5 K higher than the mean indoor night temperature in Development 6, the development with the lowest mean indoor temperature both over the 24 hour period and at night. The low minimum night-time temperatures in Development 6 appear to be influenced by the translucent roof sheeting in a number of the dwellings. In these dwellings (Dwellings 6D, 6E and 6H), mean summer minimum temperatures were consistently at least 1 K lower than in the other dwellings in Development 6 (see DATA FILE in Appendix 5).

Two interviewees commented specifically about this translucent roof sheeting. The occupant of Dwelling 6H claimed there was excessive heat gain from the translucent sheeting in summer in spite of the solar shading device (see Figure 5-10) and was, at the time of monitoring, negotiating with the public housing authority to improve the situation. There is some indication from the monitored results shown in Appendix 5,

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[1] Night-time in this instance refers to 2300 to 0600 hours.

[2] Night-time in this instance refers to 0000 to 0800 hours.

[3] Two sets of night-time mean temperatures are included. One is from 0000 to 0800 as determined by the PCA performed to facilitate hourly analysis and the other is between 2200 and 0700 to relate to Ballinger's (1993a) reference to night-time temperatures (this was interpreted as including the temperatures from 2300 to 0600 which are more closely related to likely time in bed).

that between noon and 5pm the temperature rises more rapidly in Dwelling 6H than in other dwellings in this development, but the cause of the temperature rise is unclear. The occupant of Dwelling 6E, being conscious of heat gain through the translucent sheeting in summer, had partly blocked the translucent sheeting area as can be seen in Figure 5-11. This may explain in part why summer monitored temperatures in Dwelling 6E were lower than in Dwelling 6H.

Development 3 recorded the highest summer mean indoor temperatures. In Perth, proximity to the coast has some affect on the local outdoor temperature (Bureau of Meteorology, 1995). It is possible that Development 3, the development furthest from the coast (see section 4.5.1), was least influenced by the tempering effect of a cooling sea breeze. However, if this is a critical factor in the temperature differences between the developments, the expectation would have been that Development 1 (the development closest to the coast) would have recorded the lowest mean temperatures in summer. This is not the case.

At night-time on the summer design days, some dwellings in all developments, experienced high minimum temperatures. In many developments the highest minimum night-time temperatures were higher than the mean night-time temperature for the development (refer Table 5-9). Consequently, a number of residents, particularly in Development 3, referred to the thermal discomfort in their homes at night in summer and the difficulty in sleeping. This issue of thermal discomfort at night in summer was also raised in a study of housing conditions in Adelaide, South Australia where it was perceived that insufficient design consideration was given to protecting glazing from solar radiation in summer (Marshall, 1973).

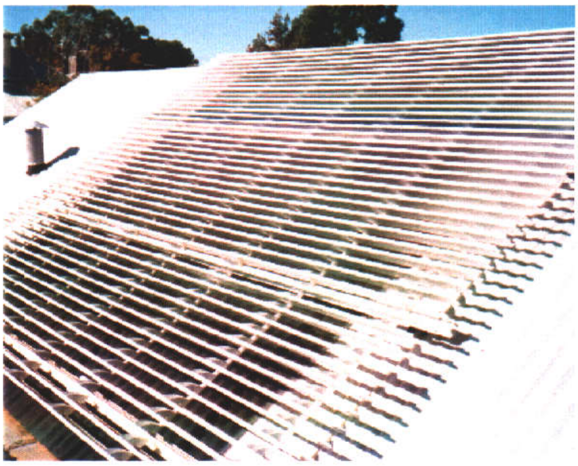

Figure 5-10 *Solar shading device (Dwelling 6E)*

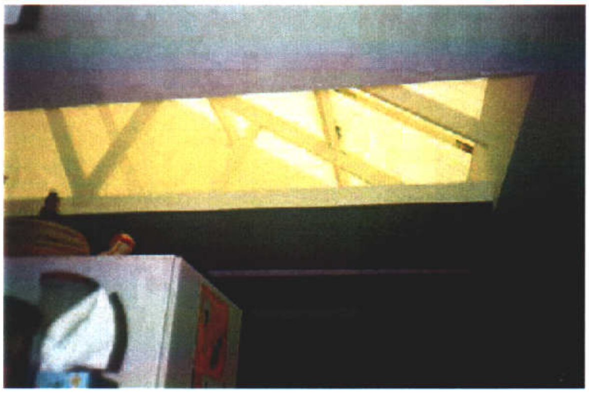

Figure 5-11 *Partly covered roof light (Dwelling 6E)*

The highest minimum temperatures varied from 24.3°C (in Development 5) to 27.4°C (in Development 3). These high minimum indoor temperatures were, in Development 3, approximately 7 K higher than minimum outdoor temperature and in Development 5, approximately 5 K higher than minimum outdoor temperature. The highest mean diurnal temperature range in summer occurred in Development 5, the development where half the dwellings were fitted with an air-conditioner (see section 5.5 for details related to numbers of air-conditioners).

Figure 5-12 shows the summer maximum monitored temperatures in the seven developments on the design days compared to the maximum acceptable January temperature in still air (27.4°C).

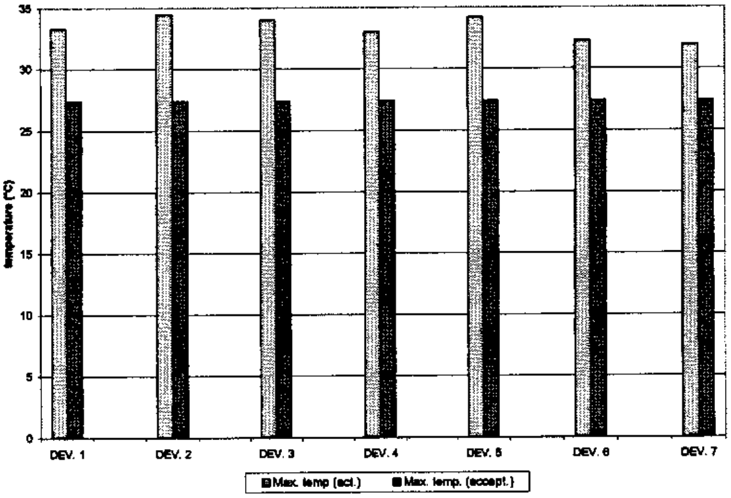

Figure 5-12 *Maximum monitored summer temperatures on design days compared to acceptable maximum temperatures on design days*

If it is assumed that fans are used when the temperature exceeds 27.4°C, a temperature 3 K higher becomes acceptable. Table 5-10 summarises the numbers and percentages of dwellings in the seven developments where the maximum temperature remained below 30.4°C on the summer design day.

Development	1	2	3	4	5	6	7	Total
Total number of dwellings below 30.4°C	2	2	0	4	2	3	2	15
Percentage of dwellings below 30.4°C	20	13	0	50	33	38	33	25
Number of non-air-conditioned dwellings below 30.4°C	2	2	0	2	0	2	2	10

Table 5-10 *Dwellings that remain below 30.4°C on summer design day*

5.3.2.2 Winter

As only two, three or four dwellings were monitored in each development in winter, a statistical analysis of the differences in temperatures between developments is not useful. However a summary of the conditions in each development as shown in Table 5-11 provides some indication of maximum, minimum and mean temperatures monitored on the design day.

	Dev. 1	Dev. 2	Dev. 3	Dev. 4	Dev. 5	Dev. 6	Dev. 7
Indoor mean	20.2	17.9	18.2	18.5	17.7	18.6	19.5
Mean day[1]	20.6	17.9	18.6	18.6	18.2	18.8	20.0
Mean night[2]	19.4	17.8	17.5	18.4	16.6	18.1	18.5
Mean diurnal range	6.9	5.0	4.4	4.7	5.2	3.7	5.7
Range of maximum	19.6-29.6	19.0-23.1	17.3-26.6	18.8-26.2	18.4-23.5	19.0-25.3	19.8-25.8
Range of minimum	16.4-19.0	16.4-17.3	14.9-17.9	16.2-17.7	14.9-16.0	16.2-18.3	16.7-17.5
Acceptable minimum	19.8	19.8	19.8	19.8	19.8	19.8	19.8

Table 5-11 *Statistical summary of monitored dry-bulb temperatures (°C) in the seven developments on the design day in winter*

On the winter design day, the mean indoor temperatures in the developments ranged from 17.7°C in Development 5 to 20.2°C in Development 1. The minimum indoor temperature of 14.9°C occurred in Developments 3 and 5. The lowest range of minimum temperatures (14.9°C to 16.0°C) and the lowest indoor mean temperature (17.7°C) in the current study were recorded in Development 5. This was despite all

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[1] Day-time refers to 0700 to 2200 hours.

[2] Night-time refers to 2300 to 0600 hours.

the dwellings being designed to receive some sunlight in winter in the living areas and the northerly glazing area being similar to the benchmark areas of northerly glazing. When the mean temperatures in all the dwellings are calculated, the mean temperature difference between thermal conditions at night and during the day is small, 0.9°C.

In individual dwellings, the indoor mean temperatures ranged from 16.8°C (Dwelling 3E) to 23.6°C (Dwelling 1E). To determine if there is a significant difference in temperature on the winter design day between all 22 dwellings, an ANOVA with post hoc tests of multiple comparisons was undertaken. Significant temperature differences are identified between the mean temperatures in the 22 dwellings, $\underline{F}$ $(21,506) = 28.395$, $\underline{p} < .05$, with no apparent relationship between the temperatures within developments. An indication of the differences is that Dwelling 1E is significantly warmer than all the other dwellings. Dwellings 3A, 4A and 7A are significantly warmer than Dwellings 3B, 3E, 5D and 6H. Dwellings 3B and 3E are significantly colder than Dwellings 1G, 1E, 3A, 3D, 4A, 6C, 6F and 7D.

As previously mentioned in regard to summer performance, the translucent roof sheeting in Development 6 also influenced the winter temperatures. The minimum temperatures are approximately 2 K lower in Dwellings 6E and 6H (the two monitored dwellings with translucent roof sheeting) than in Dwellings 6C and 6F (dwellings without translucent roof sheeting).

In all developments, the minimum temperatures were below the acceptable minimum design day temperature of 19.8°C and the maximum winter temperature in at least one dwelling in each development was also at or below the minimum acceptable temperature as shown in Figure 5-13.

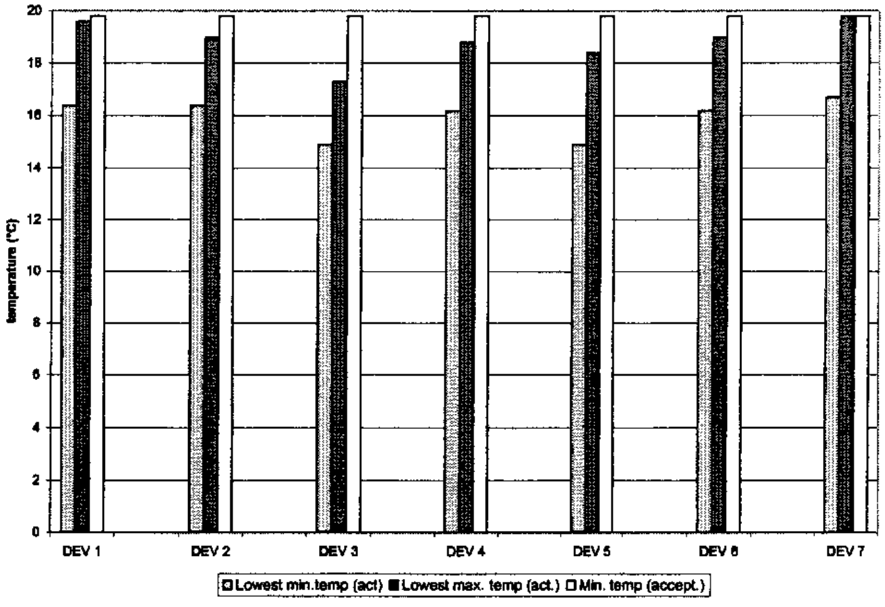

Figure 5-13 *Lowest minimum and lowest maximum monitored winter temperatures compared to acceptable minimum temperatures on the design day*

The two developments with the highest mean winter indoor temperatures, namely Developments 1 and 7, also had the highest gas consumption per square metre for space heating. The relationship between energy consumption and indoor winter temperatures is discussed in section 5.5.

5.4 Occupants and occupant behaviour

To try and identify how much effort the occupants of public housing for the aged are prepared to invest in controlling their thermal environment (in the light of the discussion regarding attitudes towards energy use in section 2.4), some of the interview questions were related to behaviour patterns.

Before elaborating on this aspect of the behaviour of the dwelling occupants, an overview of some characteristics of the occupants who participated in the current study is provided. A summary of the gender and number of occupants in a dwelling and of the age bracket of the questionnaire respondents in each development is shown in Table 5-12.

Development		1	2	3	4	5	6	7	All
Gender of respondents	male	8	6	1	1	4	4	0	24 [40%]
	female	2	9	6	7	2	4	6	36 [60%]
Number of dwelling occupants	one	4	9	5	7	3	6	6	40[67%]
	two	6	6	2	1	3	2	0	20 [33%]
Age bracket of respondent (years)	55-64	2	7	2	3	2	2	4	22 [37%]
	65-74	5	4	3	3	3	4	1	23 [38%]
	75+	3	4	2	2	1	2	1	15 [25%]

Table 5-12 *Summary of dwelling occupants in seven developments (all numbers indicate percentage of sample at particular development).*

More females than males participated in the current study, with the ratio being 60% to 40% respectively. The majority of the households (67%) have only one occupant. To determine what percentage of the single person households were female, a cross tabulation of gender of respondent and number of dwelling occupants was undertaken. The majority (75%) of single person households are female.

The majority of respondents from all seven developments were young-old (75%) and 25% were aged over 75 years. The relatively large proportion of respondents in this study who were in the 55 to 64 age bracket could be attributed to these developments being relatively new, with the newest one, Development 4, having been occupied for only approximately one year before the monitoring commenced. According to the Ministry of Housing[1], older public housing tenants who have been renting public housing over a number of years, generally choose to remain in their existing accommodation in familiar precincts rather than move into new developments, so the majority of people who move into new aged persons' accommodation are frequently those who have just retired and move into public housing for the first time.

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[1] This advice was provided by Mr.J.Thorogood, Manager Construction, Ministry of Housing at a meeting on 19th May, 2000.

There were nine questions asked of respondents in relation to their behaviour that may affect the thermal performance of their dwelling (see complete questionnaire in Appendix 5). The nine questions are listed below.

q18 Do you do anything to try and keep the house cool during the day in summer like close windows, close curtains, add external blinds?
1) a little 2) a lot 3) no

q19 Do you leave windows and doors open at night in summer if it's hot inside?
1) yes 2) no

q20 Do you feel a lack of privacy because of window placement?
1) yes 2) no

q21 Do you have difficulty in opening/closing windows?
1) yes 2) no

q23 How many hours per week on average would you use your air-conditioner in summer?
0) no a.c 1) less than 14 hrs 2)14-28 hrs 3) more than 28 hrs

q27 How sensitive would you say you are to thermal conditions?
1) very sensitive 2) sensitive 3) not so sensitive

q28 Do you do anything to try and reduce your heating needs in winter, like open curtains for sun, draft stopper at doors, heavy curtains closed at night?
1) a little 2) a lot 3) nothing

q29 If you feel cold in winter do you usually
1) turn on the heater 2) put on more clothes 3) become more active 4) other

q31 How many hours on average per week would you use your heater in winter?
1) less than 14 hrs 2)14-28 hrs 3) more than 28 hrs

The responses to the questions were based on the respondents' personal perception, although during the interviews some examples of possible actions relating to keeping the house cool in summer or warm in winter were discussed. It was recognized during the interviews that the questions were unnecessarily restrictive, so issues raised by the respondents regarding the thermal performance of their dwellings were collected as notes.

For example, one occupant considered she did a lot to try and keep her dwelling cool in summer. She had installed an external roller shutter in front of a west-facing window to eliminate heat and glare. However, because the shutter was awkward to raise and lower, it was left down for most of the summer. Consequently, natural light was reduced indoors and the possibility for night cooling ventilation was also significantly reduced. Not surprisingly indoor summer temperatures in this dwelling remained high in spite of the roller shutter, with the mean monitored temperature on the design day being 28.3°C. However this mean temperature was 0.6 K lower than the mean temperature for the development (28.9°C).

Respondents in Developments 2, 5, 6 and 7 mentioned glare from direct sunlight as being a problem for them. This supports the findings of Rubin et al. (1997), who found that some older people were highly sensitive to glare from direct sunlight. Responses from other interviewees provided some insight into whether older people actually absorb non-quantifiable transaction costs (see section 2.4.1) into controlling their indoor thermal environment rather than depending on space heating and cooling. Table 5-13 summaries the responses from the seven developments.

Development	1	2	3	4	5	6	7	All
Respondent considers they are very sensitive to thermal conditions (q27)	1	4	1	2	2	0	2	12/59 [20%]
Respondent leaves windows/doors open on summer nights (q19)	6	9	2	2	2	2	3	26/59 [44%]
Respondent does a lot to try to keep house cool during day in summer (q18)	1	4	1	0	1	2	2	11/59 [19%]
Respondent has difficulty opening or closing windows (q21)	0	2	2	4	1	0	0	9/59 [15%]
Respondent concerned with lack of privacy because of window placements (q20)	0	2	1	2	3	2	1	11/59 [19%]
Respondent has air con. And uses it more than 14 hrs per week (q23)	0	1	0	1	3	1	0	6/58 [10%]
Respondent does a lot to try to reduce need for heating in winter (q28)	0	1	0	0	0	0	0	1/56 [2%]
Respondent took action other than turning on the heater if cold in winter (q29)	2	4	2	1	3	4	2	18/52 [35%]
Respondent uses heater less than 14 hrs per week (q31)	2	5	6	2	3	4	3	25/56 [45%]

Table 5-13 *Summary of respondents' behaviour related to non-quantifiable transaction costs in each of seven developments*

From Table 5-13 it can be seen that:

- only 20% of respondents considered themselves very sensitive to thermal conditions in general; and
- in all developments, except Development 4, respondents were more conscious of doing a lot to try to keep their dwellings cool in summer (19%) than doing a lot to try and reduce the need for space heating in winter (2%). This probably reflects the ease with which occupants perceive they can heat their dwellings in winter and the perceived difficulty of summer cooling.

The data also shows that a total of 44% of occupants indicated they left windows open on summer nights, in spite of many interviewees expressing a concern for personal security at night if windows are left open. To establish if there is an association between keeping windows open on summer nights and the number of people in the household, the age of the occupant or a concern with privacy, a chi-square test of each relationship was undertaken. The results revealed that despite more two-person households (55%) than one-person households (39%) keeping the windows open on summer nights, there is no significant relationship between being a two-person household and keeping windows open on summer nights, with χ^2 (1, N =59) = 1.467, p >.05 and there is no correlation between the age of the occupant and keeping windows open on summer nights, χ^2 (2, N =59) = 0.757, p>.05. There is also no apparent significant relationship between a concern with privacy and keeping windows open, χ^2 (1, N =59) = .011, p>.05 although this result is based on unstable data due to a limited number of cases.

A chi-square test was undertaken to determine if there is a significant association between being very sensitive to thermal conditions (q27) and:

- doing a lot to try and keep the house cool in summer (q18); or
- doing a lot to try and reduce the need for heating in winter (q28).

The results indicate no significant relationship between being very sensitive to thermal conditions and doing a lot to try and keep the house either cool in summer, χ^2 (2, N =59) = 2.860, p >.05, or warm in winter, χ^2 (2, N =56) = 2.085, p >.05, although in both analyses the data is unstable due to limited numbers of cases.

In four of the developments (Developments 2, 3, 4 and 5) at least one occupant had difficulty opening or closing windows. To determine if difficulty with opening or closing windows was related to the age or gender of the occupant, chi-square tests were undertaken. The results show that difficulty with opening and closing windows is not related to the age of the occupants, χ^2 (2, N =59) = 0.287, p >.05. The majority (89%) of the occupants who had difficulty opening or closing windows were females living alone. No significant difference, (χ^2 (1, N =59) = 3.468, p >.05) between females and males in opening windows is apparent, although this could be the result of a distribution problem with the data as only one male indicated having difficulty with opening windows.

The question regarding lack of privacy referred to both visual or aural privacy. In each development, except Development 1, some occupants were concerned about their lack of privacy, due to placement of windows relative to public walkways or relative to neighbouring windows. Half the occupants in Development 5 showed concern with lack of privacy due to placement of windows close to public walkways. The consequence of this concern with lack of privacy was that curtains were kept permanently drawn across some windows or there was a reluctance to open windows for ventilation.

Although nearly half of the respondents (45%) claimed to use the heater on average for less than 14 hours per week, the majority of respondents (65%) stated they chose to turn on the heater if they were cold in winter, rather than put on extra clothes or become more active (see Table 5-13). The majority (89%) of those who indicated they did put on extra clothes or took other action to keep warm were those who lived alone. To determine if there is a significant association between the number of occupants in a household and taking an action other than turning on the heater to keep warm, a chi-square test was undertaken. The result revealed that those who lived alone were significantly more likely to keep warm by taking an action other than turning on the heater (χ^2 (1, N =52) = 5.827, p <.05).

5.5 *Operational energy consumption*

Operational energy consumption in the monitored dwellings was mainly related to the usage of hot water, space heating and lighting. All dwellings were provided with a gas space heater, a gas hot water service and electrical power.

5.5.1 Quantifying energy consumption

Table 5-14 provides a statistical summary of annual energy consumed and the mean consumption in each of the developments. The lowest mean annual gas and electricity consumption occurs in Development 6, one of the three developments with all dwellings designed with glazing oriented to the north. Development 1, another of the three developments with all dwellings designed with glazing oriented to the north, has the highest mean annual gas and electricity consumption. However in this development all the glazing is shaded, thus there is no possibility of direct solar gain.

Development		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**All**
Number of dwelling accounts		9	13	6	5	5	8	6	52
Gas & electricity	**mean**	6434	5897	5034	4845	4962	4558	5714	5472
	standard deviation	1611	1412	1864	1618	2008	1157	2366	1704
	maximum	9121	8651	7427	6962	8344	6277	8604	9121
	minimum	4252	3630	2696	2921	3512	2793	3447	2696

Table 5-14 *Statistical summary of annual gas and electricity consumption (kWh) in each development*

In Table 5-15 the energy consumption has been converted to energy consumption per square metre (kWh/m^2) as data in this form can be more accurately compared with data for individual dwellings.

Development		1	2	3	4	5	6	7	All
Gas	**mean**	69.0	75.2	65.9	65.5	64.5	51.3	75.8	67.6
	standard deviation	18.1	15.8	23.6	30.1	18.9	16.2	39.7	22.7
	maximum	101	103	99	112	97	81	135	135
	minimum	41	54	38	37	49	32	38	32
Electricity	**mean**	41.0	36.0	28.1	27.1	26.4	28.3	28.8	32.2
	standard deviation	11.0	12.3	12.0	7.8	7.0	7.2	9.6	11.1
	maximum	62	68	47	36	35	35	40	68
	minimum	28	18	14	17	19	16	17	14
Gas & electricity	**mean**	113.1	108.0	93.9	92.6	90.9	79.6	104.6	99.4
	standard deviation	20.6	20.0	34.7	35.6	23.8	15.1	47.0	28.3
	maximum	152	149	146	148	132	100	167	167
	minimum	87	74	55	60	75	59	55	55

Table 5-15 *Statistical summary of annual gas & electricity consumption in kWh/m^2 in each development*

To determine if there is a significant difference in annual energy consumption per square metre between the seven developments, an ANOVA with post hoc tests of multiple comparisons was conducted. No significant difference was identified for the total annual gas and electricity consumption per square metre, F (6,45) = 1.478, $p > .05$. There is also no significant difference identified for the total annual gas consumption per square metre for the seven developments, F (6,47) = 1.142, $p > .05$. There is an indication that there may be a significant difference for total annual electricity consumption per square metre for the seven developments, (F (6,47) = 2.312, $p < .05$), but the tests of multiple comparisons revealed no significant differences in electricity consumption per square metre.

For all developments, the mean annual gas consumption exceeded the mean annual electricity consumption by an average ratio of two to one, largely due to the installation of gas water heaters and gas space heating. Development 7 shows the greatest range in energy consumption particularly in gas consumption. The gas consumption varies from a maximum of 135kWh per square metre to a minimum of 38kWh per square metre. The very low usage (38 kWh) in one dwelling (Dwelling 7A) is due to the occupant frequently being away from her home. The mean annual combined gas and electricity consumption for all dwellings is approximately 99 kWh per square metre.

Table 5-16 provides a statistical summary of winter gas and electricity consumption per square metre in each of the developments, based on units of energy consumed in each dwelling. Table 5-16 also includes an approximation of the mean gas consumption for space heating, calculated as the difference between mean gas consumption in the six months designated as summer and the six months designated as winter.

As pointed out in Chapter 4 (section 4.3.3.3) there are different billing periods[1] for gas and electricity and the dates of billing of the two services usually do not coincide. Consequently in Table 5-16 winter consumption figures for gas consumption cover a period of six months (two billing periods that include June, July and August), whilst electricity consumption covers a period of four months, also two billing periods that include June, July and August.

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[1] The gas billing period is every three months and the electricity billing period is every two months.

Development		1	2	3	4	5	6	7	All
Gas	**mean**	46.3	44.6	40.3	41.8	40.0	31.8	49.2	42.4
	standard deviation	13.8	10.9	15.2	22.3	14.7	13.7	31.3	16.8
	maximum	69	63	56	78	65	59	99	99
	minimum	22	27	20	23	30	18	21	18
	approx. mean use for heating	23.8	14.0	14.8	18.2	15.6	12.3	22.7	17.2
Electricity	**mean**	12.8	12.6	8.2	9.8	7.6	9.6	9.2	10.6
	standard deviation	3.1	4.7	3.7	3.4	1.7	2.8	3.9	4.0
	maximum	20	22	14	13	9	14	14	22
	minimum	10	6	4	5	5	5	4	4

Table 5-16 *Statistical summary of winter gas & electricity consumption (kWh/m^2) in each development*

Using a shorter billing period for electricity than gas to determine mean winter consumption was considered acceptable on the basis that electricity consumption does not appear to fluctuate significantly during the year. Over the four month winter period, the mean electricity consumption (10.6 kWh/m^2) for all dwellings is approximately one third of the mean annual electricity consumption.

Figure 5-14 shows the relationship between mean gas consumption for heating per square metre of dwelling compared to annual gas consumption per square metre. The approximate mean gas consumption for winter space heating in the seven developments ranges from 19% of total mean gas consumption in Development 2 to 34% of total mean gas consumption in Development 1. The mean winter gas consumption for space heating in all the developments was 17.2kWh/m^2.

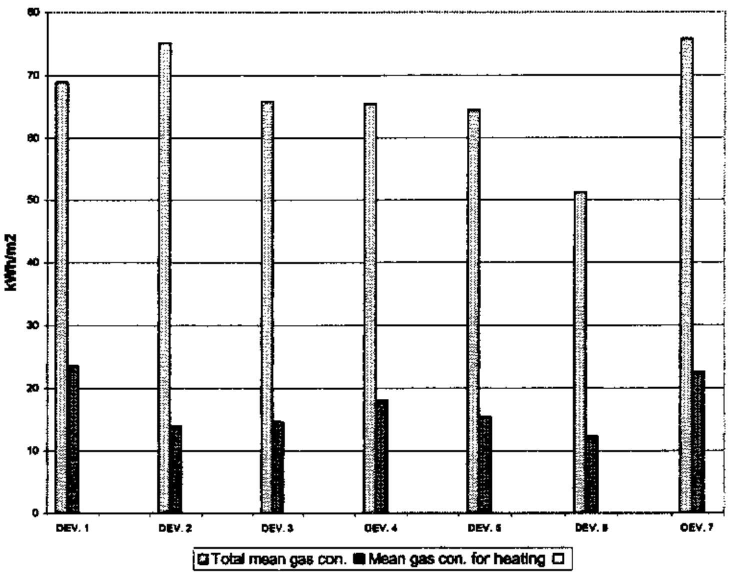

Figure 5-14 *Approximate gas consumption for space heating compared to total gas consumption (expressed in kWh/m2)*

The lowest mean winter gas consumption for space heating (12.3 kWh/m^2) and the lowest total mean gas consumption (51.3kWh/ m^2) occurs in Development 6. The low winter gas consumption may be due to all dwellings having north oriented glazing (although the glazing is shaded by occupants in two dwellings) for direct solar gain and dwellings having reasonably high levels of thermal mass. This design consideration may explain why the mean indoor winter temperature in this development (18.6°C) is very close to the average indoor winter temperature in all the developments (18.7°C), in spite of the low consumption of gas for space heating.

As in Development 6, Development 5 also provides northerly oriented glazing that allows winter sun penetration into all dwellings. This development has the third highest mean winter gas consumption for space heating (15.6 kWh/m^2) but also the lowest mean indoor winter temperature (17.7°C) of all the developments thus highlighting the apparent lack of direct correlation between northerly glazing, winter gas consumption for space heating and indoor winter temperatures. This lack of correlation is also observable in Development 1, another development with northerly oriented windows. Development 1 has the highest mean winter gas consumption for space heating (23.8 kWh/m^2), the highest mean indoor winter temperature (20.2°C) of all the developments and the highest mean winter indoor diurnal temperature range of 6.9 K (refer Table 5-11).

To determine if there is a significant difference in mean gas consumption per square metre for space heating between the seven developments, a one-way ANOVA with post hoc tests of multiple comparisons was undertaken. No significant difference was identified, F (6,47) = 0.915, p >.05.

5.5.2 Relationships between energy consumption, occupant attitudes and dwelling design

The attitude of people towards space heating and cooling in the home has an impact on energy consumption. In the course of the interviews in the current study, occupants were asked about their knowledge of how much they spent on electricity and gas (questions 25 and 26) and their use of space heating and cooling (questions 23 and 31). A summary of responses is shown in Table 5-17.

Development	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**All**
Respondent knows how much spent on last electricity bill (q25)	8	12	3	3	3	4	3	36/59 [61%]
Respondent knows how much spent on last gas bill (q26)	8	11	4	3	2	4	3	35/59 [59%1]
Respondent has air con. and used it more than 14 hrs/wk (or more than 2 hrs/day) (q23)	0	1	0	1	3	1	0	6/58 [10%]
Respondent used heater more than 28 hrs/wk (or more than 4 hrs/day) (q31)	1	2	0	1	0	0	2	6/56 [11%]

Table 5-17 *Respondents knowledge of energy bills and use of space heating and cooling*

More than half (59%) of the occupants indicated they knew how much they paid for both their last electricity and gas bills. A number of occupants (21%) advised that they considered their gas and electricity bills were high and thus were conscious of their use of space heating and cooling and wanted to minimise their expenditure on energy but found it very difficult. These people had volunteered to take part in the current study in the hope that it would assist the public housing authority to provide housing that reduced tenants expenditure on energy. Others admitted to being unconcerned about energy use. In relation to question 23, a number of occupants referred to the expense of installing air-conditioning which they considered unaffordable. As indicated in Table 5-17, only a small percentage of respondents who had an air-conditioner also used it regularly (10%).

A small percentage (11%) of occupants thought they used a substantial amount of gas heating (more than four hours per day in winter). However the approximate winter gas consumption in half of these dwellings where the occupants were concerned about their substantial use of gas heating was not in fact high, in comparison to the mean consumption of gas for space heating.

Some of the occupants who indicated they were very sensitive to thermal conditions, seemed to be more conscious of energy usage than indoor temperature. For example, the occupant of Dwelling 3B indicated she was very sensitive to the cold but frugal with the amount spent on energy. She was in the lowest quartile for total energy consumption, in the second lowest quartile for winter gas consumption per square metre, chose to wear warm clothing rather than turn on the heater and chose to live in temperatures between 15.3°C to 17.3°C on the winter design day. This occupant's dwelling had no northerly windows and little sun penetration indoors in winter but the occupant had installed lined curtains and wall-to-wall carpet to try and retain warmth in winter. In summer this dwelling was very warm reaching a maximum of 32.8°C. In contrast, the occupant of Dwelling 4A also indicated she was very sensitive to temperature and in winter the temperature in her dwelling was regularly over 25°C. She was in the second highest quartile for total energy consumption and in the second lowest quartile for winter gas consumption per square metre.

Some interviewees indicated their dislike of the cold (Dwellings 1E, 2E, 5E, 7D) and their awareness of the excessive use they made of space heating. Inevitably, when an occupant lives in a dwelling that receives little or no solar radiation through glazing and the occupant is particularly sensitive to cold (as is the case in Dwelling 7D) energy consumption will be high. The occupant of Dwelling 7D consumed 167kWh/m2 compared to the mean energy consumption for all dwellings of 99kWh/m2. The very large range in annual gas consumption in Development 7 (135kWh/m2 to 38kWh/m2) reflects the behaviour of two particular individuals. One individual was away from the dwelling for much of the time while the other liked staying home, lived in a dwelling with the main glazing oriented towards the south and disliked the cold.

To assess if there is a significant association between being very sensitive to thermal conditions and energy use, chi-square tests comparing sensitivity (q27) and the quartile of energy consumption were undertaken. The result revealed no significant relationship between being very sensitive to thermal conditions and the amount of gas and electricity used, χ^2 (3, $\underline{N}$ =51) = 0.615, $\underline{p}$>.05, the amount of gas per square metre used in winter, χ^2 (3, $\underline{N}$ =53) = 2.606, $\underline{p}$>.05 or the amount of gas per square metre in winter, χ^2 (3, $\underline{N}$ =53) = 2.714, $\underline{p}$>.05. However in all three instances there are insufficient numbers of cases of very sensitive respondents to provide a reliable indication of the association.

All occupants had portable table fans or standing fans for cooling in summer, as no ceiling fans were installed in the dwellings. As shown in Table 5-18, 19% of the sample had installed air-conditioners.

Development	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**total**
Number of dwellings with air-conditioner	0	4	2	1	3	1	0	11/59 [19%]

Table 5-18 *Summary of number of dwellings with air-conditioners*

Some of the occupants who had installed air-conditioning were conscious of the cost of operating the air-conditioner. Consequently there is 2 K mean difference between the maximum indoor temperature on the design day in summer in those dwellings making regular use of an air-conditioner and those making low use of an air-conditioner as shown in Table 5-19.

Use of air-con. in summer	Mean max. temp on design day (°C)
Regular (>14hr/wk)	29.9
Low (<14hr/wk)	31.9

Table 5-19 *Summary of frequency of use of air-conditioner and maximum temperature on the design day*

In the current study the percentage of dwellings with air conditioners was low compared with 70% of dwellings having air conditioners in retirement villages constructed by the non-government sector (Karol 1997). Because of the low numbers of dwellings with air conditioning in each development, and the energy consumption figures for some of these dwellings not being made available for use in the current thesis, it is not useful to compare the electricity consumption of dwellings with air conditioning in different developments. Instead, the electricity consumption per square metre, grouped into quartiles of consumption, was cross-tabulated with the presence or absence of an air conditioner as shown in Table 5-20.

Electricity consumption (kwh/m^2)	Quartile of energy consumption	Total no. of dwellings	Air-con.	No air-con.
Up to 24.9	1	13	1	12
25.23-31.43	2	13	2	11
31.51-35.39	3	13	2	11
35.72+	4	14	3	11

Table 5-20 *Total electricity consumption per m^2 in dwellings with & without air-conditioners, based on quartiles of consumption*

The chi-square test shows that there is no significant difference between air-conditioned and non-air-conditioned dwellings regarding electricity consumption per square metre, χ^2 (3, $\underline{N}$ =53) = 0.996, $\underline{p}$ >.05, although this result is statistically unreliable because the numbers of cases of air-conditioned dwellings are too small to draw a conclusion. It could be implied from Table 5-20 that, as three of the eight air-conditioned dwellings have electricity consumption per square metre in the highest quartile of consumption, an air-conditioner, as expected, would increase electricity consumption.

The highest percentage (50%) of dwellings with air-conditioners was in Development 5. In this development, mean electricity consumption per square metre was 33 kWh/m^2 for those dwellings with air-conditioning (in the second highest quartile for electricity consumption) and 22 kWh/m^2 for those dwellings without air conditioning (in the lowest quartile for electricity consumption).

A number of tests to determine the level of association between energy consumption and design or size of dwellings were carried out. To establish if there is a significant association between the energy consumed per square metre in terrace type dwellings and those dwellings that are free-standing, an independent samples t-test was undertaken. The result revealed no significant association, $\underline{t}$ (11) = 2.03, $\underline{p}>.05$. This lack of association may reflect the small numbers of dwellings in these two categories (six terrace dwellings and seven free-standing dwellings) as this result conflicts with modelling by the Australian Greenhouse Office, which showed that terrace type dwellings were 36% more energy efficient on a square metre basis, compared to separate dwellings (AGO 1999a).

An independent samples t-test was conducted to establish if there is a significant difference in winter gas consumption per square metre between the three developments designed for energy efficiency in regard to window orientation (Developments 1, 5 and 6) and the other developments. No significant difference was identified for the winter gas consumption per square metre, $\underline{t}$ (52) = -0.938, $\underline{p}>.05$. This lack of association confirms the results of thermal monitoring in winter previously presented (section 5.3.2.2) that showed no apparent significant difference between the mean winter temperatures in the seven developments.

However, there is a clear relationship between indoor winter temperature and mean gas consumption per square metre in winter. When average indoor temperatures over the monitored period were above 20°C, mean gas consumption during winter was 57kWh per square metre and when average indoor temperatures were less than 20°C, mean gas consumption during winter was 35 kWh per square metre. An independent samples t-test shows that this difference in the gas consumption per square metre in winter is significantly higher ($\underline{t}$ (20) =2.864, $\underline{p}$ <.05) when average indoor temperatures are above 20°C than when the average indoor temperatures are less than 20°C. There is however no correlation between the number of occupants in the dwelling and whether indoor temperatures are above 20°C or below 20°C, as shown in the results of a cross-tabulation procedure (Table 5-21).

	Average winter temperature		
	Above 20°C	**Below 20°C**	**Total monitored dwellings**
One occupant	5	10	15
Two occupants	2	5	7
Total	7	15	22

Table 5-21 *Cross tabulation of relationship between number of occupants and average indoor winter temperature*

As expected, there is a significantly higher use of gas and electricity per square metre in dwellings having two occupants than in dwellings with one occupant, as shown in an independent samples t-test ($\underline{t}$(50) = -2.149, $\underline{p}$<.05). When gas and electricity consumption per square metre is cross-tabulated with one and two occupant households, it can be clearly seen in Table 5-22 that one occupant households have significantly lower total energy consumption per square metre than two occupant households (χ^2 (3, $\underline{N}$ =52) = 9.389, $\underline{p}$ <.05).

Gas & electricity consumption (kwh/m^2)	**Quartile of energy consumption**	**Total number of dwellings**	**One occupant**	**Two occupants**
Up to 75.07	1	13	12	1
75.08-97.78	2	13	10	3
97.79-119.75	3	13	9	4
119.76+	4	13	5	8

Table 5-22 *One & two person household, gas & electricity consumption /m^2 based on quartiles of consumption*

5.6 *Detailed review of four dwellings*

Four dwellings, (Dwellings 4A, 4B, 5D and 5E), that had been monitored in both summer and winter and were typical examples of semi-detached non-air-conditioned dwellings from two developments[1] were selected for detailed examination. The construction of these dwellings was analysed and the behaviour of the occupants examined to determine the relationship between the dwelling construction, the way older people 'drive'[2] a dwelling, energy consumption and indoor temperatures. A further part of the detailed examination involved computer simulating Dwellings 4A, 4B, 5D and 5E, in order to establish theoretical hourly temperatures on the summer and winter design days and theoretical energy consumption to achieve acceptable temperatures.

5.6.1 Building features

Dwelling 4A (see Figure 5-15), a one bedroom dwelling, and Dwelling 4B (see Figure 5-16), a two bedroom dwelling, both in Development 4 are of similar design but different orientation.

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[1] Photographs of the developments appear in Appendix 2.

[2] The term 'drive' is used to capture those aspects of the behaviour of older people related to making their dwelling respond to external climatic conditions and/or to making themselves thermally comfortable.

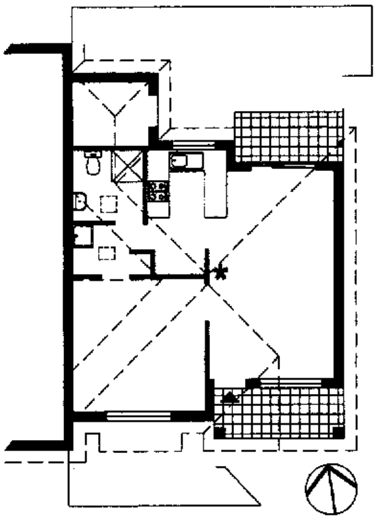

Figure 5-15 *Dwelling 4A floor plan*

Dwelling 4A is almost square in plan. All glazing is oriented approximately north or south except for one skylight that faces west. It has a north oriented glass sliding door in the living area and a north oriented kitchen window. A high fence (4 metres high) on the north boundary blocks mid-winter sun from the glazing. The roof overhang over the sliding door also reduces winter sun penetration. In summer, some sun penetrates through the kitchen window. The paved and enclosed courtyard on the north side of the dwelling is a source of radiant heat in summer, rather than in winter.

Dwelling 4B has no north-facing glazing except for one skylight as indicated in Figure 5-16. Its longer axis is oriented 5° south of east. In winter there is no sunshine indoors, due to a boundary fence to the west and a neighbouring dwelling to the east, which blocks all the morning sun (see site plan Appendix 2). In summer a little afternoon sun penetrates indoors. Dwelling 4B has the lowest temperature of the four dwellings in summer.

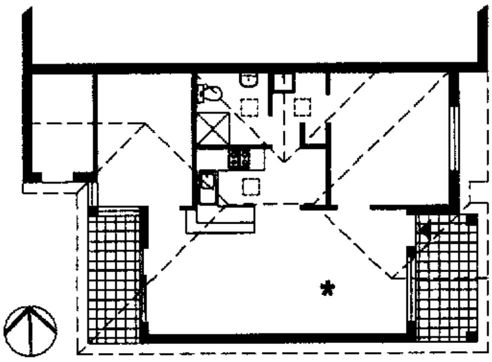

Figure 5-16 *Dwelling 4B floor plan*

Dwelling 5D (Figure 5-17) and Dwelling 5E (Figure 5-18) in Development 5 are of similar design, with the longer axis being approximately east-west. These two dwellings each have large areas of glazing, including large areas of glazing facing N20°W. The external wall construction around the living areas in these dwellings is lightweight framed construction with reflective foil insulation. In this development, common walls between dwellings are shorter than in all other developments and consequently the length of external walls is higher than in other developments.

Dwelling 5D has glazing oriented north, south and west. The glazing to the west and some of the glazing to the north (to the bedroom) is not shaded from summer sun. A pedestrian access way on the north side of the dwelling creates privacy concerns for the occupant.

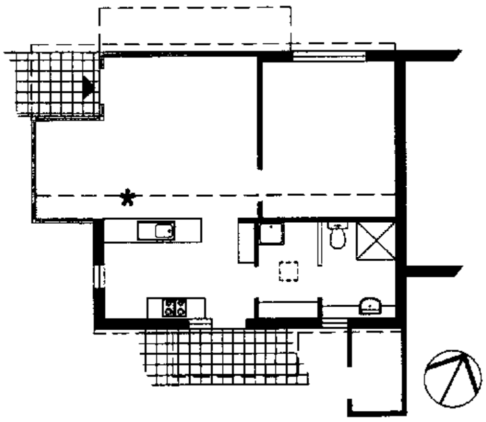

Figure 5-17 *Dwellings 5D floor plan*

Dwelling 5E has a private garden on the north side (see site plan Appendix 3). Glazing is oriented north, south and east. The northerly glazing to the bedroom is unshaded, whilst the northerly glazing to the living area is shaded in summer and exposed, to some extent to winter sun. The glazing to the east is also unshaded, thus admitting a significant amount of sun in both summer and winter. Dwelling 5E is substantially furnished with rugs covering most of the living room floor.

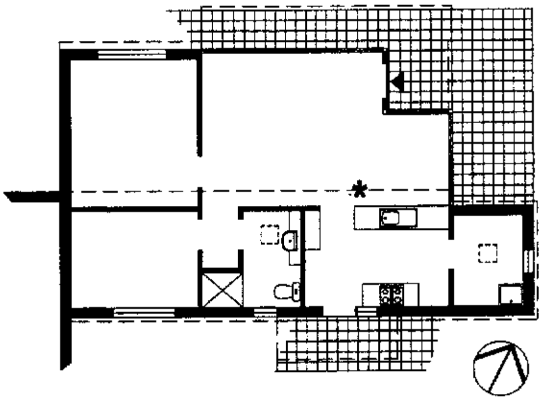

Figure 5-18 *Dwelling 5E floor plan*

As already established in Chapter 3, the area of glass and volume of thermal mass have a major influence on thermal performance. Glazing areas and thermal mass volumes in these four dwellings are compared with the benchmark levels of glazing areas and volumes of thermal mass in Table 5-23.

	benchmark		Dwelling 4A	Dwelling 4B	Dwelling 5D	Dwelling 5E
Floor area - FA	50	65	47	63	47	63
Total glazing area – TG	19.7	21.3	10.2	11.8	19.7	25.1
East & west glazing area -EWG	1.3	1.5	0.2	10.3	4.1	6.1
North glazing area - NG	15.2	16.2	5.0	0.2	12.6	13.7
Concrete volume – CV	3	5	4.7	6.3	4.7	6.3
Brick volume - BV	13	15	7.0	8.8	5.8	7.6
TG/FA	.39	.33	0.22	0.19	0.42	0.40
NG/FA	.30	.25	0.11	-	0.27	0.22

Table 5-23 *Summary of areas of glazing (square metres) & volume of thermal mass (cubic metres) of concrete & masonry walls in four dwellings*

The most noticeable differences between the actual situation and the benchmark requirements are the relatively low areas of northerly glazing (even where there is northerly glazing provided) in Development 4 and the relatively low volume of thermal mass in masonry walls in all four dwellings, but particularly in Development 5.

The relationship between the internal volume of air and indoor thermal mass is significant in the current study when considering the possibility of passive cooling. As described in section 3.3.2.2, for optimum passive cooling in a temperate climate, Baggs and Mortensen (1995) refer to approximately one square metre of 100 mm thick brick wall being required for each one and one half cubic metres of air in the room. This relationship is shown in Table 5-24 for the four dwellings.

	Dwelling 4A	Dwelling 4B	Dwelling 5D	Dwelling 5E
Volume of air	113	151	113	151
Volume of air /1.5	75	101	75	101
Actual wall area of 100mm thick internal wall (refer brick vol. Table 5-23)	70	88	58	76

Table 5-24 *Relationship between internal volume of air and area of 100mm thick masonry walls*

5.6.2 Monitored thermal conditions

Thermal conditions during the full monitoring period and on the design day are considered below.

5.6.2.1 Monitored period

An overview of the monitored temperatures and outdoor temperatures for the monitored period in summer are shown in Figure 5-19 for Dwellings 4A and 4B. Dwellings 4A and 4B have a similar thermal pattern in summer although the diurnal temperature range is lower in Dwelling 4B and maximum temperatures are lower. This is due to the walls of Dwelling 4B being mostly shaded, with only late afternoon sun reaching the west wall and window. Part of the north wall and window in Dwelling 4A is exposed to summer sun. The higher temperatures in Dwelling 4A also reflect the action of the occupant who always keeps a window open during the day.

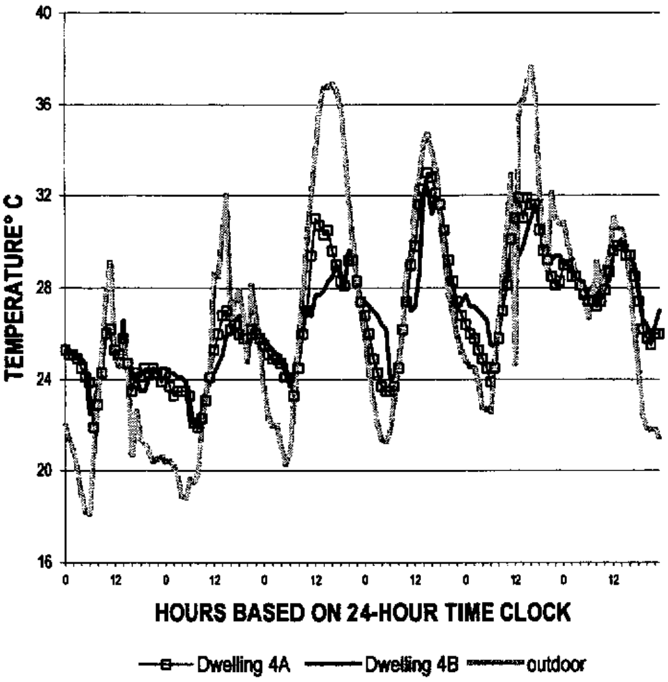

Figure 5-19 *Monitored temperatures during summer period: Dwellings 4A & 4B*

Figure 5-20 shows the monitored temperatures and outdoor temperatures for the monitored period in summer in Dwellings 5D and 5E. The effects of unshaded west and east windows in Dwellings 5D and 5E respectively can be clearly seen. Dwelling 5E recorded a maximum temperature early in the day, probably exaggerated because of the location of the data logger (see Figure 5-18). When the sun is no longer shining through the east window, temperatures fall. Dwelling 5D reaches a maximum temperature in the afternoon when the west window is affected by solar radiation.

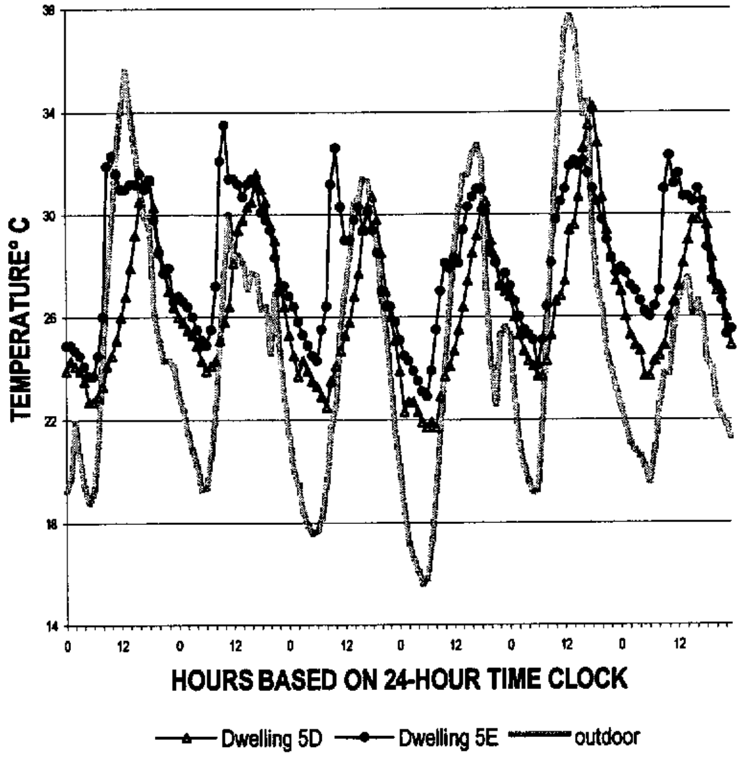

Figure 5-20 *Monitored temperatures during summer period: Dwellings 5D & 5E*

Figure 5-21 and Figure 5-22 provide an overview of the monitored temperatures and outdoor temperatures in winter for the four dwellings. Dwelling 4A consistently has the highest winter temperatures and also the highest winter gas consumption. The very high temperatures recorded in Dwelling 4A were queried. This occupant frequently used the heater (as reflected in high energy bills) which explains the numerous peaks in results. Dwelling 5D is the coldest dwelling in spite of northerly windows providing the potential for direct solar gain in winter. The low winter indoor temperatures can, at least in part, be attributed to poor thermal management of Dwelling 5D by the occupant.

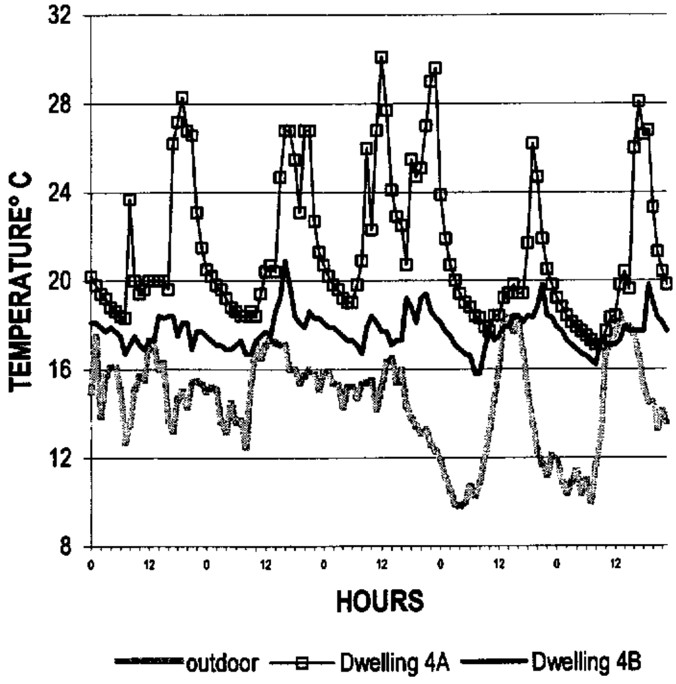

Figure 5-21 *Monitored temperatures during winter period: Dwellings 4A & 4B*

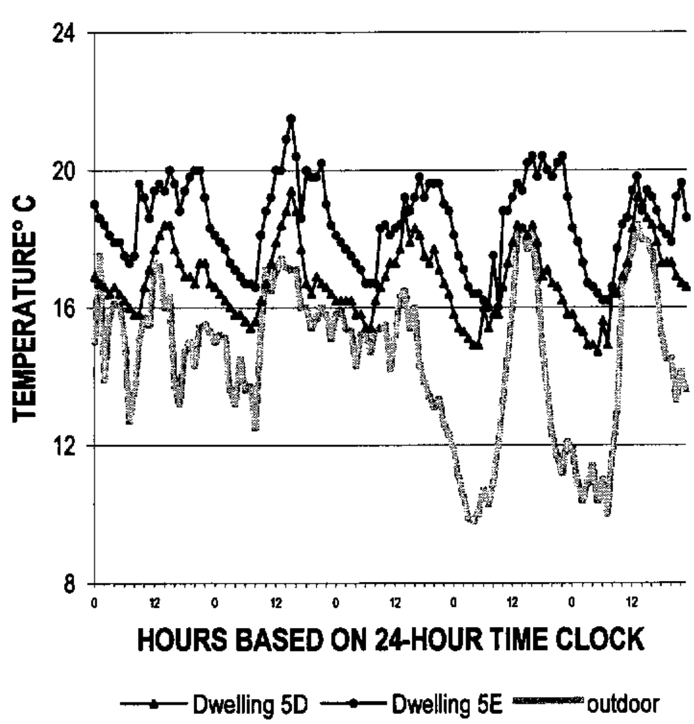

Figure 5-22 *Monitored temperatures during winter period: Dwellings 5D & 5E*

To summarise the thermal performance of these four dwellings, Dwellings 4A and 4B were less affected by outdoor conditions than Dwellings 5D and 5E. Dwelling 4B was the coolest dwelling in summer whilst Dwelling 5D reached the highest temperature in summer and the lowest temperature in winter. Dwelling 4A was the warmest dwelling in winter due to substantial use of gas heating.

5.6.2.2 Design day

As discussed in Chapter 4, one day from each monitoring period was identified as a design day. As Developments 4 and 5 were monitored during different periods in summer, the temperatures on the nominated summer design days are slightly different. However, the design day in winter was the same for both developments. Maximum, minimum and mean monitored indoor temperatures on the design days and the diurnal temperature ranges on those days are summarised in Table 5-25.

	Dwelling 4A	Dwelling 4B	Dwelling 5D	Dwelling 5E
Maximum & minimum indoor summer temperature	31.0 – 23.3	29.6 – 23.7	34.2 -23.7	32.1 – 24.1
Acceptable summer maximum	27.4	27.4	27.4	27.4
Mean indoor summer temperature	27.3	26.9	27.8	28.6
Mean indoor summer temperature from 0000 to 0800	24.6	25.0	24.8	25.7
Mean indoor summer temperature from 2300 to 0600	25.1	25.3	25.3	25.9
Summer diurnal temperature range	7.7	5.9	10.5	8.0
Maximum & minimum indoor winter temperature	26.2 – 17.0	19.8 – 16.2	18.4 – 15.4	20.4 – 16.0
Acceptable winter minimum	19.8	19.8	19.8	19.8
Mean indoor winter temperature	19.9	17.5	16.5	18.5
Mean indoor winter temperature from 0700-2200	20.1	17.7	17.1	19.2
Mean indoor winter temperature from 2300-0600	20.4	17.2	15.5	17.2
Winter temp. Difference between day and night	0.3	0.5	1.6	2.0
Winter diurnal temperature range	9.2	3.6	3.5	4.4

Table 5-25 *Maximum, minimum and mean monitored indoor temperatures (°C) & diurnal temperature range (K) on design days in summer & winter for four dwellings*

On the summer design day, monitored temperatures for Dwellings 4A and 4B are shown in Figure 5-23 together with the maximum acceptable temperature in still air.

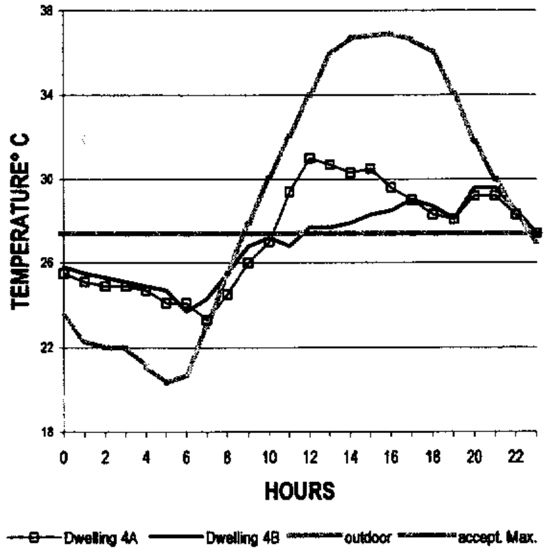

Figure 5-23 *Monitored and outdoor temperatures on summer design day for Dwellings 4A and 4B*

Figure 5-23 shows that the minimum indoor temperature is approximately 3°C higher than minimum outdoor temperature for both Dwellings 4A and 4B and occurs at 7am and 6am respectively. Minimum outdoor temperature occurs at 5am. However, the maximum temperatures show a greater difference. Although the maximum outdoor temperature of 36.9°C was reached at 4pm, Dwelling 4A reached a maximum of 31°C at noon, while Dwelling 4B reached a high of 29°C at 5pm and then the indoor temperature began to fall. However the temperature in both dwellings is seen to rise after 7pm to a maximum of 29.6°C at 8 and 9pm. This rise in temperatures may be explained by windows and doors being opened at around this time, with the expectation that outdoor temperatures were lower than indoor temperatures. On this design day though, the outdoor temperature at 8pm was still significantly higher (31.8°C) than the indoor temperatures, so the dwellings would have remained cooler by keeping doors and windows closed.

Figure 5-24 shows the monitored summer temperatures for Dwelling 5D and 5E on a design day.

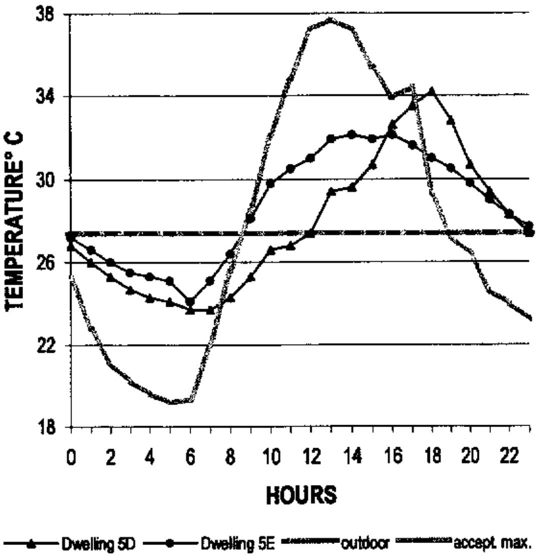

Figure 5-24 *Monitored and outdoor temperatures on summer design day for Dwellings 5D and 5E*

On the summer design day, the minimum indoor temperature in both Dwellings 5D and 5E occurs approximately one hour after minimum outdoor temperature is reached. Minimum indoor temperatures in Dwellings 5D and 5E are 4.5 K and 4.9 K higher than minimum outdoor temperature respectively. The inadequate summer protection of glazing, particularly on the east-facing window in Dwelling 5E and on the west-facing window in Dwelling 5D, is reflected in the high maximum indoor temperatures early in the afternoon in Dwelling 5E and late in the afternoon in Dwelling 5D. On the design day, the maximum summer temperatures reached in Dwellings 5D and 5E were 34.2°C at 6pm and 32.1°C at 2pm respectively.

Figure 5-25 shows the monitored and outdoor winter temperatures on the design day for Dwellings 4A, 4B, 5D and 5E, together with the minimum acceptable temperature of 19.8°C.

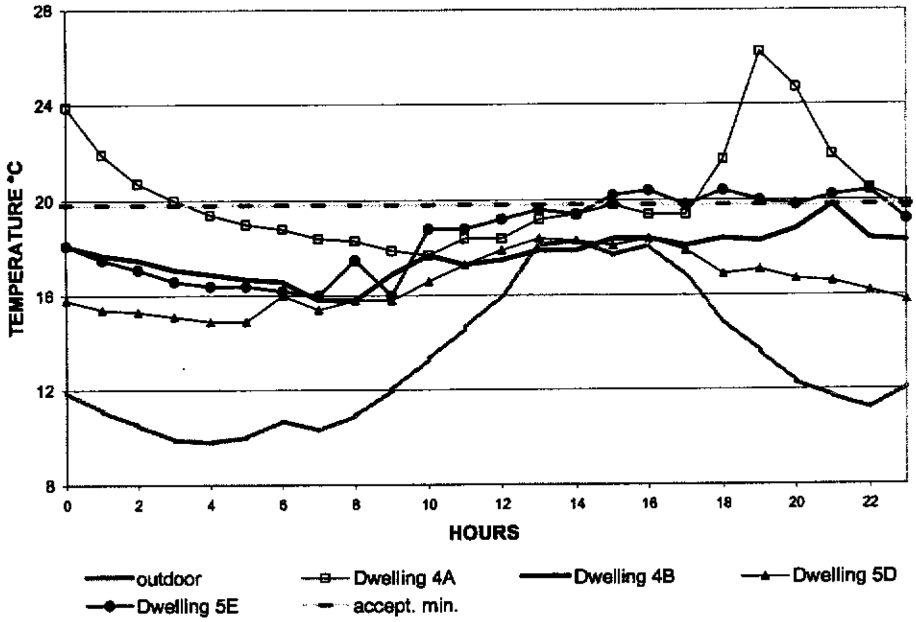

Figure 5-25 *Monitored and outdoor temperatures on winter design day for Dwellings 4A, 4B, 5D and 5E*

Winter temperatures in Dwelling 5D were particularly low, as the occupant had curtains drawn across the north windows nearly all the time, because of a concern for privacy, and he kept the bedroom window open at night. Temperatures were even lower in this dwelling than in Dwelling 4B, which has no winter sun and the lowest gas consumption in winter.

The maximum winter temperatures in Dwellings 5D and 4B were equal to or lower than the minimum acceptable temperatures. Dwelling 4A has the highest winter gas consumption per square metre and the highest indoor temperatures.

In summary, on the design days in all four dwellings, maximum summer temperatures exceeded the acceptable maximum temperatures and minimum winter temperatures were below the acceptable minimum temperatures. In light of the temperature limits for older people discussed in section 3.3.6 and the increased risks to older people at temperatures below 18°C (see section 2.2.2.1), the monitored winter temperatures are of particular concern.

5.6.3 Occupants and their behaviour

A summary of the occupants and their behaviour related to thermal performance of their dwellings, is shown in Table 5-26 (see Appendix 6 for all questionnaire results). All four occupants made use of a fan in summer, particularly at night. All four occupants also indicated that they did 'a little' to try and keep their dwelling cool in summer and reduce the need for heating in winter.

	Dwell. 4A	Dwell. 4B	Dwell. 5D	Dwell. 5E
Number of occupants	1	1	1	2
Gender	female	female	male	couple
Age bracket of respondent (years)	<65	>74	<65	65-74
Very sensitive to thermal conditions (q27)	yes	no	no	no
Occupant does anything to try to keep house cool in summer (q 18)	a little	a little	a little	a little
Occupant leaves windows/doors open on summer nights (q 19)	no	yes	yes	yes
Occupant concerned with lack of privacy through window location (q 20)	no	no	yes	no
Occupant has difficulty opening or closing windows (q 21)	no	yes	no	no
Occupant does anything to try to reduce need for heating in winter (q 28)	a little	a little	a little	a little
Occupant's reaction when feeling cold in winter (q 29)	turn on heater	put on more clothes	become more active	turn on heater

Table 5-26 *Summary of occupant description and behaviour related to thermal performance of four dwellings*

Only the occupant of Dwelling 4A claimed to be very sensitive to thermal conditions. When considering the indoor temperatures in Dwelling 4A during the winter monitoring period (see Figure 5-21), this may have been interpreted as meaning a dislike of the cold. This occupant kept the kitchen window open all day, to the extent permitted by the security lock. However, she expressed concern about security if windows were left open at night. Because of this concern, she referred to the difficulty of cooling the bedroom at night in summer.

The oldest occupant lived in Dwelling 4B, a sparsely furnished dwelling. She was the only one of these four occupants who had difficulty opening and closing windows, due to her poor physical mobility. Nevertheless, she closed windows on summer days and opened them on summer nights. Windows remained open to cool down the dwelling until she retired to bed. As already indicated in relation to temperatures on the summer design day, it seems that windows and doors were opened in the evening irrespective of the outdoor temperature. This occupant, like the occupant of Dwelling 4A , had concerns about security. She highlighted that the total area of windows that can be securely left open at night is very limited (only 100 millimetres width for each window). To deal with the cold in winter, this occupant would put on additional clothes and wrap herself in a blanket when she was sitting down in the evening.

The occupant of Dwelling 5D expressed a concern about the glare through the windows and the lack of visual privacy because of placement of windows. Consequently, he closed the curtains to the bedroom and living area nearly all the time. The occupant of Dwelling 5D is very active during the day and only uses the heater on winter evenings. During summer nights he leaves the window open in the bedroom, even though it is a sliding door. He also keeps a window open at night throughout the winter.

In contrast to the occupant in Dwelling 5D, the occupants of Dwelling 5E were not prepared to leave the bedroom sliding door open at night. Although they used a fan regularly in summer, they were conscious of being particularly warm in the bedroom on summer nights. In winter they were conscious of how quickly the living area cooled down at night, so they felt it necessary to use the heater regularly.

5.6.4 Energy consumption

Total gas consumption in winter varied widely between the four dwellings as recorded in Table 5-27. To provide some indication of gas consumption for space heating, this has been estimated as the difference between gas consumption over the winter months and gas consumption over the summer months.

	Dwelling 4A	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
q.30 Amount of winter sun in living area	a little	none	a little	substantial
Total winter gas consumption (kWh/m²)	43.7	24.1	29.5	41.2
Estimate of gas consumption on space heating (kWh/m²)	13	5	11	19
Winter electricity consumption (kWh/m²)	7.9	4.7	8.9	6.9
q.31 Perceived use of heater in winter (hrs/week)	<14	14 - 28	<14	14 - 28

Table 5-27 *Questionnaire responses & winter operational energy consumption from energy accounts*

Total winter gas consumption in Dwellings 4A and 5E was close to the mean level of gas consumption for all seven developments (42.4kWh/m2), while the gas consumption in Dwellings 4B and 5D was considerably lower than mean gas consumption. Dwelling 4B has the lowest consumption of gas for space heating in winter, though winter indoor temperatures are higher in Dwelling 4B than in Dwelling 5D. When occupants were asked about their use of space heating (q.31), in some cases (Dwellings 4A and 4B) the responses do not reflect the actual levels of gas consumption.

To determine whether direct solar gain had an effect on gas consumption for space heating, the occupant's response to the interview question related to sun penetration in the living room in winter (question 30) is also included in Table 5-27. It appears that the gas consumption for space heating is not directly related to the amount of winter sun shining into the living room area. Dwelling 5E was the only one of the four dwellings with substantial sun penetration. However, this dwelling has an average level of winter gas consumption.

5.6.5 Computer simulated conditions

Dwellings 4A, 4B, 5D and 5E as designed were simulated using NatHERS, in order to establish:

- theoretical hourly temperatures on the summer and winter design days. The simulated temperatures could then be compared with the conditions in typical dwellings that were modified to improve energy efficiency. As these simulated temperatures would not be affected by the use of space heating, space cooling or by occupant behaviour, they provide a more appropriate source of comparison of building performance than the monitored temperatures; and
- the theoretical energy consumption required to maintain acceptable indoor temperatures in typical dwellings.

5.6.5.1 Hourly temperatures

For all four dwellings, the simulated hourly indoor temperatures, when outdoor temperatures were the same as those on the monitored design days, are shown in Appendix 6. Figures 5-26 to 5-29 show the indoor temperatures as monitored and as simulated on summer and winter design days for two of the dwellings, one dwelling from each development - Dwellings 4B (two-bedroom) and 5D (one-bedroom). The monitored temperatures are included in the graphs only to demonstrate that there is a reasonable correlation between the monitored and simulated results when occupant behaviour, as discussed in Chapter 5, is taken into account.

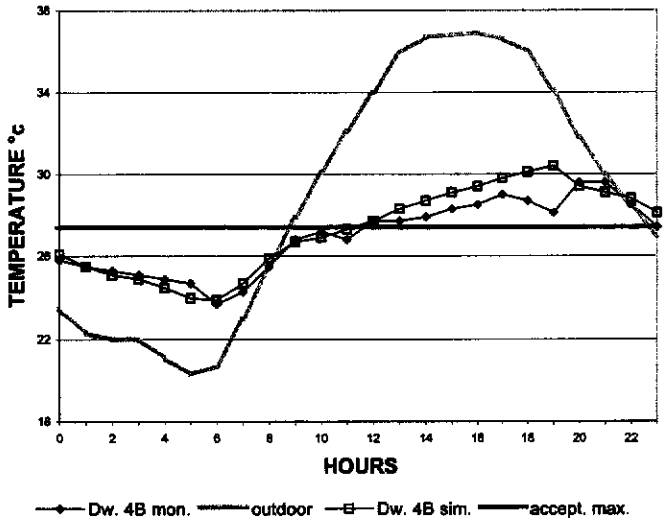

Figure 5-26 *Simulated and monitored temperatures on summer design day in Dwelling 4B*

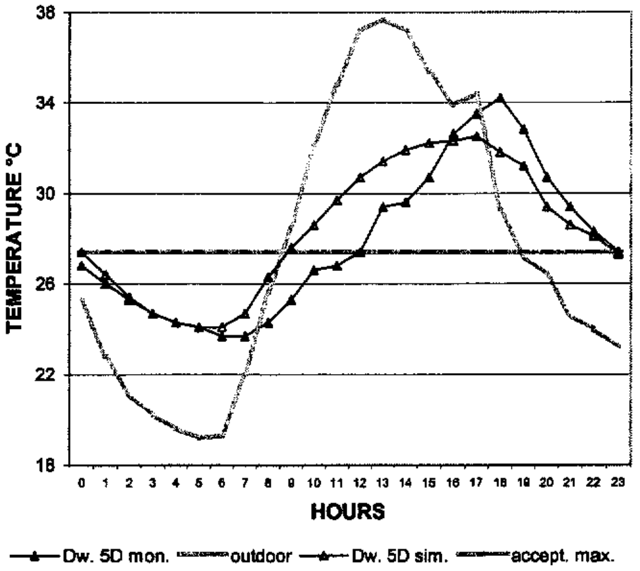

Figure 5-27 *Simulated and monitored temperatures on summer design day in Dwelling 5D*

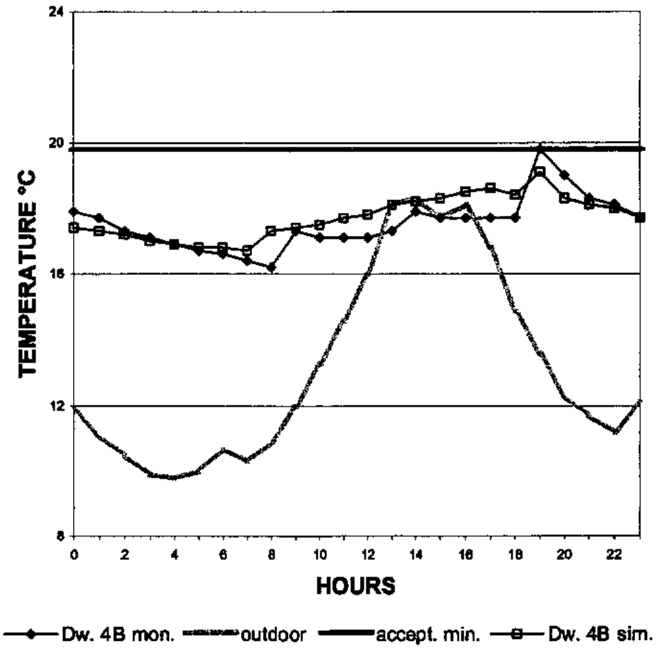

Figure 5-28 *Simulated and monitored temperatures on winter design day in-Dwelling 4B*

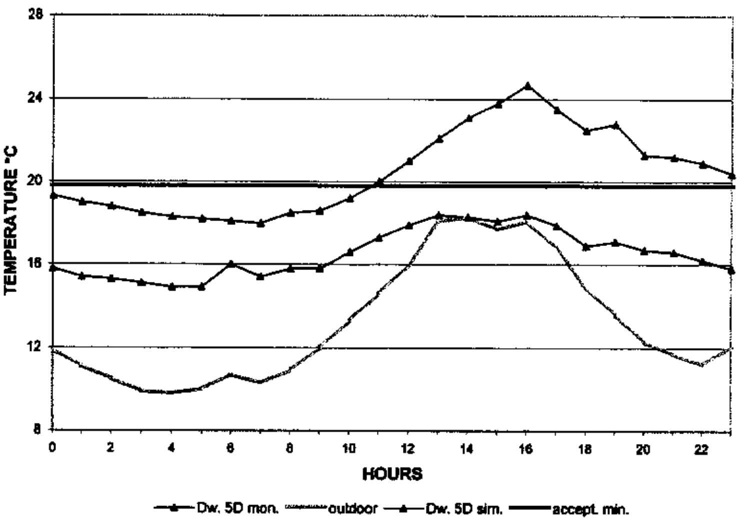

Figure 5-29 *Simulated and monitored temperatures on winter design day in Dwelling 5D*

A summary of the maximum, minimum and mean simulated indoor temperatures for the four dwellings in summer and winter on the same design days are shown in Table 5-28.

	Dwelling 4A	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
Maximum & minimum indoor summer temp. (°C)	30.7-23.9	30.6-23.9	33.1-24.2	32.4-24.4
Mean indoor summer temp. (°C)	27.2	27.4	28.7	28.8
Mean summer temp. 2300-0600 (°C)	25.1	25.3	25.3	25.9
Maximum & minimum indoor winter temp. (°C)	20.0-17.0	19.4-16.9	24.7-18.0	23.1 -17.9
Mean indoor winter temp (°C).	18.2	18.0	20.5	20.5
Mean winter temp. 2300-0600 (°C)	20.4	17.2	15.5	17.2
Mean winter temp. 0700-2200 (°C)	20.1	17.7	17.1	19.2

Table 5-28 *Simulated maximum, minimum and mean indoor temperatures on design days in summer and winter (dwellings as designed)*

The simulations confirm that, with the current designs, the temperatures in all four dwellings are outside the acceptable temperature range. The simulations also indicate a general correlation between the simulated and monitored temperatures. The 4 K difference between monitored and simulated mean temperatures in winter in

Dwelling 5D, as shown in Figure 5-29, can be largely attributed to occupant behaviour. The curtains were regularly drawn across northerly windows during the day in winter because of glare and privacy concerns and windows were open to some extent throughout the night.

5.6.5.2 Energy consumption

Using NatHERS in energy rating mode, the thermal loads required to heat or cool the living area and bedrooms to maintain acceptable temperatures[1] were established. These thermal loads reflect the design of the building and are not tempered to reflect occupants' behaviour, such as drawing curtains across north-facing windows during the day in winter, or leaving windows open on hot summer days or cold winter nights.

Using the computed thermal loads, the energy consumption was calculated by multiplying the thermal loads by efficiency factors (section 4.7.2) for gas and electricity[2]. The results are presented in Table 5-29 in terms of thermal load and energy consumption per square metre per annum and also total annual energy consumption. The simulation shows that Development 5 is more energy efficient than Development 4 in winter whilst Development 4 is more energy efficient than Development 5 in summer. For the four dwellings, the average <u>simulated</u> annual energy consumption for heating is 30.0kWh/m^2 and for cooling is 12.4kWh/m^2. The results from the multiple case study show that the <u>actual</u> mean gas consumption for heating in Developments 4 and 5 was 16.8kWh/m^2, a little over half (56%) that required to maintain acceptable temperatures in winter.

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[1] Minimum temperatures of 19.8°C during the day and 18°C between 10pm and 7am in winter; maximum temperature of 27.4°C in still air during summer.

[2] An efficiency factor of 0.7 for gas heating and 2.4 for air-conditioning was used (Fay & Treloar 1999)

	Dwelling 4A	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
Thermal load for heating	29.9	24.6	15.5	14.0
Energy consumption for heating	42.71	35.14	22.14	20.00
Thermal load for cooling	17.4	18.8	40.6	42.2
Energy consumption for cooling	7.25	7.83	16.92	17.58
Total energy consumption	**49.96**	**42.97**	**39.06**	**37.58**
Annual energy consumption for heating & cooling (kWh/a)	2008 + 340 = **2348**	2214 + 493 = **2707**	1041 + 795 = **1836**	1260 + 1108 + **2368**

Table 5-29 - *Simulated thermal loads and energy required (in kWh/m2. annum) for heating and cooling the existing dwellings to acceptable temperatures*

5.7 Summary of Findings

Well-established principles of energy-efficient design have not been adopted in the majority of dwellings observed in the current study. When the principles, at least in regard to window orientation, appear to be applied (as in Developments 1, 5 and 6),

indoor thermal conditions are not necessarily improved. This may be due to the selective application of energy efficient design principles in the dwellings, or because occupants' behaviour partly negates the benefits of the design features. As hypothesised in the current study, the way energy efficient design is used in small, medium density housing for the aged may be inappropriate.

The results also indicate that there are vast differences in how occupants manage thermal conditions in their dwellings, irrespective of the design of the dwelling. Occupant behaviour contributes to temperatures in public housing for the aged being higher than acceptable in summer and lower than acceptable in winter. The findings are summarised as follows:

- none of the monitored dwellings have northerly glazing areas in accordance with benchmark areas of northerly glazing, although in one development (Development 5) the benchmark ratios are almost achieved. The ratio of northerly glazing to floor area varies from 0 to 0.27;

- only in one development (Development 5) do dwellings have a total glazing area in accordance with the benchmark areas of total glazing. The ratio of total glazing to floor area varies from 0.15 in Development 1 to 0.42 in Development 5;
- 80% of dwellings having little or no winter sun in living areas, due to inappropriate window orientation, shading of glazing or occupant behaviour;
- 70% of dwellings have sun penetration through windows in mid-summer;
- in all developments, the volume of thermal mass of concrete is higher than the benchmark value and the volume of thermal mass of brick walls is lower than the benchmark value;
- only one of the seven developments (Development 6) incorporates wall insulation in conjunction with a masonry leaf of the external wall[1];
- in all developments, indoor temperatures on the design days are outside the acceptable ranges of 22.4°C to 27.4°C in still air in January and 19.8°C to 24.8°C in July. The actual temperatures range from 22.7°C to 34.5°C in summer and 14.9°C to 29.6°C in winter;
- where window orientation appears to have been considered in terms of solar gain, thermal conditions are not significantly different to conditions where window orientation for solar gain has been ignored;
- in all developments, occupants are more conscious of doing a lot to try to keep their dwellings cool in summer (19%) than doing a lot to try and reduce the need for space heating in winter (2%);
- 19% of occupants indicated a concern with lack of visual or aural privacy, which influenced them in keeping curtains drawn or windows closed;

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[1] This form of construction is referred to as reverse brick veneer construction.

- mean gas consumption (67.6 kWh/m2) is approximately two thirds of total mean gas and electricity consumption (99.4 kWh/m2);
- there is no significant difference between the seven developments in total gas and electricity consumption;
- there is no significant difference between the seven developments in mean gas consumption for space heating; and
- in the detailed study of four dwellings, the two dwellings awarded a prize for energy efficient design (Dwellings 5D and 5E) performed less satisfactorily than the other two dwellings in terms of temperatures and energy consumption. The poor performance of dwellings 5D and 5E appears to be related to the large area of glazing and low volume of thermal mass.

6. Designing for energy efficiency and appropriateness

6.1 Preamble

This chapter seeks to provide evidence to show how indoor thermal conditions in small, medium density housing can be affected by adopting appropriateness criteria discussed in Chapter 2 and energy efficient design principles discussed in Chapter 3. The evidence provided related to temperatures is in the form of a number of sets of computer simulations[1] that model indoor temperatures and energy consumption. The assessment of appropriateness related to affordability includes an estimate of the cost of the proposed design changes and the potential savings in energy consumption.

The results are presented in the following four sections:

- computer simulation of a hypothetical dwelling complying with the bench-marks for energy efficient design (section 6.2);
- computer simulation of a typical dwelling complying with the building regulations (ABCB 1996) for energy efficiency (section 6.3);
- computer simulations of multiple modifications to a typical dwelling to achieve acceptable indoor temperatures and appropriateness, including affordability (section 6.4); and

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[1] Numerous sets of computer simulations were performed. A typical text file, containing the building description for simulation purposes (called a SCRATCH file) and the resultant hourly temperatures on the summer and winter design days are included in Appendix 7 for the building first discussed in this chapter. The complete set of SCRATCH files and resultant temperature files for a full year are in the CD attached to this thesis.

- computer simulations of appropriate modifications to three typical dwellings with floor areas of 50 square metres, 65 square metres and 80 square metres (section 6.5).

6.2 Benchmark compliant dwelling

A hypothetical two-bedroom semi-detached dwelling, having a floor area of approximately 65 square metres and the long axis running east-west, was designed to incorporate building requirements similar to the building benchmarks for energy efficiency established in section 3.3.4. The benchmark parameters incorporated in the design are shown in Table 6-1 and a plan of the dwelling is shown in Figure 6-1.

Total north wall area (m^2)	North glazing area(m^2)	Total glazing area(m^2)	Thermal mass in brick (m^3)	Total R value		Night ventilation (ac/h)
				Roof	walls	
26.2	16.2	21.2	15	2.0	1.5	30

Table 6-1 *Benchmark parameters incorporated in simulation of hypothetical dwelling of 65 m^2.*

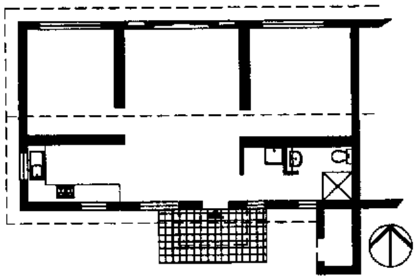

Figure 6-1 *Plan of benchmark-compliant hypothetical dwelling.*

The dwelling shown in Figure 6-1 was simulated, and maximum, minimum and mean temperatures on the design days in summer and winter are shown in Table 6-2.

	Summer (°C)			Winter (°C)		
	Max	Min	Mean	Max	Min	Mean
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
Benchmark compliant dwelling	31.0	23.2	27.4	24.3	19.7	21.7
Acceptable temperatures[1]	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-2 *Simulated temperatures in benchmark-compliant dwelling*

Thermal conditions appear to be acceptable in winter, but in summer mechanical space cooling would be highly desirable. However, the acceptable winter temperature depends on large areas of northerly glazing for direct solar gain. As indicated in the results in Chapter 5 from the multiple case study, large areas of glazing are considered to be inappropriate in small, medium density housing for the aged. Concerns were raised in the multiple case study regarding large windows in relation to impingement on visual privacy, the difficulty of opening and closing, the problems of cleaning, the expense of providing curtains, the difficulty of manually adjusting large curtains, the glare from windows and the deleterious effect of ultraviolet radiation on furnishings exposed to solar radiation. In addition, there is a possibility of overheating from direct solar radiation during the day in winter, if occupants are dressed in winter clothing. This may tempt the occupants to open windows for ventilation and thus reduce the daytime storage of solar radiation for night use.

6.3 Complying with building regulations for energy efficiency

To determine if compliance with the energy efficiency requirements in the building regulations (ABCB 1996) produce acceptable indoor temperatures in small, medium

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[1] Acceptable temperatures for January and July were determined using de Dear and Schiller Brager's (1998) adaptable approach to thermal comfort.

density dwellings in Perth[1], a typical[2] monitored two bedroom dwelling shown in Figure 6-2 was adjusted to comply with the regulatory requirements for 'acceptable construction practice'.

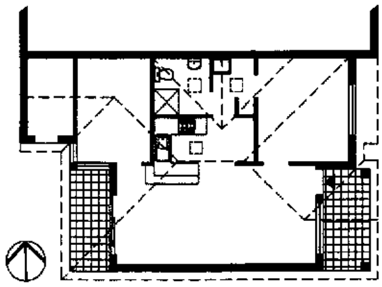

Figure 6-2 *Plan of typical dwelling complying with energy efficiency requirements in national building regulations, the Building Code of Australia (BCA).*

The only adjustment required in a typical dwelling was to increase ceiling insulation to R2.5 to achieve a total insulation level for the roof and ceiling of at least R2.7. It is pointed out that as the external walls of typical dwellings were of cavity brickwork, no wall insulation was required in these walls. Also, in regard to required ventilation openings, although the area of operable windows in all dwellings were at least 7.5% of the floor area thus complying with the building regulations for ventilation openings, in the simulation it was assumed that no cross ventilation was available to reflect usage patterns discussed in Chapter 5. The dwelling was simulated

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[1] Perth is designated within Climatic Zone 5 in the ABCB (1996).

[2] A two-bedroom dwelling from Development 4 was selected as a typical dwelling. This dwelling is typical in that it is not designed to be energy efficient, it represents the most common size of dwelling in the multiple case study (approximately 65 m^2) and the materials of construction are commonly used in residential construction in Perth, as well as being the most commonly used in the multiple case study in this thesis – a concrete slab on ground covered with vinyl tiles, uninsulated cavity brick walls, single glazing in aluminium frames, plasterboard ceiling with R2.0 insulation and terra-cotta roofing tiles on a timber framed roof.

and maximum, minimum and mean temperatures on the design days are shown in Table 6-3.

	Summer (°C)			**Winter (°C)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
BCA compliant dwelling	30.3	23.9	27.2	18.6	16.8	17.8
Acceptable	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-3 *Simulation of temperatures in BCA compliant dwelling*

Table 6-3 shows that thermal conditions are not acceptable in either summer or winter. The winter maximum temperature is below the acceptable minimum temperature. This is of particular concern in housing for the aged in the light of the findings of the study by Keatinge et al. (1997) regarding the higher risk of mortality from cold stress in regions where winter outdoor temperatures are relatively mild.

6.4 Modifications for energy efficiency and appropriateness

The results from the simulations of a benchmark compliant dwelling and a building regulation compliant typical dwelling show that acceptable indoor temperatures cannot be achieved without the use of space cooling in both cases and the use of space heating in the latter case. In addition, the benchmark compliant dwelling does not meet appropriateness criteria due to large areas of northerly glazing. Consequently, the same typical two bedroom dwelling referred to in section 6.3 was subjected to a series of design modifications to determine if energy efficient design, in excess of building regulatory requirements but responsive to appropriateness criteria in small, medium density housing, could provide acceptable indoor temperatures. In the process of modification to improve energy efficiency, particular consideration was given to addressing the following aspects of universal design:

- the maintenance of the design ethos of typical small, medium density housing for the aged in regard to area of glass and placement of glazing;
- the avoidance of environmental demand on building occupants; and
- the reduction of dependence on direct solar radiation for passive heating.

6.4.1 Initial design decisions

Two primary requirements for energy efficient design are that solar gain should be utilised in winter and glazing should be protected from solar gain in summer (Givoni 1994). Using the typical dwelling, in this section the results of testing some initial design propositions that would improve solar gain in winter and shade solar collectors in summer are presented.

From results of the thermal performances of the monitored dwellings considered in detail (Dwellings 4A, 4B, 5D and 5E) in section 5.6, it is apparent that thermal performance is directly related to the orientation and treatment of glazing. In winter, two of the dwellings (Dwellings 4A and 4B) cannot achieve acceptable temperatures in winter, as either the northerly windows are shaded by nearby structures or there are no northerly windows. The other two dwellings (Dwellings 5D and 5E) have the potential to achieve acceptable temperatures in winter through direct solar gain. However, the large areas of glazing in these two dwellings highlight the inappropriateness of such large areas of glazing in small, medium density housing for the aged. The inappropriateness may relate to reduced privacy, excessive glare, significant heat losses on winter nights or significant heat gains on summer days. The first two factors may cause occupants to close curtains during the day in winter, thus loosing the benefits of direct solar gain. The second two factors are the result of typical curtains generally having poor insulation properties. Consequently, in summer the dwelling with least exposure to solar radiation (Dwelling 4B) is relatively cool, whereas the dwellings with large areas of glazing exposed to solar radiation (Dwellings 5D and 5E) have particularly high indoor temperatures.

To determine the effects on a typical monitored dwelling of design modifications that address the observed problems of orientation, area of glazing and shading of glazing, the following three modifications were made and indoor temperatures computed for each modification.

Preliminary modification 1 (PM1) –

- A typical dwelling was oriented with the long axis running north-south thus providing a limited area of north-facing wall.
- The area of northerly glazing adopted was similar to the glazing area in typical dwellings. The northern glazing area in the living area was limited to the maximum size of any one area of glazing used in typical designs in the multiple case study (2.1 metres high by 2.1 metres wide) and the bedroom window area was similar in area to the average bedroom window area in all the developments (1.5 metres high by 1.5 metres wide). The total area of northerly glazing also took into account Givoni's (1994) recommendation that the area of northerly glazing should be approximately one sixth of the area of thermal mass exposed to northerly glazing. It was assumed that as the floor may be carpeted, only the masonry walls could reliably be exposed to direct solar gain through northerly glazing. As the typical two-bedroom dwelling has approximately 40 square metres of internal masonry wall that could be exposed to northerly glazing, the area of northerly glazing should be approximately 6.7 square metres for effective storage of the direct solar radiation.

Using the above limitations, the resultant total area for northerly glazing in the dwelling was approximately 11% of total floor area. Other glazing remained as in a typical dwelling. Consequently the total area of glazing was approximately 21% of floor area. The plan of the dwelling is shown in Figure 6-3.

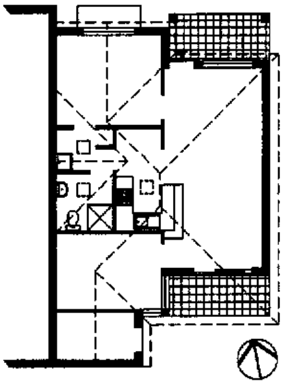

Figure 6-3 *Plan of typical dwelling PM 1*

Preliminary modification 2 (PM2) –

- The shading of the north wall was reduced, by eliminating the overshadowing from walls of the building itself and by eliminating the verandah on the north side. Typical 450mm eaves were provided on all sides. All glazing was now located either on the northerly or on the southerly side of the dwelling, adopting the same pattern of glazing as in the majority of dwellings in the multiple case study. The area of the glazing on the two opposite external walls was similar in area, and the total area of glazing remained at approximately 21% of floor area. The plan is shown in Figure 6-4.

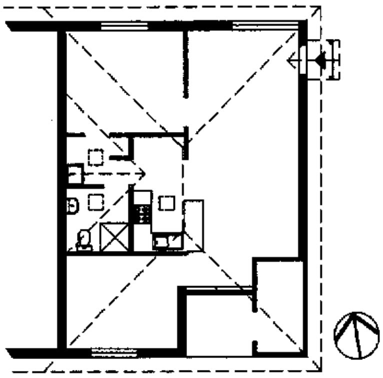

Figure 6-4 *Plan of typical dwelling PM 2*

Preliminary modification 3 (PM3) –

- In order to maximise solar collection in winter and avoid solar penetration in summer a solar pergola with fixed louvres was introduced on the north side in front of glazing, as shown in Figure 6-5.

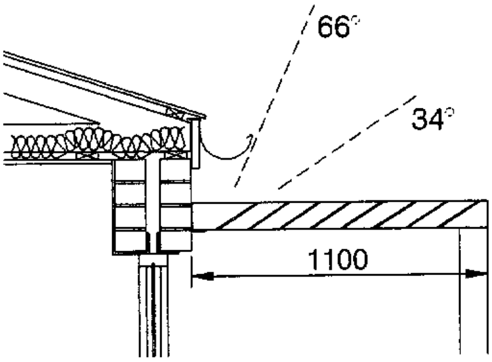

Figure 6-5 *Detail of eaves and solar pergola*

It was decided to adopt fixed louvres rather than adjustable louvres for two reasons. Firstly, fixed louvres would eliminate environmental demand on the occupants to adjust the louvres appropriately and secondly, fixed louvres would limit capital costs and maintenance costs of adjustable louvres. The extent of the proposed solar pergola was determined on the basis of fully shading the solar collectors from floor level to 2.1 metres high from mid-October until the end of February. Figure 6-5 shows the detail for the eaves and solar pergola used in the computer modelling throughout the current study.

The plan of the dwelling used in PM3 is the same as that used in PM2, except for the addition of the solar pergola as indicated in Figure 6-6. This plan provided the basis for further modifications.

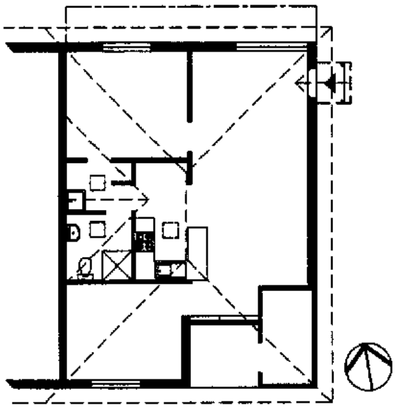

Figure 6-6 *Plan of typical dwelling with solar pergola*

In Table 6-4 a summary of the simulated temperatures resulting from the above three preliminary modifications are compared to acceptable temperatures on the design days. Details of hourly data on the design days for PM1, PM2 and PM3 are shown in Appendix 7.

	Summer (°C)			**Winter (°C)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
Northerly orientation –PM1	30.1	23.7	26.9	20.7	17.5	19.1
Overshadowing on north side reduced – PM2	30.3	23.7	27.0	21.6	18.1	19.9
Solar pergola introduced –PM3	30.2	23.7	27.0	21.9	18.2	20.1
Acceptable temperature	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-4 *Summary of simulated temperatures on design days – three preliminary modifications in typical dwelling*

The results in Table 6-4 show that the winter temperatures have progressively risen with each design modification, as northerly glazing becomes more exposed to direct solar radiation. However summer temperatures have increased marginally above those in the first modification. The minimal difference in summer temperatures on the design day between PM2 and PM3 is due to the shading of the glazing on the particular design day in early January. The 450 millimetres eaves in PM2 provide adequate shading to glazing when the vertical shadow angle[1] is more than 78°, as it is in early January. However at other times during the summer, when the vertical shadow angle is lower, the performance of PM3 is superior.

The results in Table 6-4 indicated that, to increase winter indoor temperatures and reduce summer indoor temperatures, further design modifications were required.

6.4.2 Design modifications

On the basis of the literature review regarding the dangers of cold-related stress for the elderly in regions where mild winters are common (Keatinge et al. 1997), it was decided to first explore whether winter temperatures could be raised to acceptable levels using energy efficient design, whilst also addressing issues of appropriateness for the aged. An examination of the simulated temperatures on the design days in the third preliminary design modification (PM3) showed that, in winter, the temperatures between 7am and 10am fell below acceptable levels. This indicated that there was inadequate collection and/or inadequate storage of solar radiation from the previous day.

The first modification (M1) looked at raising indoor temperatures in winter by increasing the solar collection area. In the typical dwelling with a solar pergola, shown in Figure 6-6, the available collection area for solar radiation is limited by the area of the northerly wall. The total north wall area was approximately 28% of floor area. Windows for direct solar gain, natural lighting and views occupied approximately 40% of that wall. As it had already been established that increasing the area of northerly glazing was not a viable option, in M1 it was proposed to address the additional heating requirement by utilising a Trombe-Michel wall, an acknowledged form

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[1] The vertical shadow angle denotes the angle of the sun above the horizontal plane at right angles to the window.

of indirect solar heating (section 3.3.2.2). Such a system of passive heating is particularly suitable in small medium density housing, as it is most effective in heating relatively small rooms, it does not compromise privacy and it increases the time lag between the minimum outdoor temperature and the minimum indoor temperature (Lebens 1980).

In the typical dwelling it was considered appropriate to utilise all the opaque area of north wall for a Trombe-Michel wall, based on the test results of a Trombe-Michel wall monitored in Melbourne by Charters, MacDonald and Akbarzadeh (1984). In that testing it was shown that a Trombe-Michel wall, used together with northerly glazing, reduced internal temperature swings by introducing alternative passive heating well after the peaks in solar radiation and ambient outdoor temperatures. Thus it was determined that the Trombe-Michel wall should form the remaining area of the north wall, providing approximately 13% of the floor area for indirect solar heating.

The summary in Table 6-5 (see Appendix 7 for hourly temperatures M1) shows the summer and winter simulated temperatures in the dwelling on the design days when the typical dwelling had:

- the long axis running north to south;
- 10% shading of the north wall in winter from the solar pergola;
- shading of the north wall from direct solar gain in summer with a solar pergola;
- 6.7m^2 of northerly glazing;
- 7.1m^2 of southerly glazing; and
- 8.4m^2 of Trombe-Michel wall.

	Summer (°C)			**Winter (°C)**		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
M1	30.4	23.9	27.2	23.3	19.3	21.3
Acceptable temperatures	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-5 *Simulated temperatures on design days in typical dwelling – M1*

This design modification created acceptable[1] theoretical temperatures on the winter design day but summer temperatures had risen slightly and remained outside the acceptable range.

The second modification (M1-A) looked at whether reducing the area of glazing to the minimum area permitted by the Building Code of Australia (ABCB 1996) for natural light[2], natural ventilation[3] and energy efficiency requirements for air movement[4] would improve summer indoor temperatures, whilst maintaining winter temperatures at the same level as in M1. In M1-A, the Trombe-Michel wall replaced the area of glazing that was removed on the north side. The summary of thermal conditions from this simulation is shown in Table 6-6.

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[1] 18°C was considered an acceptable temperature at night (section 3.2.6).

[2] The Building Code of Australia (ABCB 1996, p.19,701) clause 3.8.4.2 requires that natural light to habitable rooms "*have an aggregate light transmitting area ...of not less than 10% of the floor area of the room*".

[3] The Building Code of Australia (ABCB 1996, p.19,901) clause 3.8.5.2 requires that ventilation be provided by means of operable windows, doors or the like, having " *an aggregate opening or openable size not less than 5% of the floor area of the room*".

[4] The Building Code of Australia (ABCB 1996, p.30,401) clause 3.12.4.1 requires for adequate air movement in Perth's climatic zone that the area of operable windows to be at least 7.5% of the floor area of a room if there is no ceiling fan and 5% of the floor area of a room if there is a ceiling fan.

	Summer (°C)			Winter (°C)		
	Max	Min	Mean	Max	Min	Mean
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
Minimum window area (M1-A)	29.7	23.9	26.7	22.4	19.2	20.6
Acceptable temperatures	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-6 *Simulated temperatures on design days when natural light and natural ventilation were reduced to the minimum regulatory requirement (M1-A)*

The results in Table 6-6 show that in winter the temperatures fall just below (0.4 K) the acceptable minimum temperature between 7am and 9am, but otherwise remain within the acceptable temperature range. In summer, temperatures are lower (maximum temperature has fallen by 0.7 K) but are still above the acceptable maximum temperature. The concern with reducing glazing area to the minimum permitted by building regulations is that the dwellings will have less glazing than any of the dwellings in the multiple case study. Consequently the occupants may have insufficient natural light for many domestic tasks, so artificial lighting will be regularly required and, in addition, outdoor views will be more restricted. For these reasons, this alternative of reducing glazing area to the minimum permitted was not considered any further in the current thesis.

6.4.2.1 Modifications to reduce summer overheating with building elements

To try and address high summer temperatures resulting from M1 whilst retaining acceptable indoor winter temperatures, a series of building modifications based on the principles of energy efficient design (Balcomb 1987) were made to the building envelope (insulation of walls and type of glazing) and to the quantity of thermal mass indoors that was available as a heat sink. The modifications made were considered to be appropriate in small, medium density housing. Seven simulations were conducted (M2 to M8) with two variations to the walls of the building envelope, two variations in thermal mass and two variations in glazing type.

The variations, coded as indicated in brackets, are:

- cavity brick walls (W1), cavity brick walls insulated with R1.0 insulation (W2);
- typical volume of internal masonry walls (TM1), increasing the volume of internal masonry walls by doubling the thickness of masonry walls within the living/bedroom zone leading to an increase of approximately 1.5m^3 (TM2); and
- single glazing (G), double-glazing, other than the glazing incorporated in the Trombe-Michel wall (DG).

A summary of the temperatures on the design days for each of the simulations are shown in Table 6-7. Hourly temperatures for these simulations on the design days are recorded in Appendix 7.

Modification	**Summer (°C)**			**Winter (°C)**		
	Max	Min	Mean	Max	Min	Mean
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
M1 (W1, TM1,G)	30.4	23.9	27.2	23.3	19.3	21.3
M2 (W1,TM1, DG)	30.0	23.8	26.9	23.2	19.5	21.3
M3 (W2, TM1,G)	30.1	23.8	27.0	23.9	20.1	22.1
M4 (W2, TM1, DG)	29.7	23.7	26.8	23.9	20.3	22.2
M5 (W1, TM2, G)	30.4	23.9	27.2	23.3	19.3	21.3
M6 (W1,TM2, DG)	30.1	23.9	27.0	23.3	19.5	21.4
M7 (W2, TM2, G)	30.2	23.8	27.1	23.9	20.1	22.0
M8 (W2, TM2, DG)	29.8	23.8	26.8	24.0	20.3	22.2
Acceptable temperatures	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-7 *Simulated temperatures in dwelling modified to reduce summer overheating*

The results in Table 6-7 show that double-glazing appears to have the most noticeable influence on reducing maximum and mean summer indoor temperatures. The addition of wall insulation also consistently improves thermal conditions. When double-glazing is used in conjunction with wall insulation (M4), in summer the mean temperature is reduced by 0.4 and the maximum temperature is reduced by 0.7 K. Increasing the volume of internal masonry walls by approximately 17% (TM2) does not appear to have any consistent beneficial effect on temperature. According to Baggs and Mortenson (1995), the area of masonry wall exposed to the indoor air should be in the ratio of one square metre of 100mm wall to 1.5 cubic metres of indoor volume of air. This is not achievable in dwellings of small floor area.

It is evident from the results of the modifications shown in Table 6-7 that the temperatures are, in all cases, still above the acceptable maximum temperature in still air in summer. To further try and improve the summer conditions, a second series of modifications were simulated that involved drawing in cool night air by using a mechanical exhaust fan with an exhaust capacity of 30 air changes per hour. This ventilation rate is close to the benchmark ventilation rate for night cooling for a building of 65 square metres in floor area, determined from the recommendations of Baverstock and Paolino (1986).

6.4.2.2 Modifications to reduce summer overheating with mechanical system

The modification of night cooling (NC) was added to each of the building modifications simulated in section 6.4.2.1. A summary of the maximum, minimum and mean temperatures on the summer design day is shown in Table 6-8.

Modification	**Summer (°C)**		
	maximum	minimum	mean
Design day outdoor temperature	36.9	20.3	28.9
M9 (W1, TM1,G, NC)	30.2	23.2	26.9
M10 (W1,TM1, DG, NC)	29.8	23.2	26.6
M11 (W2, TM1,G, NC)	29.9	23.1	26.7
M12 (W2, TM1, DG, NC)	29.5	23.1	26.4
M13 (W1, TM2, G, NC)	30.2	23.2	26.8
M14 (W1,TM2, DG, NC)	29.8	23.2	26.6
M15 (W2, TM2, G, NC)	29.9	23.2	26.7
M16 (W2, TM2, DG, NC)	29.5	23.1	26.4
Acceptable temperatures	27.4	22.4	24.9

Table 6-8 *Simulated temperatures with the addition of mechanical night cooling*

The introduction of night cooling leads to a fall in temperature in all cases. Minimum temperatures fall by approximately 0.7 K, maximum temperatures fall by approximately 0.3 K and mean temperatures fall by approximately 0.4 K. Nevertheless, the maximum summer temperatures in the two modifications producing the lowest temperatures (M12 and M16) still exceed the acceptable maximum temperature in still air by approximately 2 K. Thus a fan would be required to provide air movement in order to achieve acceptable levels of comfort when the maximum temperature was between 27.4°C and 30.4°C (Wooley 1999). It is observed that the magnitude of the maximum temperature in the simulations may be a little distorted, particularly in summer, as in all the simulations the temperature consistently peaks at 7 pm when NatHERS introduces an increase in the internal heat load as discussed in section 4.6.3[1]. This increased heat load translates into an increase of approximately 0.6 K between 6pm and 7pm. However a rise in temperature at 7pm is not evident in the monitored indoor temperatures in the multiple case study. The maximum summer temperatures in the multiple case study occurred at different times of the day in

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[1] In hindsight simulations may have been more accurate if internal heat gain at 7pm was reduced to the same heat gain occurring at 6pm instead of that occurring in the 7 to 10pm peak period.

different dwellings. Irrespective of this possible minor distortion, maximum summer temperatures exceed 27.4°C, so a fan is required to achieve acceptable levels of comfort in summer.

Comparisons between the simulated indoor temperatures on the summer and winter design days are shown in Figure 6-7 and Figure 6-8 respectively, for a typical dwelling using a standard design layout and construction (Dwelling 4B as shown in section 5.6.5.1) and for a similar dwelling modified to be energy efficient (M12).

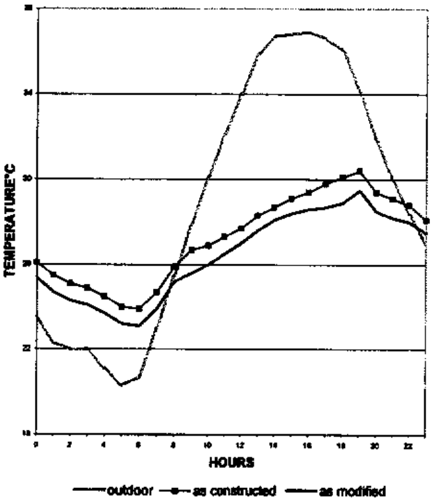

Figure 6-7 *Simulated temperatures on summer design day in typical dwelling as constructed (Dwelling 4B) and in modified dwelling (M12)*

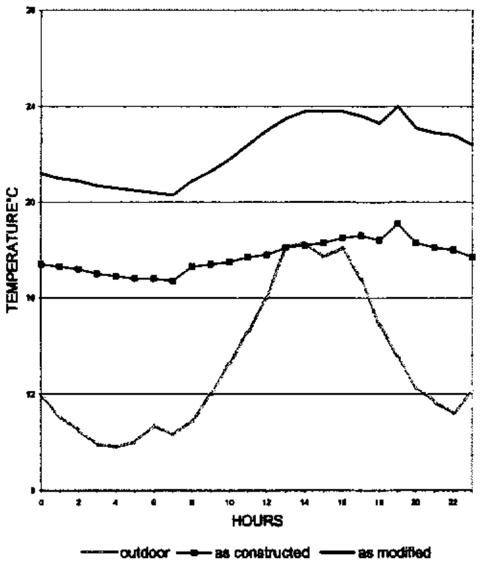

Figure 6-8 *Simulated temperatures on the winter design day in typical dwelling (Dwelling 4B) and in modified dwelling (M4)*

When comparing the conditions on the summer design day, it can be seen in Figure 6-7 that the modified design is approximately 1 K cooler than the existing design, despite the particular design of the existing dwelling where very little direct solar radiation strikes any of its walls (see Figure 5-16). In the comparison of temperatures on the winter design day shown in Figure 6-8, there is a greater improvement with the modified design. Indoor temperatures are approximately 4 K warmer than in the existing design and are at all times within the acceptable range on the design day.

6.4.2.3 Effect of substantial increase in thermal mass

As shown in previous modifications (M5 and M13), relatively small increases in thermal mass have no impact on indoor temperatures. However, small medium density dwellings may well be constructed in two or three-storey buildings. In these situations a substantial additional volume of thermal mass may be available in the floor slab forming the ceiling of the dwelling at the lower level. Would this substantial increase in thermal mass reduce summer overheating in a small energy efficient dwelling? This question was examined by simulating the typical dwelling used in M1 as a dwelling on a lower storey (referred to as M1-LS). The results are shown in Table 6-9.

	Summer (°C)			Winter (°C)		
	Max	**Min**	**Mean**	**Max**	**Min**	**Mean**
Design day outdoor temperature	36.9	20.3	28.9	18.3	9.8	13.2
M1-LS	28.7	24.0	26.4	21.9	19.4	20.7
Acceptable temperatures	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-9 *Summary of simulated temperatures in typical dwelling on a lower storey (M1-LS)*

Indoor summer temperatures have improved to a level comparable to the combined benefits gained from double-glazing, external wall insulation and night cooling (M12). However two issues arise out of this increase in thermal mass. The first is that mean winter temperatures have fallen by 0.6 K and the minimum temperature at 7am is below the acceptable minimum temperature. This indicates that on extremely cold days the indoor temperature would fall below the acceptable level for longer periods. By insulating external walls this situation could be resolved. The second issue is that an increase in thermal mass of approximately 6.4 cubic metres is not readily provided in single storey dwellings. If this volume of thermal mass was to be provided in the walls, an additional 27 linear metres of 2.4 metres high masonry wall would be required. This would increase the gross floor area of a 64 square metre dwelling by over 4%.

6.4.3 Affordability of design modifications

The question that must now be determined is whether the proposed design modifications to a small, medium density dwelling can be considered appropriate in terms of affordability. One way of considering this question is to establish the capital cost of the proposed most desirable modifications (M12) and determine what length of time is required to recoup the capital expenditure on design modifications, through savings in heating equipment and savings in annual energy costs as used in a typical dwelling.

The Net Present Value (NPV) method of discounted cash flow analysis discussed in section 4.4.2.2 was used for this purpose. The initial net capital outlay for the building elements required to provide energy efficiency in a typical dwelling was determined and annual savings in energy and equipment computed using a discount rate of 6%. When the savings were equal to the initial capital outlay, an indication of the payback period was provided.

6.4.3.1 Capital expenditure

Unit rates for all the building modifications used in the simulations (including builder's margin and GST[1]) were determined in conjunction with Mr J. McFarlane, the estimator at the Department of Housing and Works in July 2002. The rates determined are listed below.

louvred pergola to protect solar collectors from summer sun	\$279/m2
Trombe-Michel wall (less standard cavity wall)	\$340/m2 (less \$177/m2)
wall insulation	\$6.50/m2
operable double-glazing (less standard 4mm glass)	\$657/m2 (less \$97/m2)
supply & install night cooling exhaust fan[2]	\$1700
internal masonry wall	\$52/m2

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[1] GST is the Goods & Services Tax of 10%.

[2] The practical possibility of such an installation was pursued with a fan manufacturer in Perth (Smiths Fans) in January 2001. A 500mm diameter exhaust fan in a sound attenuation box could be installed in the ceiling space, possibly above the laundry, and set on a timer switch for night summer cooling. Two windows, one on each side of the dwelling, left open 100 mm would provide the best inlet ventilation and cool both the indoor air and the thermal mass. A major expense (\$1000) is automated, thermally responsive ceiling louvres.

roofing	\$49/m2
supply & install gas heater	\$900
gas heater replacement	\$750 + CPI
supply and install air-conditioner	\$1200
fan for air movement	\$200

6.4.3.2 Energy consumption

Having established that by using all the construction refinements presented in section 6.4.2.2 acceptable temperatures can be achieved in a typical 65 square metres dwelling on the design day in winter and, with the use of a fan, can be achieved in summer, the question is asked whether mechanical heating and cooling would still be required to maintain acceptable thermal conditions throughout the year, not just on a design day.

Using NatHERS in energy rating mode, the thermal load required to heat or cool the modified dwelling to acceptable temperatures was calculated. The winter temperatures were to be not less than 18°C in the bathroom zone and not less than 19.8°C during the day in the living and bedroom zone. In summer the temperature was not to exceed 30.4°C. With these parameters, virtually no space heating or cooling was required[1]. This result can be compared to the energy consumption required in a typical existing dwelling (Dwelling 4B) of 2707 kWh/a shown in section 5.6.5.2.

6.4.3.3 Financial assessment

The capital outlays and capital savings of introducing the most beneficial modifications in a typical 65m^2 dwelling are tabulated below (Table 6-10). As winter temperatures are increased such that a heater, which is a standard inclusion in public

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[1] The energy output file in NatHERS (natrep) showed an annual energy requirement of 8.8kWh.

housing for the aged, is no longer essential, the cost of the heater, including installation, is deducted from the costs of the building modifications.

	Cost of modifications to typical dwelling ($)
Louvred solar pergola	+ 1674
Trombe-Michel wall (less cavity brick wall)	+ 1369
Additional wall insulation	+ 195
Double-glazing (less standard glazing)	+ 7675
Night cooling fan	+ 1700
Room fan	+ 200
Delete heater	- 900
Reduced area of roofing	- 294
Net total	**+ 11619**

Table 6-10 *Costs of building modifications to typical dwelling similar to Dwelling 4B*

If thermal conditions similar to those in the modified dwelling were to be provided in the existing typical dwelling, in winter the amount spent on gas heating would need to be established. To achieve similar indoor temperatures in summer, a night cooling fan and a room fan would need to be installed. Thus, in carrying out a discounted cash flow analysis of the building modifications relative to energy running costs in the existing dwelling, the net total capital costs can be reduced by the costs of a night cooling fan and a room fan, as these fans are required in both situations if acceptable temperatures are to be achieved.

Using the simulated thermal loads for heating in Dwelling 4B, as designed, of 24.6kWh/m^2 (see section 5.6.5.2), adjusted by an efficiency factor of 0.7 for gas heating (Fay & Treloar 1999) and a rate of 5.88 cents per kWh for gas, the cost of annual gas consumption for heating is shown in Table 6-11. This cost of gas may be a conservative assumption as there are conflicting predictions about the trend of energy prices in Australia, due to privatisation forces potentially driving prices down, at least in the short term, whilst international conservation forces are potentially driving prices up[1]. It is assumed in these computations that the cost of gas will not change.

	Dwelling 4B	
	Energy consumption (kWh)	$
Annual space heating	2214	130

Table 6-11 *Theoretical annual gas consumption and cost to provide acceptable indoor winter temperatures in existing dwelling (Dwelling 4B)*

Using a CPI[2] of 3% per annum (as discussed in section 4.7.3) and the formula[3] $FV = PV\ (1+i)^n$ (WA Treasury Department 2001) the future replacement cost of a gas heater was determined as $1008 after 10 years, $1355 after 20 years and $ 1820 after 30 years. The replacement cost was based on advice from the Department of Housing and Works (Thorogood 2002) that the average replacement period for gas heaters was ten years. Thorogood also advised that average annual maintenance costs for gas heaters were $8 per heater.

The financial implications of the modifications compared to savings in costs of energy consumption, are computed in Table 6-12. The present value factor (PVF) is determined using the formula[4] $PVF = 1/(1+i)^n$.

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[1] This opinion was expressed by Dr. H. Saddler, the Managing Director of Energy Strategies in ACT who was in the process of writing on the matter for The Australia Institute in July 2002.

[2] CPI is the Consumer Price Index.

[3] In the formula presented, 'FV' represents the future value, 'PV' represents the present value, 'i' represents the interest rate expressed in decimals (0.06) and 'n' represents the period of time being considered.

[4] In the formula for PVF 'i' represents the interest rate (.06) and 'n' represents the period of time being considered (see section 4.4.2.2).

	Net capital costs ($)	**Running costs ($)**													
Year	0	1	2	3	4	5	6	7	8	9	10	11	15	25	30
	-9719[1]	138	138	138	138	138	138	138	138	138	1146	138	138	138	1958
PVF 6%	1.00	.94	.89	.84	.79	.75	.71	.67	.63	.59	.56	.53	.42	.23	.17
Total	-9719	130	123	116	109	104	98	92	87	81	642	73	58	32	333
PV running total		130	253	369	478	582	680	772	859	940	1582	1655	1909	2741	3191

Table 6-12 *Typical dwelling – determining payback period for design modifications*

It is clear from the above computations that after 30 years the net present value is a loss of $6527. In other words, the net capital costs cannot be recovered over 30 years and is unlikely to be recovered over the economic life of this building. Thus these modifications cannot be considered as being financially appropriate.

6.4.3.4 Responding to the financial assessment

As indicated in section 6.4.2, initial design modifications (M1) to a typical dwelling were made in order to collect sufficient solar radiation in winter for heating and to protect glazing from direct solar radiation in summer. With only these modifications, on the winter design day acceptable thermal conditions could be achieved. All the subsequent modifications, such as wall insulation, double-glazing, additional thermal mass and night cooling, were attempting to create acceptable conditions in summer, in still air conditions. However, even with all the modifications, acceptable indoor summer temperatures in still air could not be achieved. A room fan was required so that a higher maximum temperature (30.4°C) became acceptable. The

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[1] This is the net total costs of building modifications ($11619) less the cost of a night cooling fan and a room fan ($1900).

question to be answered was how many of the building modifications can be incorporated in a typical dwelling in order to provide acceptable temperatures throughout the year and be considered financially appropriate? The first modification (M1), with external wall insulation added (M3), appears to recoup the net capital costs within approximately 19 years as shown in Table 6-13, well within the economic life of the building. This payback period is reviewed in section 6.5.1.2 for another dwelling.

	Net capital costs ($)	**Running costs ($)**												
Year	0	1	2	3	4	5	6	7	8	9	10	11	15	19
	-2044	138	138	138	138	138	138	138	138	138	1146	138	138	138
PVF 6%	1.00	.94	.89	.84	.79	.75	.71	.67	.63	.59	.56	.53	.42	.33
Total	-2044	130	123	116	109	104	98	92	87	81	642	73	58	46
PV running total		130	253	369	478	582	680	772	859	940	1582	1655	1909	2064

Table 6-13 *Dwelling 4B - determining payback period for limited design modifications*

6.4.4 Implications of design modifications on construction

Modification M3 provides acceptable indoor temperatures on the design days as shown in Figure 6-9. Winter temperatures remain within the acceptable range and summer temperatures are acceptable if a fan is used to create air movement.

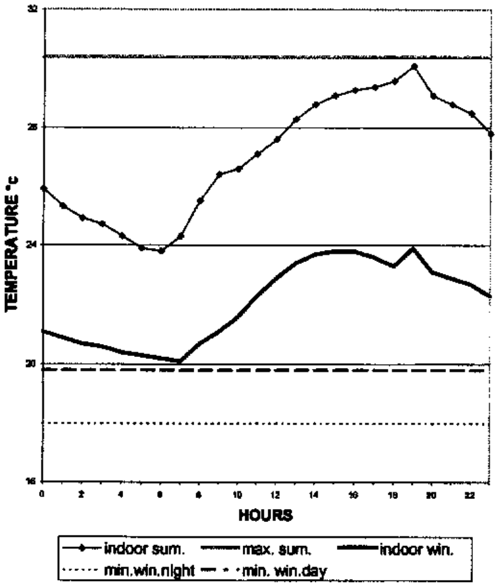

Figure 6-9 *Simulated temperatures in M3*

The building elements are appropriate in terms of both environmental demand placed on occupants and their economic viability. A plan of the dwelling is shown in Figure 6-10 and in Table 6-14, a summary of the construction elements in this appropriate solution are compared with the relevant benchmarks for energy efficient design discussed in Chapter 3.

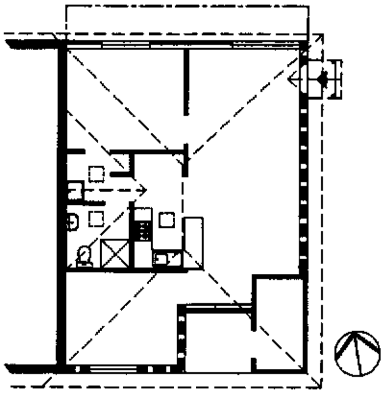

Figure 6-10 *Plan of typical appropriate dwelling*

	Appropriate energy efficient dwelling	**Benchmark**
Floor area – FA (m^2)	64	65
Total glazing area (incl. roof lights) – TG (m^2)	13.5	21.3
East or west glazing area –EWG (m^2)	0	1.5
North glazing area – NG (m^2)	6.7	16.2
Concrete volume – CV (m^3)	7.2[1]	5.0
Brick volume – BV (m^3)	8.8	15.0
TG/FA	0.21	0.33
NG/FA	0.11	0.25
Trombe –Michel wall area (m^2)	8.4	3.7
Night ventilation exhaust fan (l/s)	Not provided	1400
Total R value for wall	1.5	1.5
Total R value for roof/ceiling	2.0	2.0

Table 6-14 *Summary of construction elements in appropriate energy efficient dwelling*

In the comparison between the small, appropriate energy efficient design and the benchmarks, it emerges that the total glazing area in the appropriate design is approximately two-thirds of the benchmark glazing area. The north glazing area in the appropriate design is approximately 40% of the benchmark glazing areas. The Trombe-Michel wall area is approximately 2.3 times the benchmark area of Trombe-Michel wall. If the area of Trombe-Michel wall and north glazing area are considered together as the solar collection area, then the appropriate design has a solar collection area of approximately 24% of the total floor area compared to 31% of floor area for the benchmark.

In regard to the heat storage capacity of the appropriate dwelling, the volume of concrete is higher than the benchmark and the volume of brickwork is lower. These

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[1] The concrete volume is generally a direct reflection of the floor area. However it has increased by approximately $0.8m^3$ as a result of the method of simulation of the Trombe-Michel wall, as discussed with Mr. A. Delsante at CSIRO (refer to section 4.4.1).

volumes of thermal mass are not entirely accurate and require some interpretation as to how they may affect indoor temperature.

In relation to the volume of masonry walls, the thermal mass in the Trombe-Michel wall is included as a 100 millimetres thick concrete floor slab rather than as a 200 millimetres thick masonry wall as previously established. The internal masonry walls were in all cases simulated as 110 millimetres thick with 10mm plasterboard. However the density of the wall materials affects the heat storage capacity of masonry walls, as demonstrated when a typical dwelling was modelled with internal walls of 100 millimetres thick aerated concrete blocks, rather than 110 millimetres brick walls finished with plaster (referred to as M1 – aerated blocks). The most noticeable difference is that the indoor diurnal temperature range increases as shown in Table 6-15.

	Summer (°C)				**Winter (°C)**			
	Max	**Min**	**Mean**	**Diurnal range**	**Max**	**Min**	**Mean**	**Diurnal range**
M1	30.4	23.9	27.2	6.5	23.3	19.3	21.3	4.0
M1 - aerated blocks	31.0	23.7	27.4	7.3	23.6	19.1	21.4	4.5
M1 - carpet	31.9	23.6	28.0	8.3	24.3	18.4	21.2	5.9

Table 6-15 *Summary of the effect on temperature of heat storage capacity of materials*

With regard to the concrete floors, insulating floor coverings appear to have a similar, but even greater influence on the heat storage capacity of the concrete floor than aerated concrete blocks. The effect of limited availability of a concrete floor for thermal storage was tested when a typical dwelling was simulated with a carpet on the floor in the living and bedroom areas. The diurnal temperature range increased by 1.8 K and 1.9 K in summer and winter respectively whilst the summer mean temperature also rose by 0.8 K (refer to Table 6-15 and details in Appendix 7).

In spite of these imperfections the question now asked is whether, if building modifications similar to those made to a typical 65 square metres dwelling are made to a 50 square metres dwelling (a one-bedroom dwelling), or to an 80 square metres dwelling (a more spacious two-bedroom dwelling), acceptable temperatures would still be achieved?

6.5 Testing proposed appropriate design benchmarks

Using ratios for glazing areas and Trombe-Michel wall area as close as possible to those established in Table 6-14 for the design of an energy efficient and appropriate 65 square metre dwelling and a volume of brickwork similar to that in typical existing dwellings examined in the multiple case study in the present thesis, two other designs were simulated. The first was a typical one-bedroom dwelling[1] with a floor area of approximately 50 square metres and the other was a larger two-bedroom dwelling of approximately 80 square metres. As far as possible, modifications were made within the general constraints of a typical existing design, examined either in the multiple - case study or in a previous study carried out by the author on retirement villages (Karol 1997). The plans considered, including Trombe-Michel walls on the north side, are shown in Figure 6-11 and Figure 6-12.

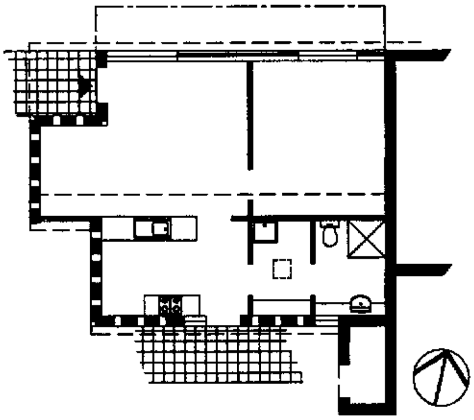

Figure 6-11 *Plan of one bedroom dwelling (50m^2)*

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[1] The design layout for the one-bedroom dwelling was identical to Dwelling 5D).

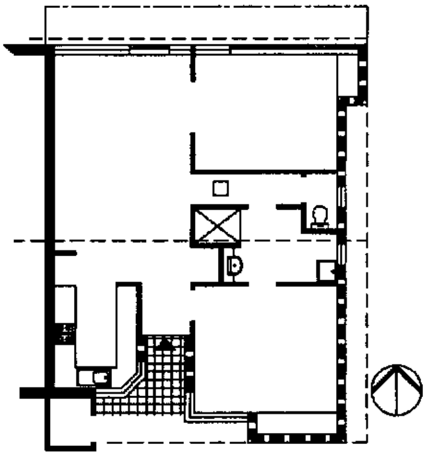

Figure 6-12 *Plan of more spacious two bedroom dwelling (80m^2)*

The construction elements adopted to improve energy efficiency in the dwellings are summarised in Table 6-16.

	50 m^2 dwelling	**80m^2 dwelling**
Floor area - FA (m^2)	47	79
Total glazing area (incl. roof lights) – TG (m^2)	10.8	17.0
East or west glazing area –EWG (m^2)	0	0.4
North glazing area – NG (m^2)	6.1	7.8
Concrete volume – CV (m^3)	5.3	8.8
Brick volume – BV (m^3)	7.0	11.6
TG/FA	0.23	0.22
NG/FA	0.13	0.10
Trombe-Michel wall area (m^2)	6.0	8.8
Total R value for wall	1.5	1.5
Total R value for roof/ceiling	2.0	2.0

Table 6-16 *Summary of construction elements in 50m^2 and 80m^2 dwellings*

6.5.1.1 Simulated temperatures on design days

For the two modified dwellings, a summary of the maximum, minimum and mean temperatures is shown in Table 6-17.

Modification	**Summer (°C)**			**Winter (°C)**		
	Max	Min	Mean	Max	Min	Mean
50m^2 dwelling	30.6	24.0	27.3	23.7	20.2	21.8
80m^2 dwelling	29.7	23.7	26.8	23.3	19.8	21.6
Acceptable temperatures	27.4	22.4	24.9	24.8	19.8	22.3

Table 6-17 *Simulated temperatures in 50m^2 and 80m^2 dwellings*

The simulated summer and winter temperatures on the design days in three energy efficient dwellings of different floor areas are shown in Figure 6-13 and Figure 6-14 respectively.

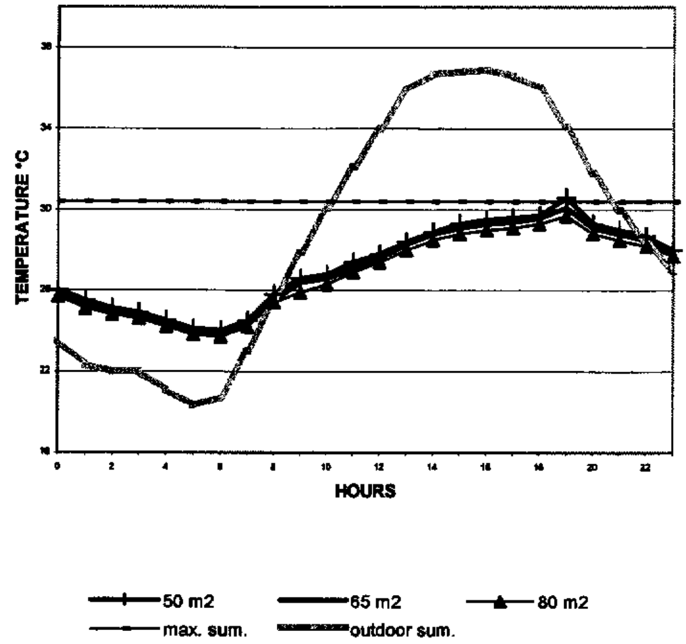

Figure 6-13 *Simulated summer temperatures in 50m^2, 65m^2 and 80m^2 energy efficient dwellings*

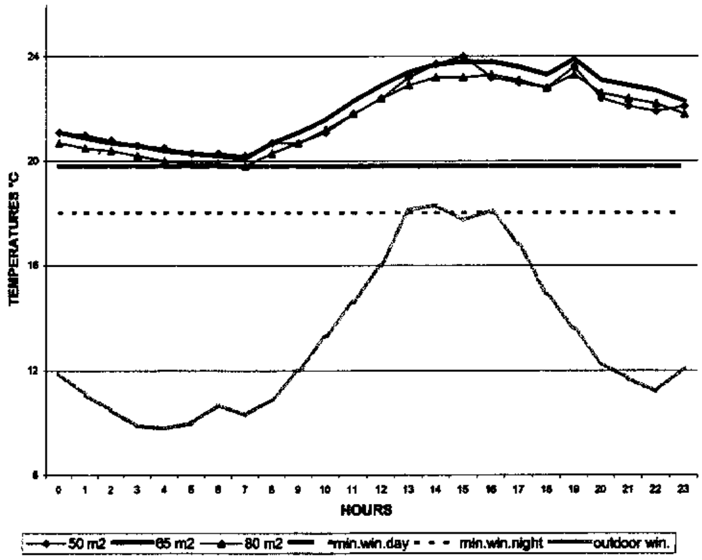

Figure 6-14 *Simulated winter temperatures in 50m^2, 65m^2 and 80m^2 energy efficient dwellings*

On the design days, these three dwellings are within the acceptable temperature range in winter but maximum temperatures still exceed the acceptable maximum temperature in summer of 27.4°C in still air. However, if the approach is taken that greater air movement in summer through the use of a fan leads to higher acceptable temperatures (maximum temperature can be increased by up to 3 K above summer maximum acceptable temperature in still air as discussed in section 3.2.3.1), the maximum summer temperature is within the acceptable range.

6.5.1.2 Testing financial implications

To establish whether a similar payback period determined for the 65 square metre dwelling (Dwelling 4B) could be anticipated in other dwellings, a one-bedroom dwelling was assessed from a development that had been designed to be energy efficient, using some of the established current benchmarks for energy efficient design. The financial assessment was carried out on a typical 50 square metres dwelling similar to Dwelling 5D. The capital outlays and capital savings of introducing the design modifications are shown in Table 6-18.

	Cost of modifications to Dwelling 5D ($)
Louvred solar pergola	+ 1674
Trombe-Michel wall (less existing wall)	+ 978
Additional wall insulation	+ 195
Room fan (supply and install)	+ 200
Delete heater	- 900
Air-conditioner required	-1200
Net total	**947**

Table 6-18 *Cost of building modifications similar to Dwelling 5D*

As winter temperatures are increased such that a heater, which is a standard inclusion in public housing for the aged, is no longer essential, the cost of the heater, including installation, is deducted from the costs of the building modifications. However, as summer temperatures in the existing dwelling exceed the maximum acceptable temperature in moving air of 30.4°C for approximately seven hours on the design day (see section 5.6.5), an air-conditioner is required. This cost is deducted from the net capital cost of the modifications.

The simulated expenditure on space heating and cooling required to maintain acceptable temperatures in Dwelling 5D as designed was established. The simulated thermal loads for heating of 15.5kWh/m^2 (see section 5.6.5.2), adjusted by an efficiency factor of 0.7 for gas heating (Fay & Treloar 1999) and assessed at a rate of 5.88 cents per kWh, indicate the cost of annual gas consumption for heating is $61. Similarly, the simulated thermal loads for cooling of 40.6kWh/m^2 (see section 5.6.5.2), adjusted by an efficiency factor of 2.4 for cooling (Fay & Treloar 1999) and assessed at a rate of 12.75 cents per kWh, indicate the cost of annual electricity consumption for cooling is $101. The total expenditure on space heating and cooling is $162. The financial implications of the modifications compared to savings in costs of energy consumption are presented in Table 6-19.

	Net capital costs ($)	Running costs ($)							
Year	0	1	2	3	4	5	6	7	8
	-947	162	162	162	162	162	162	162	162
PVF 6%	1.00	.94	.89	.84	.79	.75	.71	.67	.63
Total	-947	152	144	136	128	122	115	109	102
PV running total		152	266	401	530	652	767	876	978

Table 6-19 *Dwelling 5D - determining payback period for design modifications in $50m^2$ dwelling*

It appears that net capital costs can be recouped within approximately eight years, a much shorter time than that determined for the typical 65 square metre dwelling. This shorter pay back period is greatly influenced by the net capital cost, which reflects the need for an air-conditioner to maintain acceptable summer temperatures in the current design.

6.6 Summary of Findings

The main thrust of the findings is that without making radical changes to either the design or methods of construction, in Perth's climate thermal conditions in small medium density housing of between 50 and 80 square metres can be improved through appropriate energy-efficient design for buildings of small floor area. Indoor temperatures in winter can be raised so that mechanical heating is no longer essential. Summer temperatures can be lowered to levels close to acceptable temperatures, if fans are available for cooling the occupants. The additional costs of such improvements appear to be recoverable within the economic life of the building. The detailed findings from the simulations are summarised below.

Building design requirements to improve thermal conditions

- The traditional expectation of the long axis of an energy efficient building running east-west, with the north wall being approximately twice the length of the east and west walls, is not as desirable as long common walls between adjacent dwellings on the east or west sides. However there must be adequate area of north wall available for solar collectors.

- Direct and indirect solar collectors should be provided.
- Area of northerly glazing should form between 10% and 13% of floor area, rather than between 25% and 30% of the floor area as recommended in benchmarks.
- Area of indirect solar collectors (Trombe-Michel wall) should form between 11% and 13% of floor area.
- Total area of northerly solar collectors should be between 21% and 24% of floor area with the higher percentage applying to dwellings with smaller floor area.
- A solar pergola should be provided to fully shade solar collectors in summer but allow sun penetration in winter.
- Total area of glazing should be limited to between 21% and 23% of floor area rather than between 33% and 39% of floor area as recommended in benchmarks.
- All internal walls, including the internal leaf of external walls, should be constructed of materials having a high heat storage capacity.
- R1.0 insulation should be incorporated in external walls.

Improvements in thermal conditions

- By incorporating adequate collection areas for direct and indirect solar gain (modification M1), on the winter design day, indoor temperatures range from 19.3°C to 23.3°C. If wall insulation is added to the initial design modifications (modification M3), indoor temperatures range from 20.1°C to 23.9°C.

- By protecting the solar collection areas from summer sun (modification M1), on the summer design day indoor temperatures range from 23.9°C to 30.4°C. If wall insulation is added to the initial design modifications (modification M3), on the summer design day, indoor temperatures range from 23.8°C to 30.1°C.
- If building modifications such as double-glazing, additional thermal mass and mechanical night cooling (modification M16) are added, on the summer design day temperatures range between 23.1°C and 29.5°C and on the winter design day between 20.3°C and 24.9°C (modification M8).

Reduction in expected energy usage to maintain acceptable thermal conditions

- In typical designs, if appropriate areas of direct and indirect solar gain are provided, external wall insulation is added and all internal walls are constructed of masonry or concrete, energy consumption for space heating is no longer essential and high summer temperatures can be managed with the use of a fan.

Costs of energy efficient design

If energy-efficient design features such as a solar pergola, Trombe-Michel wall, wall insulation, double-glazing, additional indoor thermal mass walls and a night cooling fan are incorporated in typical small, medium density dwellings, net capital costs of such design features cannot be recovered through energy savings over the economic life of the building.

If limited energy-efficient design features such as a solar pergola, Trombe-Michel wall and wall insulation are incorporated in typical small, medium density dwellings and a fan is used by the occupants for summer cooling, net capital costs of these design features can be recovered through energy savings within the economic life of the building.

7. Discussion

7.1 Preamble

The hypothesis of this study was that the well-established benchmarks for energy efficient design were not appropriate in small[1], medium density housing in a temperate climate such as Perth, Western Australia. As housing for the aged was considered an important example of this form of housing, this thesis has also addressed the appropriateness of energy efficient design to housing for the aged. The following discussion revolves around the two research questions that were developed to support the main argument, namely:

Question 1 Does existing small medium density housing for the aged in Perth:

(a) satisfy the principles of energy efficient design; and/or

(b) provide acceptable indoor temperatures?

Question 2 Are current benchmarks for energy-efficient design appropriate:

(a) for small, medium density housing; and

(b) particularly for small, medium density housing for the aged?

The findings related to each question form the basis of the discussion under the following headings:

- Current designs and indoor temperatures (see section 7.2); and
- Appropriateness of current benchmarks (see section 7.3).

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[1] Small refers to buildings of floor area between approximately 50 and 65 square metres.

Each section begins with a synopsis of the findings (with key points highlighted) that form the basis of the discussion and an outline of the section structure.

7.2 Current designs and indoor temperatures

The findings of the multiple-case study show that:

- in spite of the requirements in the Homeswest design brief for consideration of energy efficiency, the majority of public housing for the aged considered in this study were not designed to be energy efficient (sections 5.2.2 and 5.2.3);
- there is no significant difference between average indoor temperatures and average energy consumption in those developments where there is an obvious attempt to design to address fundamental aspects of energy efficiency (Developments 1, 5 and 6) and other developments (sections 5.3.2 and 5.5.1);
- on the design days in winter, mean temperatures in public housing for the aged in Perth were generally below an acceptable minimum temperature (5.3.2.2);
- on design days in summer, maximum temperatures in only one dwelling were less than the acceptable maximum temperature in still air and maximum temperatures in just under three quarters of the dwellings were above the acceptable maximum temperature in moving air when a fan is used (5.3.2.1);
- if indoor temperatures were to be within the acceptable temperature range in winter, energy consumption for heating would need to be approximately double the current average level of energy consumption (section 5.6.4); and
- if indoor temperatures in still air were to be within the acceptable temperature range in summer, an air-conditioner would be required and additional energy consumption for space cooling would be required of approximately 40% of energy consumption for space heating (sections 5.6.4).

These findings are reviewed here specifically in relation to aspects of energy-efficient design (as discussed in section 3.2.4) and acceptable temperatures (as referred to in section 3.3.6). The following headings are used:

- design and energy efficient design principles (see section 7.2.1); and
- indoor temperatures (see section 7.2.2).

7.2.1 Design and energy efficient design principles

The principles of energy efficient design as discussed in Chapter 3, such as the aspect ratio of the building, adequate northerly glazing area for solar collection, shading of windows in summer, limited areas of glazing on east and west sides, insulation of the roof, walls and glazing, adequate indoor thermal mass for thermal storage and opportunity for night cooling through cross-ventilation, have been shown to be inconsistently applied in the seven developments considered in the multiple - case study. Table 7-1 summarises this inconsistency in the seven developments by indicating the developments that generally adopted particular energy efficient design principles.

	Dev 1	**Dev 2**	**Dev 3**	**Dev 4**	**Dev 5**	**Dev 6**	**Dev 7**
Aspect ratio	√				√	√	
Substantial exposure of northerly glazing for solar collection					√	√	
Area of northerly glazing similar to benchmark					√		
Shading of windows in summer	√					√	
Limited areas of east or west glazing	√						
Insulation of roof & walls						√	
Indoor thermal mass similar to benchmark							
Allowance for cross-ventilation in living area	√		√	√	√	√	√

Table 7-1 *Summary of compliance of developments with principles of energy efficiency*

The circumstances of the non-compliance are discussed below under the following three headings

- solar collection, glazing and shading (section 7.2.1.1);

- building envelope and thermal mass (section 7.2.1.2); and
- ventilation (7.2.1.3).

7.2.1.1 Solar collection, glazing and shading

In their design brief for public housing for the aged, the Department of Housing and Works sets out guidelines that address solar collection and shading of glazing. One provision requires that the long axis of an aged person's dwelling be within 15° of the east-west axis (see section 4.4.1). This provision is more restrictive than the design limitation for solar collection in a temperate climate established for the Green Village designed for the Sydney Olympic Games[1] (see section 3.2.2), although the same assumption applies that if the long axis of a building is east-west, significant areas of glazing can be provided on the northerly side for solar collection. This northerly glazing is essential for adequate passive heating of a house in winter. The other advantage of northerly glazing in a temperate climate is that it can also be shaded most readily from summer sun.

Table 7-1 shows that public housing for the aged does not conform with basic requirements for glazing for energy efficient design in a temperate climate, such as northerly orientation, adequate area and exposure of solar collectors in winter and shading of glazing in summer. Why is solar collection and shading of glazing poorly addressed in public housing for the aged?

One reason appears to be a reluctance of designers to adopt the recommended (Baverstock & Paolino 1986) aspect ratio of approximately 2:1 for the plan form of dwellings with the longer side facing north. Notwithstanding the guidelines by the Department of Housing and Works, only 24 of the dwellings (40%) monitored in the current study have the long axis east-west <u>and</u> main glazing areas on the northerly side (see section 5.2.2). Of the 24 dwellings that have these two features, 12 have

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[1] A variation between N20°W and N30°E for northerly glazing were considered acceptable (Prasad & Veale 1998).

northerly windows that are substantially shaded from winter sun. This leaves 12 dwellings (in Developments 5 and 6) with the longer axis east-west, appropriate orientation of glazing and substantial areas[1] of northerly glazing exposed to the sun. But even these two developments confirm the evidence from a survey by Rossit (1993, p.170) that suggests that:

"*there is an inconsistency between the emphasis that designers* [say they] *place on thermal performance and an attention to the factors necessary to reduce energy use*".

For example, shading of glazing is inadequate in Development 5 and the area of northerly glazing for solar collection is inadequate in Development 6. Table 7-2 provides a pictorial summary of the treatment of northerly glazing in the three developments (Developments 1, 5 and 6) where all dwellings have a substantial area of northerly glazing.

In these three developments there are obvious design factors that conflict with energy efficiency such as shading of northerly glazing in winter and lack of shading of northerly glazing in summer. In addition to design factors, there are also appropriateness factors that result in particular avoidance action being taken by occupants related to solar gain. To maintain privacy or to avoid glare, or to avoid exposure of furniture to ultraviolet light, in some cases curtains are permanently drawn across windows, in other cases plants are used to shield windows, or the skylights are partially blocked to reduce solar access as shown in Table 7-2.

The orientation and shading of glazing in the other four developments (Developments 2, 3, 4 and 7) can only be described as 'hit or miss'. This is largely the result of site planning (refer Appendix 2), where at least 37% of dwellings in any particular development have no northerly glazing. Table 7-3 provides a pictorial summary of the treatment of northerly glazing in these four developments. The lack of northerly

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[1] A substantial area of northerly glazing is considered to be an area of more than 10% of the floor area.

glazing, and/or the shading of the northerly glazing when it is provided, shows that solar collection has not been a priority in these designs.

To return to the question asking why solar collection and shading of glazing is inadequately addressed in public housing for the aged, it is clear that part of the answer depends on site planning. As discussed, the site planning in Developments 1, 5 and 6 has obviously been determined by the acknowledged principles of energy efficient design in relation to building aspect ratio and location of primary glazing, whilst energy efficient design has been less influential in the site planning of Developments 2, 3, 4, and 7. For energy efficiency, the site planning of these latter four developments would require more individual design of dwellings to respond to particular orientations in order to provide the opportunity for energy efficiency. This means that for maximum flexibility in site planning, the current practice of designing standard floor plans with fixed positions for glazing is inappropriate. Instead, each dwelling would need to be individually designed to accommodate northerly glazing, leading to increased design and construction costs.

Another part of the answer to the question regarding solar collection relates to the area of northerly glazing. In the current study, areas of northerly glazing varied widely. In the three developments where all dwellings had northerly glazing, typical ratios of northerly glazing to floor area varied as shown in Table 7-2. Development 5 was closest to the benchmark ratio of northerly glazing to floor area referred to in Chapter 3, having between 25% and 30% of floor area. This issue of area of glazing is further discussed in sections 7.2 and 7.3 in relation to the appropriateness of large areas of glazing in dwellings of small floor area and housing for the aged.

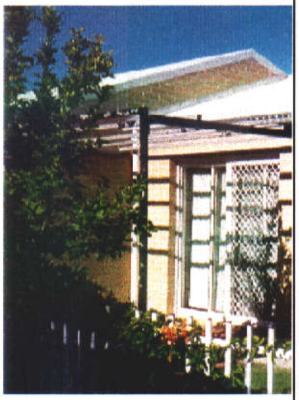
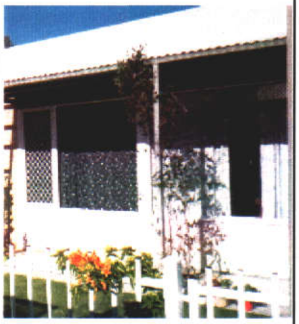
	Development 1	**Development 5**	**Development 6**
Area of northerly glazing	11% of floor area	22% of floor area	14% of floor area
Treatment of northerly glazing	Totally shaded with extended eaves  Totally shaded with extended eaves and planting 	Totally unshaded  Partly shaded with roofed pergola  Occupant keeps opaque curtains closed 	Winter access/ summer shade with a solar pergola  Partly shaded by high wall to the north of the dwelling  Occupant keeps blinds closed & creeper encouraged to grow in front of the north windows  Skylight partially blocked by occupant 

Table 7-2 *Treatment of northerly glazing in Developments 1, 5 and 6*

	Development 2	**Development 3**	**Development 4**	**Development 7**
Total number of dwellings with northerly glazing	20%	29%	38%	63%
Treatment of northerly glazing	Totally unshaded  Totally shaded with covered pergola 	Living room window shaded by eaves 	Living room window shaded by eaves  Shaded by high wall on north side of dwelling  Shaded with carports 	Living room window shaded by eaves and planting  Living room window shaded by eaves 

Table 7-3 *Treatment of northerly glazing in Developments 2, 3, 4 and 7*

The final part of the answer to the question regarding solar collection and shading relates to providing glazing that both allows winter solar collection and is protected from summer solar gain. In public housing for the aged, the typical method of shading windows, if shading is provided at all, is with eaves and verandahs. The extent of these eaves and verandahs seem to be determined primarily to address design priorities required by the design brief, such as minimum dimensions of outdoor covered areas, rather than by solar performance of glazing. Only one development in the current study (Development 6) consistently addressed the design issue of solar collection in winter and glazing protection in summer.

Planting in front of northerly glazing also impacts on the thermal performance of dwellings in all developments. Although planting such as that in Development 7 is aesthetically pleasing, it can totally shade northerly windows in winter.

Another aspect of the performance of glazing indirectly associated with energy efficient design is the insulation provided for glazing to control heat transfer. As double glazing is not commonly used in Perth (Lim & Williamson 1999) and is not a realistic financial option in public housing, undesirable heat gain or heat loss through glazing is only managed with the use of curtains, blinds or shutters as installed by the tenants.

Because of the costs involved, most dwellings in the current study have unlined curtains or vertical blinds that provide no assistance in insulating glazing (section 5.2.2). Also, the public housing authority does not install pelmets above glazing, although a curtain board is provided to enable a pelmet to be readily fitted by a tenant. Only four tenants interviewed in the current study had invested in well-insulated curtains while only one interviewee had also installed curtain pelmets. This tenant advised that she had taken this step in an attempt to reduce the heat loss from space heating through glazing in winter.

The extent of non-compliance with principles of energy efficiency related to orientation and glazing in public housing for the aged in Perth suggests that this part of the brief by Homeswest is symbolic, and not taken literally by either the Department of Housing and Works in approving designs, or by designers.

7.2.1.2 Building envelope and thermal mass

The effectiveness of using solar heat generated during the day to warm a dwelling in winter and using the coolness of summer nights to maintain a cool dwelling during the following day, depends to a large extent on the time lag provided by the insulation of the building envelope and the heat storage capacity of the indoor thermal mass (Balcomb 1984).

In regard to the building envelope, the current design brief for public housing for the aged only addresses heat transfer through the roof of the building, specifying a minimum insulation level of R2 insulation on top of the ceiling. There is no minimum insulation level specified for external walls, thus ignoring an important area of heat transfer through the building envelope. This also ignores the benchmark for insulation of external walls of R1.5 in energy efficient design (see section 3.3.4). The designers of only one development (Development 6) in the current study specified insulation for all external walls.

The general lack of wall insulation has particular significance in semi-detached dwellings that are designed in accordance with accepted practice of energy efficient design, where the long axis of a dwelling is to be east-west. In such semi-detached dwellings (as demonstrated in Development 5), the length of any common wall between dwellings on the east or west side is relatively short in comparison with other external walls. Consequently the heat transfer through the external walls will be greater when the aspect ratio is in accordance with the current accepted practice, rather than when there is a long common wall as in Development 6. The Australian Greenhouse Office (AGO) (1999) refers to improved energy efficiency in non-detached dwellings due to reduced heat transfer through shared walls or floors. Although the results in section 5.5.2 regarding the lack of association between the energy consumption per square metre in terrace type dwellings and free-standing dwellings in the current study do not support the AGO study, this most probably reflects the small number of such cases available for assessment in the current study. The design solution of northerly roof glazing in Development 6 clearly demonstrates one way of minimising the external wall perimeter, whilst complying with the aspect ratio requirement of the design brief.

As discussed in section 3.3.2.2, a building's heat storage capacity takes the form of thermal mass that is exposed to the indoor space. In the current design brief for public housing for the aged there is no specific indication of the amount of thermal mass required in a dwelling to stabilise indoor temperature. However there are requirements for a 100 mm concrete slab on ground and internal masonry walls (Ministry of Housing 1999). As the required heat storage capacity for the masonry walls is not specified, walls considered to be acceptable can be lightweight concrete blocks that have a relatively low thermal heat storage capacity compared to solid bricks. These types of lightweight blocks were used extensively in Development 1, contributing to the lack of heat storage capacity during the day in this development and influencing the high indoor mean temperature on the summer design day (section 5.3.2.1).

As demonstrated by Balcomb (1987) and seen in the results in section 5.2.3, the heat storage effectiveness of thermal mass in a concrete floor is reduced when the floor is insulated from indoor air. Floor insulation may be in the form of wall-to-wall carpet or numerous rugs and pieces of furniture. Carpet appears to be a favoured floor finish in housing for the aged in Perth. This was observed by the author in the previously mentioned study of thermal conditions in retirement villages in Perth in 1996, where eighty percent of occupants in typical retirement village dwellings were found to have a carpet floor finish. In public housing a lower percentage[1] have installed carpet, as the provided floor finish is vinyl floor tiling. If the heat storage effectiveness of the thermal mass of the concrete floor slab is reduced by not being directly

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[1] Twenty-seven percent of the dwellings examined in the current thesis had wall-to-wall carpet.

exposed to indoor air, the floor slab in housing for the aged may not be a primary source of heat storage.

The possibility of the floor being only minimally involved in the daily heat collection and heat transfer process means that internal masonry walls become particularly important as the operative areas of heat storage in these types of dwellings. As established in section 5.2.3, thermal mass incorporated in internal walls in different developments varied by approximately 30% in 50 square metre dwellings, from 5.8 cubic metres in Development 5 to 8.3 cubic metres in Development 1 (section 5.2.3). The recommended benchmark volume of thermal mass in walls is 13 cubic metres (section 3.3.4). This volume of thermal mass in walls could not be provided in dwellings of small floor area without increasing the thickness of walls and thus increasing the floor area of the dwelling. This has financial implications that are discussed in section 7.2.

Development 5 is the only development where some internal walls (the internal leaf of the external walls around the living area) are of framed construction, having very little thermal mass. It appears that the low level of thermal mass in the walls in Development 5 contributes to the high mean summer diurnal temperature range in Development 5 (sections 5.3.2.1).

As well as depending on a minimum volume of thermal mass, thermal performance also depends on how thermal mass is distributed. In dwellings for the aged, thermal mass in masonry walls is well distributed, as a small floor area is divided into separate rooms by masonry walls. In semi-detached dwellings, thermal mass in common walls between dwellings also contributes to heat storage. Where these walls are solid 230 millimetres thick masonry walls, they are particularly useful for heat storage. However because they are not as effective for noise transfer without an air cavity, they are not the construction of preference in public housing for the aged[1].

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[1] Mr. J. Thorogood, Manager Construction, Department of Housing and Works expressed this policy of the Department at a meeting on 19th May 2000.

To use thermal mass effectively for passive cooling, the thermal mass should be distributed in as large an area as practical (Ballinger 1993a). As discussed in Chapter 3, if a floor is insulated and thus does not play a major role in passive cooling, the thermal mass in the walls should be able to store heat generated during a typical summer's day. The thermal mass in the walls should be in the ratio of one square metre of available brick wall[1] for each one and a half cubic metres of air to provide adequate thermal mass for passive cooling (Baggs & Mortensen 1995).

As can be seen from the tabulation of internal volume of air and area of masonry walls for Dwellings 4A, 4B, 5D and 5E in section 5.6.1, in a typical two bedroom dwelling (Dwelling 4B) where all internal walls are of masonry, the masonry walls alone do not provide sufficient area of thermal mass to store the heat generated during the day in summer, whereas in a typical one bedroom dwelling (Dwelling 4A) there does appear to be sufficient area of thermal mass in the walls to store the daily generated heat. Table 7-4 shows the monitored and simulated diurnal temperature ranges on the design days in summer.

	Dwelling 4A	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
Summer temp. range (monitored) (K) (see section 5.6.2.2.)	7.7	5.9	10.5	8.0
Summer temp. range (simulated) (K) (see section 6.2.1)	6.8	6.7	8.9	8.0

Table 7-4 *Diurnal temperature ranges (K) in non-air-conditioned existing dwellings*

The simulated results in Table 7-4 provide some indication of the thermal effect of different building envelopes and different levels of thermal mass. A comparison between dwellings in Development 4 and Development 5 shows that, in Development 5, the greater length of external wall (between 20% and 40% longer, depending on the floor area of the dwelling) and lesser volume of thermal mass in the form of internal masonry walls (approximately 20% less) contributes to a consistently greater

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[1] The area of brickwork is based on a brick density of 1700kg/m3 (refer section 3.3.2.2) although the density of brickwork was not able to be determined in the current study.

diurnal temperature range in summer than in Development 4. The monitored indoor summer diurnal temperature ranges on the design days also reflect this difference between Developments 4 and 5, with the range in Development 5 being consistently greater. The effect of occupant behaviour is reflected in the different temperature ranges between dwellings within the two developments. For example, the occupant of Dwelling 4B closed all windows during the day and only opened them after sunset, whereas the occupant of Dwelling 4A had the kitchen window open at all times

7.2.1.3 Ventilation

In Perth's climate natural ventilation, particularly at night, is an important part of maintaining acceptable indoor temperatures in summer, as discussed in section 3.3.2.5. To maximise the use of summer breezes in Perth, inlet openings are needed, particularly on the south and west sides, to take advantage of cooling breezes (Baverstock & Paolino 1986).

In the current study, all dwellings had openings on two opposite sides of the dwelling, theoretically providing the possibility for effective cross-ventilation, at least in living rooms. This potential for night cooling is not consistently used in public housing for the aged as can be seen by the difference between minimum indoor and minimum outdoor summer temperatures on the design days (section 5.3.2.1). In every development, there was at least 4 K difference between minimum indoor temperatures and minimum outdoor temperatures, whilst in Developments 2 and 3 the difference in some dwellings between minimum indoor and minimum outdoor temperatures was over 7 K. The lack of night cooling seems primarily related to concerns about personal security.

Although operable windows are aluminium framed sliding windows with security grills installed (typical security grills are shown in Figure 7-1) and locking devices to enable the windows to be locked into an open position to provide a 100 millimetre wide vent, personal security at night was raised as a matter of concern by a number (55%) of interviewees (see section 5.4). For example, one individual (Dwelling 4D) voiced a particular nervousness about leaving windows open after dark so she closed all windows and doors at sunset. The summer temperatures in her dwelling were approximately 2 K higher on the design day than in other dwellings in the same development (see the data set in Appendix 5).

Another issue raised by two tenants (Dwellings 6G and 6F) in regard to opening windows at night was the potential noise from neighbours through adjacent windows. Noise from a radio, a television or snoring could reduce the desirability of leaving a bedroom window open at night.

Primarily because of security concerns, less than half (44%) of the interviewees in the current study (see section 5.4) tried to cool their dwellings at night by leaving windows open. This indicates that if natural ventilation is to be more effective in cooling dwellings for the aged, either the means of ventilation must be reconsidered, the physical provisions for security must be seen to be adequate or the perceptions of security must be addressed.

Perceptions of security are outside the scope of the current study, as they are more influenced by societal factors than by the building elements. The physical provisions for security on operable windows in public housing for the aged appear to be adequate but require the occupant to be actively involved in locking the window into the open position at night and fully closing or fully opening the window at other times. A different type of security screen, such as shown in Figure 7-2, that is seen to permanently protect an operable window, could increase the numbers of tenants prepared to leave windows open at night in summer.

Figure 7-1 *Typical security grills in front of doors and operable windows*

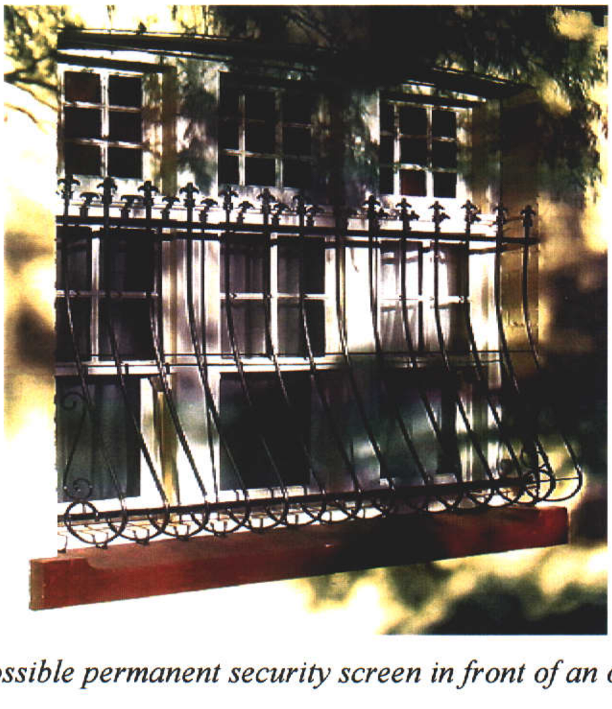

Figure 7-2 *A possible permanent security screen in front of an operable window*

A mechanical ventilation system could be installed to overcome the unreliability of breezes and concerns of the aged about personal security. According to the benchmark requirement for mechanical ventilation, the capacity of an exhaust fan for such a system would need to be approximately 1400 litres per second (see section 3.2.4). A mechanical night cooling system is not recommended in the current study for two reasons. Firstly, a mechanical night cooling system in housing for the aged would add approximately $1700 to construction costs (see section 6.5). Secondly, because of the significant number of occasions[1] when outdoor minimum temperatures do not fall below 20°C (section 4.4.2), a mechanical night cooling system would still result in dwellings being uncomfortably warm on a number of occasions in summer, as shown in the computer simulations on the design day, when night ventilation was introduced (section 6.4.2.2).

At present, to address the high indoor summer temperatures, the current study shows that portable fans are widely used in all developments, even if air-conditioners are also installed. As discussed in section 3.3.2.5, air movement increases the convective heat exchange of the body with the surrounding air. As a result, the acceptable comfort temperature can be increased for those exposed to the air movement.

7.2.2 Indoor temperatures

It is suggested by researchers such as Baverstock and Paolino (1986) and Reardon (2001) that energy efficient design in Perth leads to acceptable indoor temperatures without requiring space heating or cooling. This would largely explain why the public housing authority calls for energy efficient design in their design brief for housing for the aged.

From the discussion in section 7.2.1 it is clear that the majority of public housing for the aged is not designed to comply with the accepted principles of energy efficient

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[1] Twenty-five nights between December and March are relatively warm, with minimum temperatures remaining above 20°C, as previously established in section 4.3.2.2.

design. This raises two questions that are considered integral to the idea of appropriateness of housing for the aged and are discussed below. Firstly, are indoor temperatures in the existing dwellings within an acceptable range and thus not a cause of stress on the physically vulnerable (see section 7.2.2.1)? Secondly, could the existing designs provide acceptable indoor temperatures, without requiring a substantial use of space heating and cooling that could cause financial stress (see section 7.2.2.2)?

7.2.2.1 Current indoor temperatures, acceptable temperatures and design

In order to determine whether current indoor temperatures in public housing for the aged were acceptable, it was necessary to establish a basis for comparison. Acceptable indoor temperatures were considered from two vantage points. Firstly, the adaptive model of thermal comfort for non-air-conditioned buildings presented by de Dear and Schiller Brager (1998) (section 3.2.5) was used to compute an acceptable temperature for Perth. The computed temperature range was 19.8°C to 24.8°C in July and 22.4°C to 27.4°C in January in still air conditions. Secondly, the expected temperature in housing designed to be energy efficient in a temperate climate were considered. Researchers such as Givoni (1992), Ballinger (1993) and Baverstock and Paolino (1986) consistently refer to energy efficient housing in a temperate climate being able to provide temperatures between a minimum of 18°C in winter and a maximum of 27°C or 28°C in summer (see section 3.2.6).

In the current study the higher minimum winter temperature (19.8°C) was considered acceptable for daytime hours (8am to 9pm). The reason for this adoption was that the adaptive approach to thermal comfort was based on a compilation of acceptable daytime temperatures in office buildings, where building occupants were sedentary for much of the day (de Dear & Schiller Brager 1998). This level of activity reflects that of the more vulnerable older people likely to occupy housing for the aged and addresses some of the issues raised in section 2.3.3.1 regarding the reduced ability of older bodies to adapt to environmental cold. A minimum night-time temperature[1] of 18°C, the lowest temperature for rooms occupied by old people recommended by the World Health Organisation (1984) and also the minimum temperature considered achievable for energy efficient design in a temperate climate, was considered acceptable.

The maximum summer temperature of 27.4°C in still air as calculated for Perth, using the adaptive approach, was considered acceptable, in spite of there being no definitive recommended maximum summer temperature for older people living in their own homes. This maximum temperature could be increased by up to 3 K (to 30.4°C) to reflect the cooling effect of air movement with the use of a fan in hot conditions (Wooley 1999) as the results from the multiple - case study in the current thesis showed that fans were used in summer by all occupants. The multiple - case study also showed that the mean maximum temperature was 29.9°C in air-conditioned dwellings where the occupants claimed that they used their air-conditioner regularly[2] (section 5.5.2). As there is only 0.5 K difference between the temperatures in the air-conditioned dwellings and the suggested maximum temperature, this may be a confirmation that 30.4°C is an acceptable maximum temperature in summer, when a fan is used. However, there is insufficient data from the multiple - case study to determine at what temperature regular users of air-conditioning switched on the air-conditioner.

Chapter 5 included findings from on-site thermal monitoring of dwellings. The monitoring showed that temperatures were generally not significantly different between all seven developments, irrespective of dwelling design (section 5.3.2). The only exception to this general finding was a statistically significant difference identi-

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[1] Night-time refers to the period 10pm to 7am, as expressed by Ballinger, di Franco and Prasad (1993). However, as the day-time was considered as the period 7am to 10pm, in the current study the hourly night-time temperatures from 11pm to 6am were used in all assessments.

[2] The questionnaire asked respondents how frequently they used their air-conditioner – a response of more than 14 hours per week was considered regular use.

fied on summer nights between Development 6 and Developments 2 and 3 (section 5.3.2.1). Dwellings in Development 6 were significantly cooler between midnight and 8 am, possibly due to a combination of no direct solar gain collected during the day, reasonable levels of thermal mass, long common walls between dwellings and exposure to westerly cooling breezes due to the elevated position of the site.

The thermal monitoring carried out showed that actual maximum summer temperatures in all seven monitored developments exceeded 31.9°C (some dwellings reached 34.5°C) on the summer design day. In one development (Development 3) maximum temperatures in all dwellings exceeded 30.4°C and in the other six developments some dwellings exceeded this temperature.

Only one dwelling remained below 27.4°C (Dwelling 4H)[1], whilst 25% of dwellings (see section 5.3.2.1) remained below 30.4°C. The majority (66%) of these cooler dwellings were not air-conditioned. There was at least one non-air-conditioned dwelling that remained below 30.4°C on the summer design day in each development, except in Developments 3 and 5. These cooler non-air-conditioned dwellings had well shaded glazing, generally well shaded walls and a higher than average length of common wall with adjoining dwellings (section 5.2.3).

Thermal monitoring also showed that on the winter design day in all seven developments minimum temperatures fell below 16.7°C (some dwellings fell to 14.9°C) (see section 5.3.2). Only one dwelling (Dwelling 1E)[2] remained above 19.8°C during the day and above 18.0°C at night on the design day in winter.

There was a clear relationship between high indoor temperatures and high energy consumption in winter, with Development 1 having the highest mean energy consumption (section 5.5.1) and the highest mean indoor temperature on the design day (section 5.3.2.2). Development 6 had the lowest mean gas consumption (section

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[1] Dwelling 4H was an air-conditioned dwelling occupied by an invalid.

[2] An occupant in Dwelling 1E was ill during the winter monitoring period and had the heater on for most of the monitoring period.

5.5.1) and the third highest mean indoor temperature on the winter design day. The monitored winter temperatures in Development 6 indicated that, although the north-facing translucent roof sheeting assisted in passive heating during the day, those dwellings with translucent roof sheeting (Dwellings 6E and 6H) fell to a minimum temperature that was approximately 2 K lower than those without translucent roofing (Dwellings 6C and 6F). Development 5, the development that came closest to adopting the benchmarks for orientation and area of northerly glazing, provided the lowest minimum temperatures of all the developments and summer indoor temperatures were so high that half the occupants had found it necessary to install an air-conditioner (see section 5.3.2.1).

Based on the monitored indoor temperatures in the seven developments, it appears that older people in public housing for the aged are living in temperatures outside the acceptable temperature range. It is unclear whether this is a real choice or controlled by a lack of funds to pay for space heating and cooling or, as discussed in section 2.3.3, by a reduced sensitivity to thermal conditions or by habitual behaviour. This is in spite of the evidence discussed in section 2.3.3 that, in winter, 18°C seems to be a transition point below which cold-related stress increases and, in summer, there is a direct relationship between increased age, high temperatures and susceptibility to death from hyperthermia.

A detailed explanation of the reasons behind the acceptance of temperatures outside the acceptable range is outside the scope of issues considered in the current thesis. However, a number of interviewees mentioned that they could not afford to install an air–conditioner, so they suffered during hot periods. The results of the survey questions regarding occupant behaviour also indicate that indoor thermal conditions are not a primary motivator for older people. For example, less than half of the respondents tried to cool their dwellings on summer nights by leaving windows open (section 5.4). Females who lived alone indicated a particular concern about leaving windows open at all after dark, in spite of security screens on all operable windows. In winter only a very small number of the respondents (2%) did 'a lot' to try and keep the house warm, by maximising the amount of sunshine available indoors, by installing well insulated curtains and by closing windows when it was colder outside than inside.

7.2.2.2 Indoor temperatures and energy consumption

One of the provisions of the Ministry of Housing public housing design brief (1999) refers to using solar design to optimise energy effectiveness. However, none of the developments in the current study achieve the theoretical figure of 7.5 kWh/m2 gas consumption for heating[1] claimed by Lim and Williamson (1999) to be all that is needed to adequately heat a passive solar designed house in Perth (see section 5.5 for actual operational energy consumption). Dwellings in Development 6 have the lowest mean winter gas consumption for space heating, of approximately 12.3 kWh/m2. However, in Development 6 the indoor mean temperature on the winter design day was 18.6°C and the minimum temperature fell to 16.2°C, nearly 2 K below the minimum acceptable night-time temperature discussed above in section 7.2.2.1.

In housing for the aged, the phenomena of winter life-style[2] observed by Davison et al. (1993) is rare. The floor area is small, all the rooms are generally used and the gas heater installed is able to warm the entire dwelling. However in the current study there is an indication of the psychological importance of the feeling of warmth mentioned by Yamasaki and Tominaga (1997). In approximately one third of the dwellings monitored in winter, the <u>mean</u> temperature between 8 pm and 10 pm was dramatically increased to a temperature close to or above the <u>maximum</u> acceptable winter temperature of 24.8°C. It seems that being very warm for a short period of time is preferable to having minimum comfort temperatures over a longer period.

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[1] 5.2 kWh/m2 heating load is converted to energy consumption using an efficiency factor of 0.7 (Fay & Treloar 1999)

[2] Winter life-style refers to the behaviour of older people when they close up part of the house and live in only one or two rooms that are kept warm with space heating.

In regard to energy efficiency in summer, temperatures in all seven developments exceeded 30.4°C. Only a small percentage (19%) of dwellings in the seven developments had air-conditioners installed (section 5.5.2). Even in the majority (73%) of dwellings with an air-conditioner, the maximum temperature on the design day was allowed to exceed 30.4°C (section 5.3.2.1). Although the occupants of the air-conditioned dwellings were not asked to record when they were away from their homes, it is possible to detect, from the monitored data, the time when the air-conditioner was switched on. It is clear that occupants did allow the temperature to exceed 30.4°C even when they were home.

In Development 5, between 3pm and 7pm on the design day, the mean monitored temperature (32.0°C) in non-air-conditioned dwellings was 1.6 K higher than the maximum acceptable temperature in moving air and 4.5 K higher than the mean monitored temperature (27.5°C) in those dwellings that were air-conditioned. The mean temperature in the non-air-conditioned dwellings in Development 5 was also more than 3 K higher than the mean monitored temperature (28.8°C) in non-air-conditioned dwellings in Development 6 over the same four-hour period on the design day.

Unfortunately nearly a third (27%) of the interviewees with an air-conditioner were not prepared to reveal their energy accounts. As the number of interviewees with an air-conditioner was already small, an average figure for actual energy consumption related to the air conditioning usage from the available annual energy bills was not considered to be meaningful. The only comparison that can be made is between the theoretical annual cooling load of 5.2 kWh/m2 in energy efficient housing in Perth as referred to by Lim & Williamson (1999) and the computer modelling of annual cooling loads in typical dwellings. The simulated annual thermal load for cooling to maintain acceptable temperatures in Dwellings 4A, 4B, 5D and 5E as designed ranged from 17.4 kWh/m2 to 42.2 kWh/m2 (section 5.6.5.2), well above the theoretical annual cooling load in energy efficient housing in Perth.

In order to compare the actual expenditure on space heating and the expenditure required to maintain acceptable winter temperatures, the energy consumption in the four dwellings studied in detail was considered. The estimated actual annual energy consumption on space heating (section 5.5.1) is compared with the simulated energy consumption required for space heating in order to maintain acceptable temperatures (see section 5.6.5.2). As shown in Table 7-5, if acceptable temperatures were to be maintained, the mean gas consumption for space heating could increase in some dwellings by more than 700% (Dwelling 4B). At current prices, this would mean an additional annual expenditure for the occupant in Dwelling 4B of $114.

	Dwelling 4A		**Dwelling 4B**		**Dwelling 5D**		**Dwelling 5E**	
	kWh	$	kWh	$	kWh	$	KWh	$
Estimated actual annual gas consumption for space heating	611	36	315	19	517	30	1197	70
Simulated annual energy consumption for space heating to achieve acceptable indoor temperatures	2008	118	2214	130	1041	61	1260	74

Table 7-5 *Additional energy consumption in winter to maintain acceptable temperatures in existing dwellings*

It is rather more difficult to establish actual additional expenditure on space cooling than on space heating. The total amount of electricity used in the air-conditioned dwellings varied widely from a maximum of approximately 68kWh/m^2 in Dwelling 2C to approximately 25 kWh/m^2 in Dwelling 3A, providing little indication of the amount used for air-conditioning.

One way of trying to gauge the impact of air-conditioning on electricity consumption was to look at electricity consumption in the one development (Development 5) that had 50% of the dwellings with air-conditioning. The mean electricity consumption in those dwellings with air-conditioning was compared with mean electricity consumption in the dwellings without air-conditioners (see section 5.5.2). There was 11 kWh/m^2 more mean electricity consumption in the dwellings with air-conditioners.

In a one-bed room dwelling this translates into an additional energy expense for cooling of approximately $70 per annum[1] and in a two bedroom dwelling into an additional energy expense of approximately $91 per annum. This additional expenditure would not necessarily provide acceptable summer temperatures, but would improve current conditions. Such an increase in electricity consumption may be unaffordable to some, such as the tenant in the single bedroom Dwelling 3E, whose total annual electricity account is approximately $110. In addition to running costs, the capital cost of purchasing and installing an air-conditioner (approximately $1200) would probably be unaffordable.

An alternative indication of the potential cost of space cooling can be provided by considering the simulated energy consumption for cooling in the existing Dwellings 4A, 4B, 5D, 5E as shown in Table 7-6. This space cooling would provide acceptable indoor summer temperatures. From these figures the <u>average</u> annual cost of energy consumption for air-conditioning in a one bedroom dwelling is $73[2] and in a two bedroom dwelling is $102[3].

	Dwelling 4A		**Dwelling 4B**		**Dwelling 5D**		**Dwelling 5E**	
	kWh	$	kWh	$	kWh	$	kWh	$
Simulated energy consumption for air-conditioning to achieve acceptable temperatures in still air	343	44	491	63	795	101	1108	141

Table 7-6 *Simulated energy consumption for air-conditioning in existing dwellings*

By considering the cost of both space heating (Table 7-5) and space cooling (Table 7-6) to maintain acceptable temperatures in the existing dwellings, total <u>additional</u> annual expenditure would be a minimum of $126 in a one-bedroom dwelling and a

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[1] This figure is the product of floor area (50 m^2) by electricity cost (12.75c/kWh) by electricity consumption (11kWh/m^2).

[2] This cost is the average expenditure in Dwellings 4A and 5D.

[3] This cost is the average expenditure in Dwellings 4B and 5E.

minimum of $145 in a two-bedroom dwelling as shown in Table 7-7, plus a capital outlay of approximately $1200 for the purchase and installation of an air-conditioner.

	Dwelling 4A	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
Total additional annual expenditure on space heating & cooling ($)	(118 –36) + 44 = 126	(132-19) + 63 = 176	(61 – 30) + 101 = 132	(74 – 70) + 141 = 145

Table 7-7 *Total additional annual costs for space heating and cooling*

This magnitude of recurrent expenditure is considered financially inappropriate in public housing for the aged.

7.3 Appropriateness of current benchmarks

The discussion related to appropriateness of current benchmarks for energy efficient design in small medium density housing draws on results from computer simulations, the multiple case study in the current thesis, aspects of universal design discussed in Chapter 2 and the notion that there are unintended consequences related to improvements in energy performance of housing that Morrill (1994) calls transaction costs[1]. It is relevant to use the results of the multiple case study in this discussion, as many of the appropriateness issues in small medium density housing are related to the nature of constructing medium density housing in general, rather than to an occupant group in particular.

The findings suggest that a major part of the reason for thermal conditions in small medium density housing being outside an acceptable thermal range is related to some conflict between current benchmarks for energy efficiency and appropriateness. This conflict should not be surprising given the complexity of the building design process, its iterative nature (Papamichael & Selkowitz 1990) and the variety of expectations of building users (Shove 1995).

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[1] As discussed in section 2.4.1, transaction costs are not included in typical economic analyses used to promote energy efficiency but are non-quantifiable costs related to personal knowledge, perception, behaviour and choice.

In small, medium density housing the current benchmarks for energy efficient design may be inappropriate due to:

- a large north wall area restricting the plan configuration of a dwelling by requiring the long axis of each dwelling to be east-west;
- the extensive area of northerly glazing:
    - -limiting the options for site planning by requiring the long axis of each dwelling to be east-west;
    - -not being explicitly required to be fully exposed to winter sun;
    - -impacting on privacy of occupants;
    - -inevitably exposing furniture to ultraviolet radiation;
    - -restricting the ability to furnish rooms; and
    - -requiring a large investment in window coverings;
- the large volume of thermal mass required in walls in typical single storey buildings leading to a potential increase in gross floor area of between 5% and 6% (section 5.2.3);
- the lack of recognition of the effect of a large volume of thermal mass potentially incorporated in the ceiling in dwellings within a multistorey building; and
- the thermal storage capacity of the floor being reduced as a consequence of a substantial part of the floor area being covered in furniture and/or rugs.

In housing for the aged, the current benchmarks for energy efficient design may be inappropriate for the following additional reasons as the current benchmarks do not address universal design criteria related to accessibility, adaptability and long term affordability (Demirbilek & Demirkan 1998). The reasons include:

- the extensive area of northerly glazing:
    - -causing undesirable glare (Rubin, West et al 1997);
    - -requiring occupants to actively respond to climatic conditions;
    - -increasing the environmental demand (Lawton 1989) on occupants trying to adjust window coverings to maximise winter solar gain and eliminate direct solar gain in summer; and
    - -increasing the environmental demand (Lawton 1989) on occupants trying to maintain window coverings;
- imposing a daily environmental demand on occupants to manage any glazing on the east or west elevations in summer;
- the popularity of carpet on the floor rendering the thermal mass in the floor unavailable for heat storage; and
- the concern of older people regarding security so windows are not generally left open throughout summer nights for natural night cooling.

These findings are reviewed here by considering whether small medium density housing in general, and housing for the aged in particular, may have appropriateness criteria not evident in typical Australian suburban houses. The following headings are used:

- Appropriateness in small medium density housing (see section 7.3.1); and
- Appropriateness in housing for the aged (see section 7.3.2).

7.3.1 Appropriateness in small medium density housing

Findings from the computer simulations of a benchmark compliant energy efficient dwelling (section 6.2) show that the most obvious design features of such a dwelling (shown in Figure 1, Chapter 6) are:

- a plan with the long axis east-west;
- a large north wall area;
- glazing to more than half the area of the northerly wall; and
- thick internal walls in single storey dwellings.

There is an interaction between these design features and the resultant site planning, internal planning and occupant use, as indicated in the following discussion.

7.3.1.1 Long axis east-west and north wall area

There is general consensus (Balcomb 1987, European Commission Directorate General XVII 1999, Reardon 2001) that it is desirable to have the long axis of a dwelling running approximately east-west with the area of northerly glazing maximised. But in medium density housing developments this orientation can result in a lack of flexibility in site planning.

The lack of flexibility in site planning can be seen particularly in the site planning for Developments 1 and 5 (refer to plans in Appendix 2), even though the area of north wall in both these developments was less than the benchmark area of north wall. All the dwellings within these developments are parallel, with major windows facing north. On sites that are relatively small, such as the site for Development 5, parallel dwellings inevitably result in outdoor public thoroughfares being close to northerly windows, thus creating problems of privacy.

Computer simulations reported in Chapter 6 show that energy-efficient design of small buildings does not require that the long axis of the building run in the east-west direction. The long axis of a building can run in any direction, provided that there is an area for northerly solar collectors of between 21% and 24% of the floor area (compared with the benchmark requirement for northerly wall area of between 49% and 60% as referred to in section 3.3.4) and that these solar collectors are fully exposed to winter sun and protected from summer sun.

In small, medium density dwellings, a large north wall area equivalent to approximately half the floor area not only places a major constraint on site planning but also results in short common walls between semi-detached dwellings. Consequently there is a greater external wall area that in turn leads to greater heat transmission gains and losses.

7.3.1.2 Northerly glazing

There is no recognition in the benchmarks for energy efficient design that in medium density dwellings of small floor area, the physical requirement for a large area of northerly glazing may be inappropriate for reasons of privacy and general liveability.

The effect of large areas of northerly glazing on occupant privacy in medium density housing in Australia has been identified at Newington, the accommodation village constructed for the athletes at the 2000 Olympics in Sydney. In analysing the reasons for poor energy performance in winter of energy efficient housing projects, the developers[1] of Newington recognized that where northerly glazing faced a public thoroughfare that permitted visual intrusion, occupants would tend to prefer to protect their privacy than benefit from solar collection in winter. Similar occupant concern regarding privacy was also identified in the multiple case study carried out in this thesis, even though the area of northerly windows were generally smaller than the area required by the benchmarks. This can be identified as a transaction cost of energy efficient design.

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[1] Ms. M. Atkinson, National Environment Manager with the developer, Bovis Lend Lease, discussed this issue at the "Breaking Frontiers" joint IEA, RAIA, Property Council conference in Perth, 28th March 2000.

To protect privacy, window coverings are most commonly installed. The types of window coverings in housing range from the transparent to the heavily insulated and seem to respond to fashions of the day. However only transparent window coverings do not inhibit passive heating from direct solar radiation and can provide privacy during the day.

If window coverings are opaque, only the air between the window covering and the glazing is warmed by direct solar radiation. In this situation, if there is no box pelmet, the warm air rises, circulates into the room and draws cooler air in from the bottom of the curtain. At night this circulation pattern is reversed, as the air close to the window becomes cooler and sinks to the floor, dragging warm air down on the face of the window and leading to a draught in the room (Aynsley 1996). This form of heat transfer in winter does not contribute to effective heat storage and is insufficient to passively heat a dwelling in winter. In the multiple case study in this thesis, none of the northerly windows adjacent to a public thoroughfare were provided with transparent window coverings that enabled solar collection whilst providing privacy for the occupants. Vertical blinds, opaque fabric curtains or roller blinds were the most common form of window covering. These window coverings were detrimental in terms of solar collection, but also inadequate in reducing undesirable heat transfer through the glass at night in winter and during the day in summer.

Though transparent curtains afford privacy during the day and permit direct solar radiation in winter, they do nothing to improve thermal comfort at night in winter and during the day in summer. To minimise thermal discomfort from glazing[1], well-insulated curtains are required to overcome the effect of thermal radiation (Szokolay 1997). In both summer and winter, radiation from a large area of glazing causes discomfort. In buildings of small floor area having a large area of northerly glazing, occupants inevitably will be sitting close to such glazing. If discomfort is to be avoided, window coverings such as lined curtains, extending between a box pelmet

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[1] In the current study glazing refers to single glazing, the prevalent glazing used in housing in Perth.

and a projecting window sill are necessary. Such curtain installations are expensive, require maintenance and can be awkward to adjust across wide areas of glass. Consequently they are not a standard feature of homes in Western Australia and in the multiple case study in this thesis, only one occupant had invested in such window coverings.

Another transaction cost of large areas of northerly glazing is the deterioration of furnishings. Pryor (1984) recorded that in energy efficient public housing where the floor area in the living space was small, a large percentage of the floor area was covered with furniture or rugs. Inevitably the furniture was exposed to winter sun through the northern windows. The occupants were concerned particularly with the bleaching of timber furniture. In the multiple - case study conducted for this thesis, similar concerns about ultraviolet light on timber and upholstery were expressed by occupants.

In dwellings of small floor area, extensive glazing on the north wall restricts internal planning. This can be considered as a further transaction cost, as the choice of furniture layouts in rooms on the north side becomes limited and built in fixtures such as wardrobes and kitchen benches cannot abut the north wall.

An additional aspect of solar collection in dwellings of small floor area is related to the area of exposure of glass. In order to have sufficient area of collection for solar radiation in dwellings of small floor area, <u>all</u> the northerly glazing area needs to be exposed to winter sun. Conversely, in summer, <u>all</u> the glazing needs to be shaded. The traditional way of shading glass from summer sun is to provide eaves of 450 or 600 millimetres. However these eaves are, at best, only effective as a shading device between approximately mid-November to the end of January. With only typical eaves for shading, in February and March the sun shines through glass that is close to floor level. Occupants would be expected to use blinds or curtains to block out solar radiation at these times.

7.3.1.3 Thermal mass for heat storage

For energy efficient design in a temperate climate, thermal mass is required to serve as a collector of solar radiation and thus as a desirable heat source in the evenings in winter and as a heat sink during the day in summer (Givoni 1992). If the thermal mass is to function as a heat source and as a heat sink, it must remain accessible to the indoor air. In addition, in a temperate climate, the thermal mass must be of a thickness that enables the heat flow to change direction from being absorbed by the thermal mass during the day to radiating from the thermal mass at night (Balcomb 1987). Ideally, in a temperate climate a thickness of between 60 and 100 millimetres is recommended if the thermal mass is exposed to indoor air on one side only. In dwellings of small floor area, there are particular issues with providing:

- an adequate volume of thermal mass in single storey dwellings;
- a useable thickness of thermal mass; and
- contact between the indoor air and the thermal mass.

In single storey dwellings, the typical volume of thermal mass in brick walls is between 55% and 60% of the benchmark volume of thermal mass (section 5.2.3). One way of increasing the volume of this thermal mass to benchmark levels is to increase the thickness of internal walls. If this is done, the gross floor area of a dwelling must be increased by up to 6% (section 5.2.3). This increase in gross floor area would add significant costs to medium density housing, both in terms of increased materials and in terms of additional land area for such developments. To achieve the benchmark levels of thermal mass, some walls must be 330 millimetres thick. However, as already discussed, if internal walls are greater than approximately 200 millimetres thick[1], the thermal effectiveness of the walls in the daily heat transfer cycle is less than optimum as some heat continues to be absorbed by the thermal mass in the walls even after the air in the room cools down and it is desirable to utilise the heat stored in the wall to heat the room (Balcomb 1987).

Some improvement in heat storage capacity would be achieved in semi-detached dwellings by constructing thicker common walls between dwellings, rather than cavity walls as is the current practice. However, acoustic privacy would have to be maintained.

Another way of increasing the heat storage capacity of internal walls is to consider whether higher density materials can be used in the construction of internal walls. Walls could be of concrete instead of brick, as concrete has approximately 1.4 times the thermal capacitance of brick (NatHERS Chenath data file 1999). Computer simulation (Appendix 7) indicates that if internal 110 millimetres thick brick walls with 10 millimetre plasterboard either side are replaced with 150 millimetre concrete walls, indoor thermal conditions are improved. Maximum summer temperatures in particular are reduced. They were shown to fall by 1.5 K. A similar improvement in temperature was found when the internal 110 millimetres thick brick walls were replaced with 220 millimetres thick brick walls with rendered hard plaster both sides instead of plasterboard. In this thesis, an in-depth analysis of thermal properties of specific materials has not been pursued, as this is considered to be outside the scope of the hypothesis.

In dwellings within a building of two or three storeys[2], total thermal mass of concrete in the floor and ceiling is more than double the benchmark for required volume of

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[1] The 200 mm thickness assumes that the walls are in contact with indoor air on both sides. Where walls are in contact with indoor air on one side only, 100 mm is effective in storing and releasing heat in a 24-hour cycle.

[2] The assumption in this discussion is that medium density housing includes single storey buildings and buildings of 2 or 3 storeys. In 2 or 3 storey buildings it is assumed that floors are of concrete and the upper floor slab forms the exposed ceiling of the dwelling below.

concrete. The results of computer simulation of a dwelling on the lower level of a two storey building with a concrete floor and concrete ceiling (section 6.4.2.3) suggest that acceptable temperatures can be achieved in summer, but a slight increase in the area of solar collectors may be required to achieve acceptable indoor temperatures in winter. This is a significant finding for energy efficient design in small, medium density housing.

In the multiple - case study in the current thesis, there were some indications of the thermal effect of a concrete floor slab between dwellings. Dwellings on the lower level of a two storey building (Development 2 was the only example in the multiple case study) were considerably cooler in summer than other non-air-conditioned dwellings (refer data base in Appendix 5). Unfortunately, as these monitored dwellings had no northerly glazing, there is no data to assess the thermal storage performance of the additional thermal mass in winter.

In dwellings of small floor area it may be difficult to maintain contact between the indoor air and all the thermal mass. The thermal mass in the floor may frequently not be accessible to the indoor air. In the multiple case study in the current thesis, it was observed that in many dwellings numerous pieces of furniture and/or floor coverings inhibited the contact between the indoor air and the thermal mass. It may be that the walls, and perhaps the ceiling in multistorey buildings, provide the primary area of thermal storage in small, medium density housing.

7.3.2 Appropriateness in housing for the aged

In addition to some elements of current benchmarks being inappropriate in small, medium density housing in the Australian context as discussed in section 7.3.1, there are further inappropriate elements specific to housing for the aged. These additional inappropriate elements have been identified via the opinions expressed by tenants of public housing for the aged in the multiple case study (Chapter 5), a study of retirement village housing by the author (Karol 1997) and from a recognition that the demands of the physical environment in housing for the aged must be able to accommodate falling personal competence (Lawton 1989).

The elements that are inappropriate in housing for the aged do not address three criteria of universal design referred to by Demirbilek and Demirkan (1998), namely accessibility, adaptability and affordability. The way these three criteria may be compromised by the current benchmarks is identified in Table 7-8. As discussed in section 2.3.2, in the current thesis the concepts of accessibility and adaptability expressed by Demirbilek and Demirkan are extended to address thermal comfort conditions, as well as the traditional notion of dwellings being free of physical barriers.

Compromised universal design criteria	**Benchmark**	**Inappropriateness in housing for the aged**
Accessibility to winter warmth	Extensive northerly glazing	Curtains closed across northerly glazing in winter due to • sensitivity to glare • high environmental demand to adjust for solar gain • high environmental demand to maintain window coverings
Accessibility to daylight	Extensive northerly glazing	Curtains closed across northerly glazing in winter due to sensitivity to glare
Accessibility to daylight	Any east or west glazing	External shading devices closed throughout the summer due to high environmental demand to adjust for solar protection
Accessibility to winter warmth and summer coolness	Thermal mass in the floor	Wall-to-wall carpets are popular
Accessibility to winter sun exposure	Northerly glazing fully exposed to winter sun	Typical eaves shade part of the glazing
Adaptability for summer cooling	Natural ventilation for night cooling	Windows not left open on summer nights due to security concerns
Affordability of summer shading	Northerly glazing fully protected from summer sun	Fixed eaves inadequate to deal with shading of glazing from summer sun but high environmental demand to adjust external shading devices. Consequently a solar pergola is required.

Table 7-8 *Relationship between universal design criteria as applied to thermal comfort and current benchmarks for energy efficiency*

If direct solar gain is to be considered as the only source of winter heating in housing for the aged, older people may not gain the benefits of such heating. Large areas of glazing exposed to the sun inevitably lead to indoor glare that some older people find painful (Rubin et al. 1997). Consequently curtains may be drawn across northerly glazing.

Large areas of glazing also inevitably mean large and unwieldy window coverings. During interviews in the multiple case study, a number of issues were raised in relation to large curtains. Unless the system for drawing window coverings is mechanised, the old-old found difficulty in opening and closing wide window coverings. There was also concern expressed about being able to keep wide, long curtains clean and about the expense of having such curtains professionally cleaned. The issue of large curtains flapping in the breeze and knocking over small items was also raised as a disincentive to open large windows.

Large areas of glazing provide good day lighting, but if the glazing faces the sun and therefore curtains are drawn, day lighting as well as passive heating is compromised. Thus an alternative means of natural lighting and an alternative means of capturing solar radiation should be considered.

The general reasons for limited glazing on east and west elevations are because of high solar heat gain on the east and west sides in summer (Spencer 1976) and the difficulty of shading such glazing from the low altitude sun in summer, without blocking views and daylight (Phillips 1996). The shading devices on the east and west must inevitably be adjustable, external devices that require opening and closing on a daily basis in summer. Otherwise, when the glazing is not exposed to sunlight, the glazing cannot be effectively utilized for natural light, views or night ventilation.

For the old-old, this necessity to manually adjust external shading devices may exceed their physical abilities. Thus, provisions for mechanical adjustment of shading devices on the east and west sides becomes a necessity if housing for the aged is to satisfy universal design criteria.

As discussed, fixed eaves on the northerly side are inadequate to both accommodate maximum winter sun and shading throughout the summer. A solution to this inadequacy is to provide a solar pergola to northerly glazing. This building element will not create an environmental demand on older people but it adds to the construction cost. The net additional cost in public housing for the aged would be approximately 1.5% of the total construction cost[1].

In housing for the aged the popularity of wall-to-wall carpet was noted (Karol 1997). The reasons for the popularity included the perceived warmth underfoot in winter, the ease of vacuuming carpet and the perceived lower likelihood of slipping than on a polished surface. Consequently the thermal mass in the floor was virtually removed from its role as a heat collector.

Benchmarks for energy efficient design in a temperate climate call for night cooling via natural ventilation in summer. In the Perth climate Baverstock and Paolino (1986) refer to a desirable night ventilation rate of 10 air changes per hour. However, irrespective of local wind velocities and external temperatures, the elderly have a security concern with leaving windows open throughout the night to maximise night cooling in summer. As a result, even when external temperatures are low on summer nights and the wind could be used for cooling, the multiple case study showed that less than half the occupants of aged person's housing indicated they kept their windows open on summer nights. Those who claimed to keep windows open in some cases only kept the windows open 100 millimetres, a position determined by the security locking on the sliding windows. This area of opening is generally inadequate to enable a dwelling to be cooled at night.

7.4 Answering the research questions

The discussion in this chapter is summarised by presenting succinct answers to the two research questions.

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[1] Mr. J. McFarlane, estimator at the Department of Housing and Works in 2001, confirmed this amount based on the average cost of aged persons' units constructed by the public housing authority.

Current designs and indoor temperatures

Small, medium density housing for the aged in Perth is not designed in accordance with energy efficient design principles, nor in accordance with Baverstock and Paolino's (1986) benchmarks for energy efficient design. In spite of the provision of space heating in each dwelling, indoor temperatures are well below acceptable temperatures in winter. Only 19% of dwellings have an air-conditioner. Consequently in summer the acceptable maximum temperature is frequently exceeded.

Appropriateness of current benchmarks

Current benchmarks for energy efficient design related to aspect ratio, north wall area, source of passive heating, area of northerly glazing and area of total glazing all require modification if they are to be applicable to small, medium density housing, including housing occupied by the aged. In addition, shading of glazing, the provision of thermal mass and dependence on night cooling in summer require particular attention in small dwellings occupied by the aged.

8. Design strategy

8.1 Preamble

The hypothesis of the current study was that the well-established benchmarks for energy efficient design were not appropriate in small, medium density housing in a temperate climate such as Perth, Western Australia. Having addressed the two research questions that were developed to support the main argument, it is now possible to formulate the final stage of this thesis. In that final stage it is suggested that a new design strategy could be developed that is appropriate in typical, medium density housing, including housing for the aged where the floor area is between approximately 50 and 80 square metres.

The design strategy proposed is developed and discussed in section 8.2 and a summary of the key findings that support the strategy are presented in section 8.3.

8.2 Design strategy

The findings from the multiple case study and the discussion of the appropriateness of current benchmarks for energy efficient design, suggest that acceptable indoor temperatures in summer and winter can be achieved in small, medium density housing without the use of space heating and cooling, if the principles of energy efficient design are integrated with appropriateness criteria for housing for the aged. The specific design recommendations that reflect this integration in a climate such as that in Perth are that:

- the aspect ratio requiring the long axis of a dwelling to be east-west is unnecessary (section 6.6) but a wall facing between N30°E and N20°W should be provided;

- the area of northerly solar collectors should be between 21% and 24% of the floor area;

- passive solar heating should be provided by a combination of direct and indirect means with glazing for direct solar gain limited to approximately 13% of floor area;
- a solar pergola should be provided on the northerly side of each dwelling in association with solar collectors;
- total area of glazing should be between 21% and 23% of floor area;
- glazing areas should be oriented north and south unless a mechanised external shading device is provided to east and west glazing;
- external walls should have a total minimum insulation level of R1.4;
- the combined roof and ceiling insulation should have a minimum insulation level of R2.7[1];
- all internal walls should be of masonry or concrete; and
- a fan for personal cooling should be provided.

The manner in which a response to appropriateness in energy efficient design has been developed is discussed in section 8.2.1. A proposition for expressing energy efficient design parameters as performance provisions, as well as prescriptive design solutions for passive heating and cooling in a temperate climate, are discussed in section 8.2.2. This is followed by considering the implications of the design strategy for energy efficient design in small, medium density housing for the aged in section 8.2.3.

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[1] This is a new requirement in building regulations (ABCB 1996). However, the computer simulations in this thesis adopted the level of insulation in the monitored dwellings (R2.0), thus providing a combined roof and ceiling insulation of approximately R2.4.

8.2.1 Dealing with appropriateness

The current thesis has shown that if particular physical design features are incorporated in small, semi-detached, medium density housing, the indoor thermal conditions can remain within an acceptable range, without the need for space heating and cooling. Overall, to achieve energy efficient design, to meet the needs of physically and financially vulnerable older people and to enable the site planning and form of typical, medium density aged persons housing developments to be integrated into suburban Australian housing developments, some particular design features are adopted.

Only two of these design features are likely to be identifiable to the casual observer. One is the incorporation of indirect solar collection for passive heating and the other is a solar pergola associated with solar collectors. Both features contribute to energy efficiency and are a response to the need for appropriateness in small, medium density housing for the aged.

The introduction of indirect solar collection and the consequential reduction in northerly glazing area leads to:

- a reduction in the potential loss of privacy;
- a reduction in solar glare;
- a reduction in heat losses and heat gains through glazing protected only by poorly insulated curtains or blinds;
- a reduction in the cost of investment in and maintenance of curtains or blinds;
- a reduction in environmental demand on the occupants;
- a reduction in the exposure of furnishings to ultraviolet light; and
- an increase in flexibility of furniture layouts in rooms.

The introduction of minimal eaves and a solar pergola on the northerly side of a dwelling enables:

- virtually the entire area of solar collectors to be exposed to direct solar radiation in mid-winter; and
- the solar collectors to be shaded in summer without depending on the action of the occupant.

It could be argued that the two design features referred to above - indirect solar collectors and a solar pergola - significantly increase the capital costs of construction and thus conflict with the affordability component of universal design. In the current thesis (section 6.4.3.4), it has been shown that the savings related to the elimination of space heating compensate for the net additional capital expenditure of incorporating energy efficient design features within 19 years, well within the economic life of the dwellings[1]. Thus the expenditure is justified as being affordable.

A further six design features, less physically conspicuous than the two features mentioned above and involving little, if any, capital expenditure should also be incorporated in medium density housing for the aged. Each of these features, listed below, have particular dimensions of appropriateness as discussed. The six design features are:

- the main axis of a dwelling not being prescribed;
- glazing predominantly on two opposite sides of a dwelling;
- total glazing area of approximately 23% of floor area;
- insulation incorporated in external walls;

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[1] The economic life of public aged persons housing is at least 50 years, as advised by Mr. J. Thorogood, Manager Construction, Ministry of Housing at an interview 6 October 1999.

- all internal walls having a high heat storage capacity; and
- each dwelling having a fan.

As it is proposed that the main axis of a dwelling can have any orientation, there is greater flexibility in site planning and internal planning of individual dwellings, even with basically standardised repetitive designs as currently produced, than would occur with standardized, repetitive designs which are typical at present. Another distinct benefit of removing the benchmark aspect ratio that traditionally led to a long, narrow floor plan with short common walls in small, semi-detached dwellings is that the length of the common wall between dwellings can be increased, thus reducing the thermal heat transfer through external walls and assisting in achieving acceptable indoor temperatures. A possible consequence of the greater emphasis on flexibility in planning could be an additional emphasis on the design of individual, rather than standardised, dwellings although this is not construed as an outcome of the approach taken in this thesis, as non-standardised, non-repetitive designs could lead to marginally higher design fees and higher construction costs.

In dwellings of small floor area, glazing predominantly on the north and south sides provides access to cross ventilation in summer and adequate day lighting throughout the year. The maximum distance from a window is approximately four metres. At this distance occupants would be exposed to summer cooling breezes (Aynsley 1996). The maximum distance from a source of natural light is approximately three metres (due to strategic placing of skylights), thus providing daylight to all areas. None of the glazing introduces direct solar radiation[1] indoors in summer so there is no environmental demand on occupants to draw curtains, thus blocking out access to

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[1] The solar pergola blocks direct solar radiation in summer from the north and shading of glazing on the south side is considered to be non-essential for locations located south of latitude 20° south (ABCB 1996) as such glazing is only exposed to direct solar radiation in summer early in the morning and late in the afternoon, when the intensity of solar radiation is low.

daylight. On the other hand, if east or west glazing was provided occupants would be required to make daily adjustments of shading devices in summer if natural lighting was to be utilised for even part of the day.

By limiting the total glazing area to 23% of floor area, heat gains and heat losses through the glass, even when no blinds or curtains are provided, are not excessive as shown in computer simulations. This glazing area is more than double the regulatory minimum area of glazing required for natural lighting (ABCB 1996) and is typical of the area of glazing in the majority of dwellings in the multiple case study. In addition, the size of any one glazing panel can be limited to a maximum size of 2.1 metres high by 2.1 meters wide, thus controlling the investment cost and maintenance costs of window coverings for privacy. In addition, the limited size of openings reduces the difficulty of moving curtains.

Although the energy efficiency requirements in the building regulations generally require that external walls in temperate climatic zones such as Perth have a minimum total insulation level of R1.4, walls that have a surface density of at least 220kg/m^2 are exempt from this insulation requirement. This exemption is based on the ability of walls with high thermal mass to slow down heat transfer through conduction in mild climates (CSIRO 2000a). This means that established forms of construction such as cavity brick walls are not required by regulation to incorporate insulation. However, computer simulations in the current thesis show that <u>mean</u> temperatures in a 65 square metres medium density dwelling can be reduced by 0.2 K in summer and increased by 0.8 K in winter (section 6.4.2.1) if R1.0 insulation is incorporated in cavity brick walls.

The requirement that all internal walls have a high heat storage capacity allows for necessary absorption of solar radiation in winter, and necessary absorption of indoor heat gain in summer. The heat storage capacity of internal walls is particularly vital in small, single storey dwellings for the aged where the thermal mass of a concrete floor may not be available. As small dwellings by their very nature have relatively small areas of internal walls, it would be desirable if either the material of construction of the walls had a very high thermal capacitance or the walls were thicker. This thesis suggests that an increase in gross floor area of dwellings resulting from thicker internal walls is not financially viable, but consideration could be given to using materials with higher thermal capacitance in the walls.

Finally, the computer simulations show that acceptable temperatures in still air in summer cannot be consistently achieved in small, medium density dwellings, even if natural ventilation is utlized throughout the night. Having established previously that security concerns inhibit the use of natural ventilation at night in housing for the aged anyway, it is apparent that a fan is required to maintain personal comfort on those occasions in summer when indoor temperatures exceed 27.4°C.

8.2.2 Performance based and prescriptive solutions

It is now possible to prepare a design strategy that draws together the two fundamental strands of the current thesis, namely energy efficient design in a temperate climate and appropriateness of energy efficient design in small medium density housing, including housing for the aged. The design strategy includes only those aspects of energy efficient design[1] that have been identified through the multiple case study and through computer simulations as requiring particular attention in regard to thermal conditions in small, medium density housing for the aged.

The design strategy that has been developed proposes functional objectives and prescriptive design solutions as shown in Table 8-1.

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[1] Those aspects of energy efficient design related to choice of light fittings, choice of hot water services and choice of white goods, including cooking equipment, have not been included.

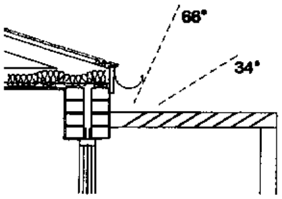
	Functional Objective	**Prescriptive Design Solution**
1	General requirements for siting Each dwelling shall be sited so that a sufficient area of solar collectors can be exposed to direct solar gain in winter	Each dwelling shall incorporate an external north facing wall oriented between 30° east of true north and 20° west of true north
2	General requirements for solar collection in a building Each dwelling shall be provided in winter with adequate areas of unshaded solar collectors for direct and indirect solar gain to maintain acceptable indoor temperatures in winter	Each dwelling shall provide in winter unshaded: • indirect solar collectors on the northerly wall having an area of between 11%-13% of floor area • glazing areas on the northerly side of between 10%-13% of floor area • total area of northerly solar collectors between 21%-24% of floor area with the higher percentage applying to smaller dwellings
3	General requirements for protection of solar collectors and glazing Each dwelling shall have all solar collectors and other glazing fully shaded between 7.30am and 4.30pm (solar time) during the three months when mean daily hours of sunshine are highest	Northerly solar collectors shall be protected from direct solar gain in summer by a fixed shading system such as that shown in Figure A. If fixed shading devices cannot adequately shade glazing from direct solar radiation, shading devices shall be operable with a device that creates low environmental demand on occupants.  Figure A
4	General requirements for limitation of glazing area The total area of glazing in each dwelling shall be limited to the area required to provided adequate natural light to all rooms during daylight hours	Total area of glazing shall not exceed 23% of the floor area. Glazing shall generally be oriented north & south.
5	General requirements for insulation Each dwelling shall be adequately insulated against heat transfer to minimise excessive indoor heat gain in summer and indoor heat loss in winter	• Total roof/ceiling insulation shall be at least R2.7 (regulatory minimum) • External walls shall have a minimum total insulation level of R1.4 (regulatory minimum)
6	General requirements for indoor thermal mass Each dwelling shall be provided with sufficient thermal mass in internal walls to help stabilize indoor temperatures	Floors shall be of concrete and if a dwelling is constructed above another dwelling the underside of the floor slab shall form the ceiling of the lower dwelling. All internal walls, including the inner leaf of external walls, shall be of concrete or masonry.
7	General requirements for indoor air movement In each dwelling air movement shall be adequate to enable sufficient convective heat exchange between the occupants and the surrounding air	A fan shall be provided in the living area in each dwelling

Table 8-1 *Design strategy for energy efficiency in small, medium density housing occupied by the aged*

The functional objectives are applicable to small, medium density dwellings in general and are included for two primary reasons. Firstly, the functional objectives elucidate the intent of each design solution in terms of passive heating and cooling and secondly, functional objectives provide for flexibility in design solutions, thus encouraging innovative thinking. The prescriptive design solutions are applicable to small, medium density dwellings, including housing for the aged, with floor areas between 50 and 80 square metres.

Table 8-1 is discussed below in terms of why each prescriptive design solution has been adopted and how the design solution addresses heating and/or cooling requirements in energy efficient design.

8.2.2.1 Heating

In spite of gas space heaters being installed in all dwellings in the multiple case study in the present thesis, indoor temperatures were well below acceptable levels in winter because of limited use of the space heaters. The position has been adopted that the principles of energy efficient design, when overlaid with dimensions of appropriateness, can remove the need for space heating. If acceptable minimum temperatures are to be achieved in winter without the use of space heating, the building must be able to utilize an alternate form of heating. The proposed functional objectives are based on the premise that solar radiation is the alternate heat source. Thus the prescriptive design solutions discussed below incorporate this design intent.

Functional Objective 1 – General requirements for siting
Prescriptive Design Solution 1

Solar collectors must be oriented to maximise their collection potential, without being overly restrictive on site planning (that is between N30°E and N 20°W). This flexibility of orientation has only a marginal effect on the performance of solar collectors (Balcomb 1987) but provides for greater design choice.

Functional Objective 2 – **General requirements for solar collection in a building**

Prescriptive Design Solution 2

Solar collectors must also provide an adequate area of collection. Through the use of computer modelling it has been established that an unshaded area of no more than 24% of floor area was required for solar collection in winter. To address appropriateness criteria, the solar collection area should be divided approximately equally between direct solar collection through glazing and indirect solar collection, possibly with the use of a Trombe-Michel wall. The Trombe-Michel wall is a proven method of indirect solar gain (Balcomb 1984). It has a number of advantages when introduced into small, medium density housing such as:

- limiting the length of a north-facing external wall required for glazing;
- reducing the likelihood of deterioration from ultraviolet radiation of furniture fabrics that inevitably are placed close to windows;
- reducing the impact on privacy of large, glazed openings;
- easing the difficulty of internal planning when one wall is almost fully glazed;
- reducing the investment required in window coverings; and
- increasing the indoor thermal mass for heat storage.

A Trombe-Michel wall also addresses issues specific to housing for the aged, such as a sensitivity to glare and the potential difficulty of dealing with large window coverings. For effective operation, the Trombe-Michel wall requires only that the wall not be insulated with large pieces of furniture butted directly against the wall. The Trombe-Michel wall is not dependent on action from the occupier in order to function appropriately.

The possible appearance of one of the dwellings from the multiple - case study, if it incorporated both direct and indirect passive heating instead of depending exclusively on direct passive heating, is shown in Figure 8-1. The existing dwelling is shown above and the dwelling including a Trombe-Michel wall is shown below. When both direct and indirect solar collection is used, the area of glazing is similar to the area of glazing on a typical elevation in housing for the aged. This means that the size of window coverings remain manageable[1].

Functional Objective - General requirements for insulation
Prescriptive Design Solution 5

In general, the smaller the floor area of a dwelling, the higher the ratio of external wall area to floor area. As a result, the thermal heat transfer through external walls is proportionately greater in small dwellings than in larger dwellings. Consequently insulation of the building envelope has a noticeable effect in small dwellings as observed in computer simulations (Appendix 7). Further, recent amendments to the building regulations specify minimum levels of insulation for the building envelope of a house. For the Perth climatic zone, the building regulations require the total roof and ceiling insulation to provide a minimum insulation of R2.7. The building regulations also require external walls to have a total insulation level of R1.4. However, for the Perth climatic zone cavity brick walls are permitted to have no additional insulation "*due to their ability to store heat and therefore slow the heat transfer through the building fabric*" (ABCB 1996, p.30,142). In this thesis, the computer simulations show that in dwellings of small floor area, wall insulation in cavity brick walls is beneficial.

The total area of glazing has an effect on heat transfer through the building envelope, particularly when the type of glass used is single clear glass and typical curtains provide little or no insulation. Single clear glass is the standard glass used in residential

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[1] In this context manageable includes the cost of providing a window covering, adjusting the window covering and maintaining the window covering.

Figure 8-1 *Possible changes to appearance of existing dwelling (upper image) with a Trombe-Michel wall incorporated (lower image)*

construction in Perth. The multiple - case study in this thesis showed that single clear glass was exclusively used in all developments and curtains typically provided minimum levels of insulation. These factors provided further support to limiting the total area of glazing to approximately 23% the floor area, to reduce heat losses/gains through the building envelope.

Functional Objective 6 - General requirements for indoor thermal mass
Prescriptive Design Solution 6

In energy efficient design, acceptable indoor temperatures in winter depend on both solar collection and on storage of the solar energy for use at night. The results of the computer simulations demonstrate that in small, single storey, semi-detached dwellings there is generally an inadequate area of mass for thermal storage. This is mainly due to the volume of thermal mass in the walls being insufficient. It is also affected by the thermal mass in the floor not being exposed to the indoor air and thus not being available for storage of incoming direct solar gain. Consequently it is proposed that all internal walls, including the inner leaf of external walls, be of concrete or masonry. The higher the density of the wall material, the better will be the thermal performance of the dwelling. The Trombe-Michel wall, which is primarily a solar collector, also provides additional thermal mass thus contributing to the storage capacity of small dwellings.

8.2.2.2 Cooling

As air-conditioning is not a viable option for space cooling in all small, medium density dwellings for the aged, it is suggested in the current thesis that the building itself should be able to maintain acceptable temperatures in summer. The prescriptive design solutions propose four passive elements and one active element that must be addressed, if energy efficient design is to provide acceptable temperatures in summer without placing unacceptable demands on the occupants.

Functional Objective 3 - General requirements for protection of solar collectors and glazing

Functional Objective 4 - General requirements for limitation of glazing area

Prescriptive Design Solutions 3 and 4

To maintain acceptable indoor temperatures in summer it is essential that solar collectors used for winter heating are fully shaded in summer from direct solar radiation. Because of the marked changes in the sun path between summer and winter in latitudes outside the tropics (Phillips 1996), it is possible to design a fixed solar pergola on the northerly side that will totally shade the solar collectors in December, January and February (section 4.4.2).

Glazing on the east or west sides is not so easily shaded with fixed shading devices because of the low elevation of the sun in the east and west skies. As a result, the design solution recommends that east and west glazing be avoided. If glazing is provided on the east or west, a system of shading that does not place environmental demand on the occupants is required, as previously indicated.

If glazing of approximately 13% of floor area is provided on the north side and glazing of approximately 10% of the floor area is provided on the south side, a high level of day lighting can be maintained in dwellings of small floor area. This total glazing area (23% of the floor area) can provide more than twice the minimum level of natural light required by the building regulations[1] as discussed in section 8.2.1. Further, this area of glazing is similar to the glazing area in the majority of dwellings considered in the multiple case study in this thesis.

Functional Objective 6 - General requirements for indoor thermal mass

Prescriptive Design Solution 6

In a temperate climate, thermal mass is required both in summer and winter to increase the time lag and to reduce indoor temperature fluctuations. The design solution proposes that all internal walls, including the inner leaf of external walls, be of

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[1] The building regulations require the area of glazing for natural lighting to be at least 10% of floor area in habitable rooms.

concrete or masonry. However this does not provide the amount of thermal mass considered by Baggs and Mortensen (1995) as adequate to store heat generated during the day in summer. As shown in section 6.4.2.3, a substantial increase in thermal mass in a 65 square metres dwelling can reduce summer overheating but can only be appropriately incorporated in dwellings of more than one storey where a concrete ceiling/upper floor slab can provide additional thermal mass. In single storey buildings, consideration could be given to using a material for internal walls that has a higher thermal capacitance than the commonly used extruded bricks.

Functional Objective 7 - General requirements for indoor air movement

Prescriptive Design Solution 7

The active element for cooling (a fan for air movement) is necessary, as the passive elements alone cannot reduce indoor temperatures below 27.4°C. The computer simulations show that energy efficient design can reduce indoor temperatures below 30.4°C (the maximum acceptable temperature when there is air movement over the body) even when there is no cross ventilation for night cooling. This assumption was made in the simulations as it reflects the expressed concerns by those participating in the multiple case study about the lack of security if windows remain open on summer nights. The assumption also acknowledges that indoor temperatures must remain acceptable even when personal competencies may fall to the extent that the old-old may not be able to regularly open and close windows when fingers become arthritic.

To improve conditions without jeopodizing the security of occupants, the introduction of a night cooling system was considered in the current study. However to install a mechanised system was prohibitively expensive. The conclusion was that reliance on a fan to provide air movement was the most realistic way of providing acceptable thermal conditions in summer.

8.2.3 Implications of design strategy

The implications of the proposed design strategy for energy efficiency in small, medium density housing for the aged are considered from two points of view. The first viewpoint considers how the model of environmental decision-making proposed by

Coldicutt (1992) and discussed in Chapter 1 has been applied to make the design strategy acceptable, and the second viewpoint summarises how universal design elements have been addressed.

8.2.3.1 Participants in energy efficient design

By approaching the development of the design strategy for energy efficiency in small, medium density housing for the aged through Coldicutt's model of environmental decision making, it is clear that there is a line between specific design related decisions for energy efficiency and non-specific design related decisions. In the current thesis only the specific design related decisions effected by 'passive subjects ends'[1], 'active subjects ends'[2] and 'active subjects means'[3] have each been addressed.

By considering appropriateness of energy efficient design, 'passive subjects ends' have been taken into account as discussed in section 8.2.1. 'Active subjects ends' have been addressed to the extent that the basic premise of the design strategy is clearly stated. The premise is that space heating and cooling equipment is not essential for thermal comfort and thus occupants are not committed to energy bills for space heating and cooling. In addition, active subjects ends have been addressed by ensuring that the design strategy elucidates functional objectives that could be included in a design brief, as well as prescriptive design solutions that could be readily adopted by designers. 'Active subjects means' have been addressed only to the extent of financial viability within the economic life of the building. It is acknowledged that non-specific design related decision making that could impact on active subjects ends and means, such as the will of designers and developers to pursue energy efficient design are considered outside the scope of this thesis.

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[1] In Coldicutt's terms, passive subjects ends refer to the needs of those occupying energy efficient dwellings.

[2] In Coldicutt's terms, active subjects ends refers to the needs of those participating in the decisions to design energy efficient dwellings.

[3] In Coldicutt's terms, active subjects means refers to the resources required by those wanting to provide energy efficient housing.

In spite of addressing only specific design related decision making, the two government policies referred to in section 1.2 – one to encourage ageing in place and the other through building regulation to improve energy efficiency in housing - have been made achievable by the prescriptive design solutions offered in the current thesis.

8.2.3.2 Addressing universal design

The four design criteria for universal design, namely accessibility, adaptability, aesthetics and affordability (Demirbilek & Demirkan 1998), as far as they relate to thermal conditions, have been incorporated in the proposed design strategy for energy efficiency in small, medium density housing including housing for the aged. Accessibility and adaptability have been addressed by considering the appropriateness of each of the prescriptive design solutions, so that unacceptable environmental demands are not made on the occupants. Aesthetics have been addressed by enabling existing patterns of development and internal planning to be unaffected by the prescriptive design solutions. In spite of a common adage (Reardon 2001) that energy efficient design does not increase the capital cost of construction, the current thesis shows that if space heating and cooling is to be eliminated in small, semi-detached dwellings, the capital cost of construction increases. However, this is considered affordable as the additional capital cost can be balanced by savings in space heating in a 65 square metres dwelling within 19 years, well within the economic life of a dwelling. If the elimination of air-conditioning is taken into account, the capital costs could be recouped within less than half that time. This is of particular significance when applying these findings to small, medium density housing outside of the public sector, where air-conditioners are more commonly used.

8.3 Summary of key findings

1. Results from the multiple case study and computer simulations indicate that none of the existing small, medium density housing for the aged could achieve acceptable indoor temperatures on design days in winter or summer without the use of space heating and cooling, even though the design brief for these dwellings included requirements for energy efficiency.

2. There is a discrepancy between energy efficient design in Perth as applied to small, medium density housing for the aged and theoretical requirements for energy efficient design.

3. Theoretical requirements for energy efficient design do not incorporate notions of appropriateness. This appears to be crucial in the formulation of an effective design strategy for energy efficient design in small, medium density housing, including housing for the aged.

4. An effective design strategy for energy efficiency in small, medium density housing, including housing for the aged, must provide flexibility, should not inhibit innovative design solutions and should be considered affordable over the medium term.

5. The present study of small, medium density housing shows, via computer simulations, that in Perth's climate:

   - through the use of the prescriptive design solutions, winter temperatures can be maintained within an acceptable range, without space heating, in energy efficient dwellings. This result supports the contention of researchers such as Reardon (2002), Givoni (1992) and Baverstock and Paolino (1986) that energy efficient design in a temperate climate can maintain an indoor temperature range in winter of between 18°C and 25°C.

- through the use of the prescriptive design solutions summer temperatures can be maintained within an acceptable temperature range, without space cooling, but only if a fan is provided for personal cooling thus allowing temperatures to rise to a maximum of 30.4°C. This result does not support the contention by Baverstock and Paolino (1986) that energy efficient design, when used together with night cooling, can maintain an indoor temperature range in summer of between 20°C and 28°C.

9. Conclusion and further research

9.1 Conclusion

This thesis began by establishing a number of connections. Firstly there is a connection between energy efficient design and small, medium density housing. This connection was identified as a contemporary issue related to Australian Government policies in two disparate areas. One policy area is reflected in the Government's commitment to assist older people, whether they are active, early retirees or the frail elderly, wealthy or poor, to live in their chosen place of residence. Increasingly, this chosen place of residence may be a small, medium density dwelling. The other policy area is that related to reducing energy consumption in buildings. This policy is reflected in recently proclaimed building regulations aimed at reducing space heating and cooling requirements in housing. The building regulations include details of acceptable construction practice for energy efficiency that may not be appropriate in small, medium density housing.

Another identified set of connections revolved around the idea of energy efficient design in relation to appropriateness, where appropriateness is related to the size of a dwelling and environmental demand on the occupants of a dwelling. In Australia, well-established benchmarks for energy efficient design in a temperate climate are commonly discussed in relation to typical suburban housing. This type of housing has a reasonably large floor area[1] thus providing significant choice as to which rooms will be occupied at a particular time of day or in a particular season. The benchmarks also are silent on the effort (or environmental demand) required by occupants to adequately drive the house so that it is energy efficient. Consequently the current benchmarks for energy efficient design have not addressed in any depth these issues

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[1] New housing as exemplified by the project home market is generally greater than 150 square metres in floor area.

of appropriateness in small medium density housing, particularly housing occupied by the aged.

Having identified the connections, the thesis drew on a pilot study of thermal conditions and energy consumption in three retirement villages in Perth that had been previously carried out by the author. That pilot study found that extensive use of space heating and cooling was required in order to provide acceptable indoor temperatures in summer and winter. The pilot study also highlighted that even basic energy efficient design principles such as glazing oriented to the north for solar gain were rarely adopted. These finding provided a direction for the development of the current thesis.

It was proposed in this thesis that the extensive use of space heating and cooling in housing for the aged was required, because well-established benchmarks for energy efficient design in a temperate climate were not generally appropriate in small, medium density dwellings and were particularly inappropriate in housing for the aged. Appropriate in this context referred to:

- being suitable to enable indoor temperatures to remain within an acceptable range generally without the need for space heating and cooling;
- fitting into the site planning and general form of typical, medium density aged persons housing developments in suburban Australia;
- being cost effective in the medium term; and
- fitting the needs of physically and financially vulnerable older people.

The methods used to examine the notion of appropriateness commenced with a literature review that related to the general physical and economic status of older people and their needs and responses to space heating and cooling in the home. Further, the literature review considered the principles of energy efficient design and benchmark criteria for energy efficiency.

Based on matters related to energy efficiency in design arising from the literature review, two tools of study were used in order to develop a set of data encapsulating the salient features of small, medium density housing. The first tool was a multiple case study of typical housing for the aged. This was conceived as a way of determining if small, medium density dwellings could provide appropriate indoor thermal conditions and/or were designed in accordance with general principles of energy efficiency. The indoor temperatures were monitored in summer and winter and annual energy consumption was established. The building designs were analysed in terms of their orientation, glazing areas, wall areas, volumes of thermal mass and ventilation capacity, and these features were compared with benchmarks for energy efficient design. Statistical analyses of the data were carried out. This tool provided the means of addressing the first research question[1] related to thermal conditions in small, medium density housing for the aged in Perth.

The second tool of study involved a series of computer simulations of a typical small, medium density dwelling using a CSIRO validated computer program, the Nationwide House Energy Rating Scheme for Australian conditions (NatHERS). The simulation process was utilised to determine if a new set of benchmarks for energy efficient small, medium density dwellings was required that would incorporate the notion of appropriateness. This computer modelling tool provided the means of addressing the second research question[2] that revolved around the notion of appropriateness of current benchmarks for energy efficient design.

From the multiple - case study it was found that the majority of small, medium density housing for the aged in Perth were not designed with energy efficiency as a de-

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[1] Research question 1 was: 'Does existing small, medium density housing for the aged in Perth: (a) satisfy the principles of energy efficient design; and/or (b) provide acceptable indoor temperatures?'

[2] Research question 2 was: 'Are current benchmarks for energy-efficient design appropriate: (a) for small, medium density housing; and (b) particularly for small, medium density housing for the aged?'

sign parameter. Further, it was discovered that, irrespective of design, recorded indoor temperatures in all[1] dwellings were:

- in summer above 27.4°C, the acceptable maximum temperature in still air, and 75% were above 30.4°C, the acceptable maximum temperatures in moving air; and
- in winter below 19.8°C, the acceptable minimum daytime temperature.

The findings also showed that some aspects of the benchmarks for energy efficient design were not appropriate in typical, medium density housing constructed specifically for the aged. From the simulation process it was discovered that acceptable temperatures could be achieved in small medium density housing, if the principles of energy efficient design were integrated with appropriateness criteria for housing for the aged.

As a result a new set of benchmarks for energy efficient design in small medium density housing was developed. The approach taken was to create both performance based benchmarks and benchmarks in the form of prescriptive design solutions. The performance model differs from the current benchmarks for energy efficient design in that it establishes key functional objectives for energy efficient design in small medium density housing. The prescriptive design solution is more akin to the current form of benchmarks but the particular details differ from the current benchmarks in a number of ways.

Compared to the current benchmarks, the prescriptive design solution shows a significant reduction in the area of northerly glazing and total glazing. To compensate for the reduced area of northerly glazing, both direct and indirect means of solar gain are utilised for passive heating. Key features of the prescriptive design solution for

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[1] There was one monitored dwelling in summer and one different monitored dwelling in winter that remained within the acceptable temperature range, as a result of extensive use of space heating and cooling for ill occupants.

medium density dwellings having a floor area between approximately 50 square metres and 80 square metres are summarised in Table 9-1.

Floor area (m^2)	**Orientation of solar collectors**	**Area of solar collectors as % of floor area**	**Exposure/ shading of solar collectors**	**Shading of glazing on east and west**	**Thermal mass**	**Minimum level of insulation of total construction**	
						ceiling	**walls**
50-80	between 20° west and 30° east of true north	21% - 24% with higher percentage applying to smaller dwellings and approx. equal distribution between direct and indirect solar collectors	full exposure in mid-winter to 2.1m high & full shading from mid-October until end of February	no solar penetration from end November until end March	concrete floor slab and inner leaf of external walls of concrete or masonry	R2.7	R1.4

Table 9-1 *Parameters for energy efficient public housing for the aged in Perth*

Using this prescriptive design solution, energy efficient design can be successfully incorporated in small, medium density housing, including housing for the aged, to improve indoor thermal conditions. However some accepted features of energy efficient design must be reconsidered to suit buildings of small floor area and to suit a particular occupant group. In typical small, medium density housing, acceptable temperatures can be achieved if a combination of direct solar gain and indirect solar gain is utilised, solar collectors are unshaded in winter and fully shaded in summer, external walls are insulated, all internal walls are of masonry and a fan is available for personal cooling in summer.

In small, medium density housing, two aspects of the conventional wisdom with regard to passive solar heating are put aside. Firstly, it is not necessary that the long axis of the building runs east-west. Secondly, solar collection should come from an approximately equal combination of northerly facing glass and northerly facing solar collection panels, together having an area approximately 24% of floor area. Contrary to popular commentary, additional costs are incurred in energy efficient design if the design is to minimize placing the onus of performance on the building occupant. In housing for the aged this is a necessary prerequisite. The additional costs of energy efficient design can be offset by savings in energy use and space heating and cooling equipment during the life of the building.

With these findings, the current thesis has shown that the established benchmarks for energy efficient design do require adjustment if they are to be appropriate in medium density housing of small floor area occupied by the aged. The thesis has also shown the benefits and limitations of energy efficient design in small, medium density housing. Looking towards the future, with building regulations requiring a reduction in energy consumption in dwellings and unpredictable energy prices potentially creating financial hardship for those least able to afford increased costs for space heating and cooling, it is suggested that the design strategy developed in this study could be adopted. It is recognized that the strategy does not provide a single panacea to reducing energy consumption in small, medium density housing. Rather, it provides an opportunity to reconsider current benchmarks for energy efficient design in particular circumstances.

The thesis outcomes have implications for three areas of the construction industry. In regard to building regulations, the thesis shows that the prescriptive design solutions presented in building regulations for energy efficiency in housing need to be qualified for small, medium density housing. The implication for those preparing design briefs for housing that is to be energy efficient is that, as the current benchmarks cannot be applied successfully to all types of housing, performance requirements should be incorporated in design briefs rather than prescriptive solutions and finally, the implication for designers of energy efficient small, medium density housing is that their standard design parameters must be reconsidered.

9.2 Further research

In electing to focus on thermal conditions and energy efficient design in small, medium density housing, particularly housing for the aged in Perth, the thesis has raised a number of questions about how the findings and the approach taken can be further explored and extended.

Energy efficiency in housing

As discussed in Chapter 2, there is every indication that the majority of elderly Australians in the foreseeable future will continue to live out their lives in typical suburban family dwellings or in private rented premises. These elderly people may face many of the same physical limitations and financial constraints as those living in housing for the aged. Consequently, the performance based strategy for energy efficient design in small, medium density housing could be developed so as to be adopted in the general housing market, both to reduce the need for space heating and cooling and to reduce possible financial stress on the aged related to the cost of energy.

Indirect solar heating

In housing for the aged, dependence on direct solar gain for passive heating is not desirable. A Trombe-Michel wall as discussed in the current study provides one method of indirect solar gain. It seems that future research might look into the design of indirect solar heating devices, particularly devices that could be fitted into existing small, medium density housing.

A possibility for indirect solar gain may take the form of indirect solar heating through a ceiling panel. Although still in the process of testing, one way of utilising indirect solar heat gain was given preliminary consideration in the current study, as it provided the potential of addressing all four universal design criteria. This was a solar heated radiant ceiling panel exposed to solar radiation through a glazed roof panel as shown in Figure 9-1. Such a ceiling panel could readily be incorporated in small, medium density housing where dwellings have an extent of roofing exposed to the north but no northerly walls. Such a ceiling panel would protect occupants from glare[1] normally associated with solar collection from roof glazing. If this system of utilising indirect solar heat proves to be successful, the system could also be readily incorporated in current housing stock. A prototype is being constructed in Perth at the time of writing, but no performance data is as yet available.

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[1] Glare was a noted concern in Development 6 where roof glazing was provided for solar collection.

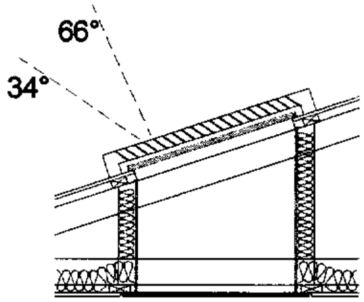

Figure 9-1 *Suggested alternative indirect solar heating panel*

Measurement of energy use

Another potential area for research relates to the measurement of energy use. To carry out objective comparisons of energy use in different types of housing, issues arise regarding how energy use should be normalised. Energy use per square metre of floor area, or energy use per person, or energy use per person-hour of occupancy can be compared. In the current study, energy use per square metre of floor area was used, as this is the most common measure in housing. It is recognized however, that further research is required to determine if this is the most informative measure in housing for the aged, as those over 65 years spend more time at home than other householders (see section 2.3).

Acceptable temperatures

In the current study, the acceptable temperature range was determined using a number of sources. None of the sources were specific in relation to non-air-conditioned housing in a temperate climate occupied by the aged. The adaptive theory of thermal comfort for non-air-conditioned buildings, as espoused by de Dear and Schiller Brager (1998) and Humphreys and Nicol (2000), was primarily based on conditions in office buildings. It is acknowledged that there is evidence to show that the attitudes of building occupants towards acceptable temperatures in the work place are less tolerant than in the home (Griffiths, Huber & Baillie 1988) so the temperatures considered as acceptable in the current study may err on the conservative side. Future research may look to confirm this position.

There is also no clear indication relating acceptable temperatures to thermal conditions when people are in bed. These conditions may be tied up with the insulation values of mattresses. Considerable research has been done on determining the insulation values of office chairs, to establish how they affect perceptions of thermal comfort. As far as can be determined, no similar research has been carried out to establish how summer temperatures may be influenced by the insulation values of different types of mattresses. Such research may provide additional information regarding acceptable summer temperatures, particularly at night, as the only guide to an acceptable maximum summer temperature at night in non-air-conditioned dwellings is 24°C provided by Ballinger, di Franco & Prasad (1993). However it is unclear whether this temperature of 24°C is related specifically to local climatic conditions.

Climatic conditions

With indications of global warming, heat stress for the aged may become an increasing problem. As shown in the current study, energy efficient design in Perth cannot, even with current climatic patterns, avoid some indoor discomfort on days of extreme heat in summer. It may be that in the foreseeable future more emphasis will need to be placed on night cooling in summer. In the current study, security concerns were identified as the primary inhibitor to leaving windows open at night although a detailed examination of the security concerns was not undertaken. The design development and field testing of security screens is a potential area for future research, as it could encourage the use of cool night air for passive cooling in housing in general and in housing for the aged in particular.

Affordability of design and construction

Two distinct areas of research are related to affordability. One is related to design and the other to the financing of developments. If as shown in the current thesis, there is a significant amount of flexibility in planning to achieve energy efficient design in small, medium density housing, with flexibility comes a potential emphasis on design of individual dwellings, rather than standardised plans. This rise in design flexibility could affect affordability of small, medium density housing in terms of higher design fees and higher construction costs. This aspect of affordability needs to be tested in the market place.

There is currently no financial incentive to developers to consider costs over the life of a building, particularly when the building occupants gain the financial benefits. A suggested area of research could examine whether the proposed design strategies could be incorporated into the work of public housing authorities who may be able to structure innovative financial packages. The public housing authority in Western Australia could lead the way in improving indoor thermal conditions in small, medium density housing including housing for the aged. It is in a unique position to provide a model for the rest of the community in energy efficient design in housing, as it can regularly refine its design brief based on the experience of continuously building and owning energy-efficient housing. This may provide leadership to the wider construction industry to pursue energy efficient design in small, medium density housing, including housing for the aged.

The potential of energy efficient design to be accepted as a basis for design in public housing for the aged has been illustrated here, as it appears that the additional cost of energy efficient design features in Perth can be recovered through energy savings within the medium term and within the economic life of the building. Exactly how the additional capital expenditure impacts on the short term financial viability of developments is beyond the scope of the current study, but might provide a fertile area for future research.

Prototype

The most potent area for future research would be the construction, occupation and thermal monitoring of a dwelling that was designed using the benchmarks for glazing, Trombe-Michel wall and shading of glazing as presented in the current thesis. The construction costs, indoor thermal conditions, as well as the needs of the occupants (similar to that described by Rohles 1976) could be assessed. Transaction costs, satisfaction with the design features and long term ability to thermally manage the dwelling could all be determined.

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Appendix A1 - Regression analyses for energy efficient design in buildings of small floor area in Perth, West Australia

(Based on-Baverstock & Paolino (1986) north facing semi-detached house)

A1.1.	Total north wall area
A1.2	Northerly glazing area
A1.3	East/west glazing area
A1.4	Total glazing area
A1.5	Trombe-Michel wall area
A1.6	Volume of concrete
A1.7	Volume of brick
A1.8	Night ventilation system

A1.1 Total north wall area

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
N_WALL	LIN	.973	2	73.22	.013	30.6771	.0836	
N_WALL	QUA	.999	1	513.73	.031	22.5927	.1532	-.0001

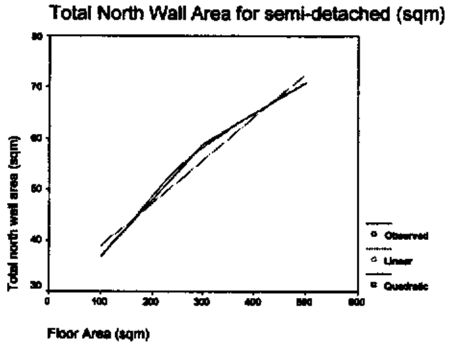


Figure A1-1 *Graphic description of regression analysis for north wall area*

Using quadratic function:

North wall area (NWA) = 22.5927 + 0.1532x – 0.0001x^2
If x = 50, NWA = 30.0027. Adopt north wall area 30 m^2
If x = 65, NWA = 32.1282. Adopt north wall area 32 m^2

A1.2 Northerly glazing area

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
N_GLASS	LIN	.944	2	33.89	.028	16.3234	.0318	
N_GLASS	QUA	.997	1	168.70	.054	11.8429	.0703	-6.E-05

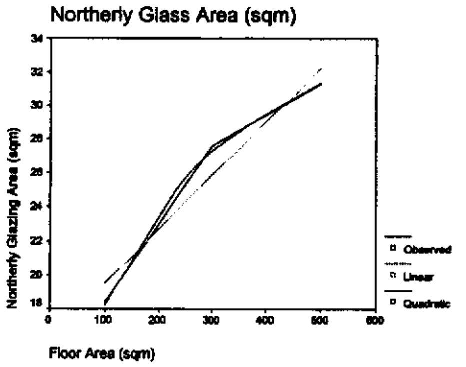


Figure A1-2 *Graphic description of regression analysis for northerly glazing area*

Using quadratic function:

Northerly glass (NG) = 11.8429 + 0.0703 x – 0.00006 x^2
If x = 50, NG = 15.2079. Adopt northerly glazing area 15.2m^2
If x = 65, NG = 16.1589. Adopt northerly glazing area 16.2m^2

A1.3 East and west glazing areas

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
W_AREA	LIN	1.000	2	.	.	.5000	.0150	
6 W	_AREA	QUA	1.000	2	. .	.5000	.0150	

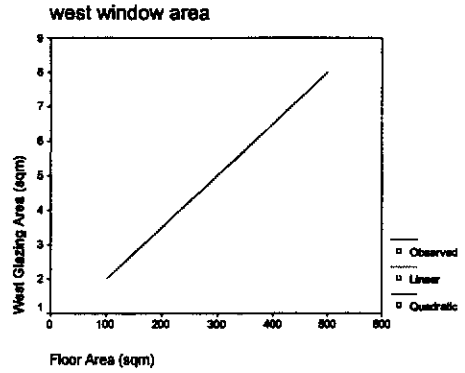


Figure A1-3 *Graphic description of regression analysis for west window area*

Using linear function:

Westerly glass (WG) = 0.5 + 0.015 x

If x = 50, WG = 1.25. Adopt westerly glazing maximum area 1.25m^2

If x = 65, WG = 1.5. Adopt westerly glazing maximum area 1.5m^2

A1.4 Total glazing area

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
T_GLASS	LIN	.979	2	93.53	.011	19.8857	.0661	
T_GLASS	QUA	1.000	1	86016.7	.002	14.1227	.1157	-8.E-05

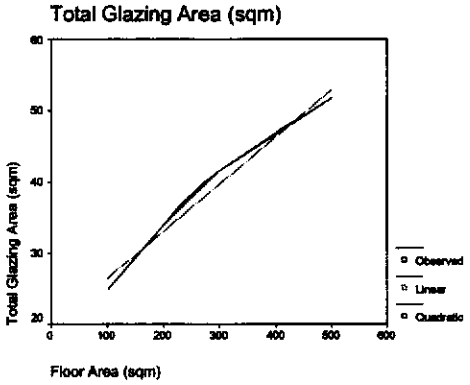


Figure A1-4 *Graphic description of regression analysis for total glazing area*

Using quadratic function:

Total glazing area (TG) = 14.1227 + 0.1157x –8 x10^{-5}x^2

If x = 50, TG = 19.7077. Adopt total glazing area 19.7 m^2

If x = 65, TG = 21.3052. Adopt total glazing area 21.3 m^2

A1.5 Trombe-Michel wall area

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
TROMBE	LIN	.966	2	56.33	.017	3.2857	.0371	
TROMBE	QUA	.998	1	274.50	.043	-.7727	.0720	-6.E-05

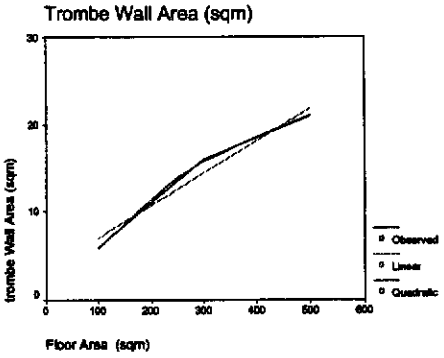


Figure A1-5 *Graphic description of regression analysis for Trombe-Michel wall area*

Using quadratic function:

Trombe wall (TRW) = $-0.7727 + 0.0720x - 6x10^{-5}x^2$

If $x = 50$, TRW = 2.6773. Adopt trombe wall area 2.7 m^2

If $x = 65$, TRW = 3.6538. Adopt trombe wall area 3.7 m^2

A1.6 Volume of concrete

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
TM_CON	LIN	.980	2	99.42	.010	2.6286	.0877	
TM_CON	QUA	.996	1	130.20	.062	-4.0273	.1450	-9.E-05

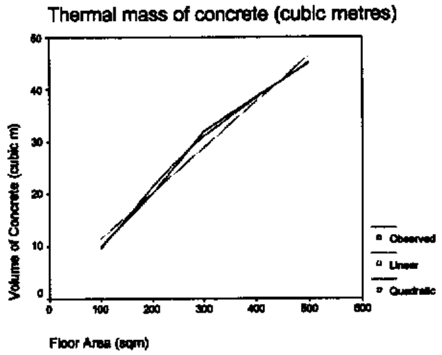


Figure A1-6 *Graphic description of regression analysis for concrete thermal mass*

Using quadratic function:

Thermal mass of concrete (TMC) = $-4.0273 + 0.1450x - 9x10^{-5}x^2$

If $x = 50$, TMC = 2.9977. Adopt thermal mass of concrete $3m^3$

If $x = 65$, TMC = 5.0152. Adopt thermal mass of concrete $5m^3$

A1.7 Volume of brick

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
TM_BRI	LIN	.943	2	32.84	.029	15.7143	.0729	
TM_BRI	QUA	1.000	1	1.4E+15	.000	5.0000	.1650	-.0001

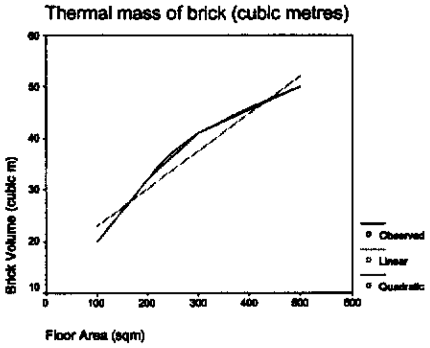


Figure A1-7 *Graphic description of regression analysis for brick thermal mass*

Using quadratic function:

Thermal mass brick (TMB) = 5.0000 + 0.1650x – 0.0001x^2

If x = 50, TMB = 13.0000. Adopt thermal mass of brick 13m^3

If x = 65, TMB = 15.3025. Adopt thermal mass of brick 15m^3

A1.8 Night ventilation system

Independent variable: F_AREA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
FAN	LIN	.865	2	12.77	.070	1677.14	5.1286	
FAN	QUA	1.000	1	58560.8	.003	467.727	15.5295	-.0169

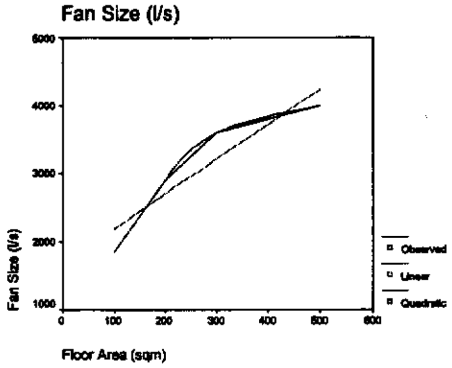


Figure A1-8 *Graphic description of regression analysis for night cooling fan*

Using quadratic function:

Fan size (FS) = 467.727 + 15.5295 x – 0.0169 x^2

If x = 50, FS = 1201.952. Adopt fan size 1200 l/s

If x = 65, FS = 1405.742. Adopt fan size 1400 l/s

Appendix A2 - Description of seven developments in multiple - case study

A2.1 Development 1

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
14	10	3

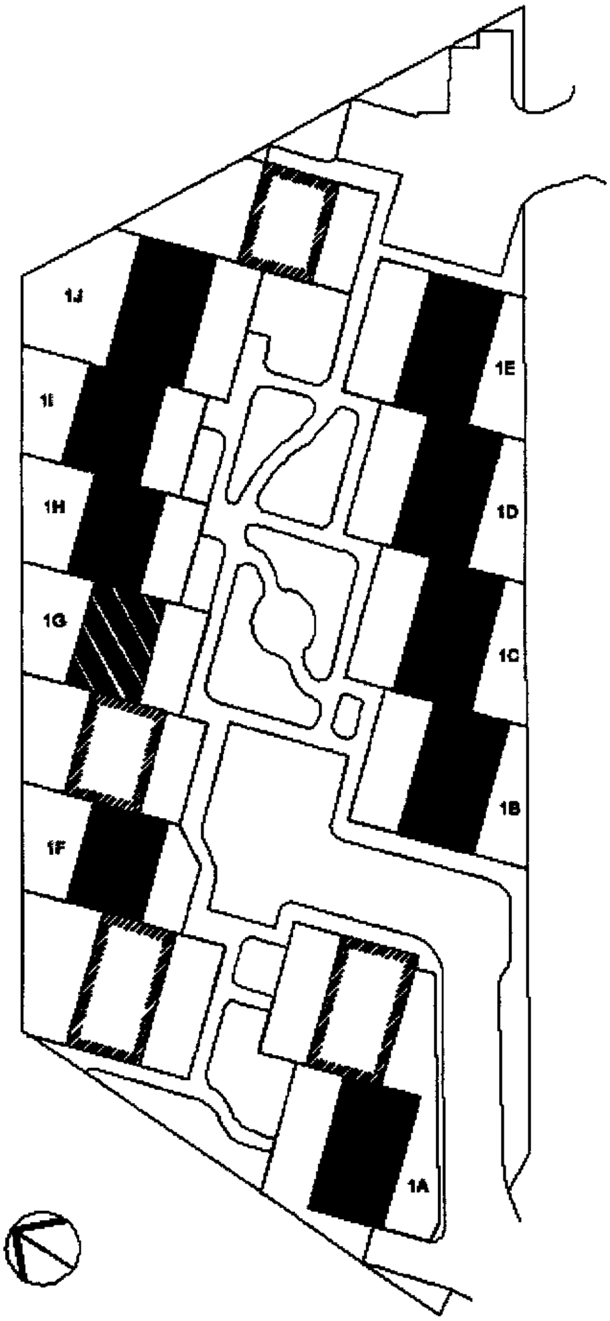


Figure A2-1 *Site Plan – Development 1*

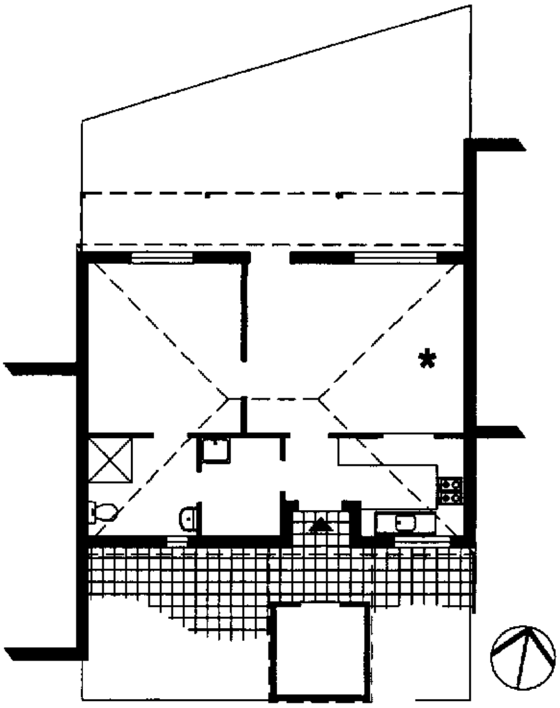


Figure A2-2 *Floor Plan Dwelling 1G – Monitored in summer and winter*


Dwelling 1G – northerly shading of glazing


Dwelling 1E –private outdoor space on northerly side


Dwelling 1C – northerly shading of glazing

Figure A2-3 *Images of Development 1*

A2.2 Development 2

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
25	15	4

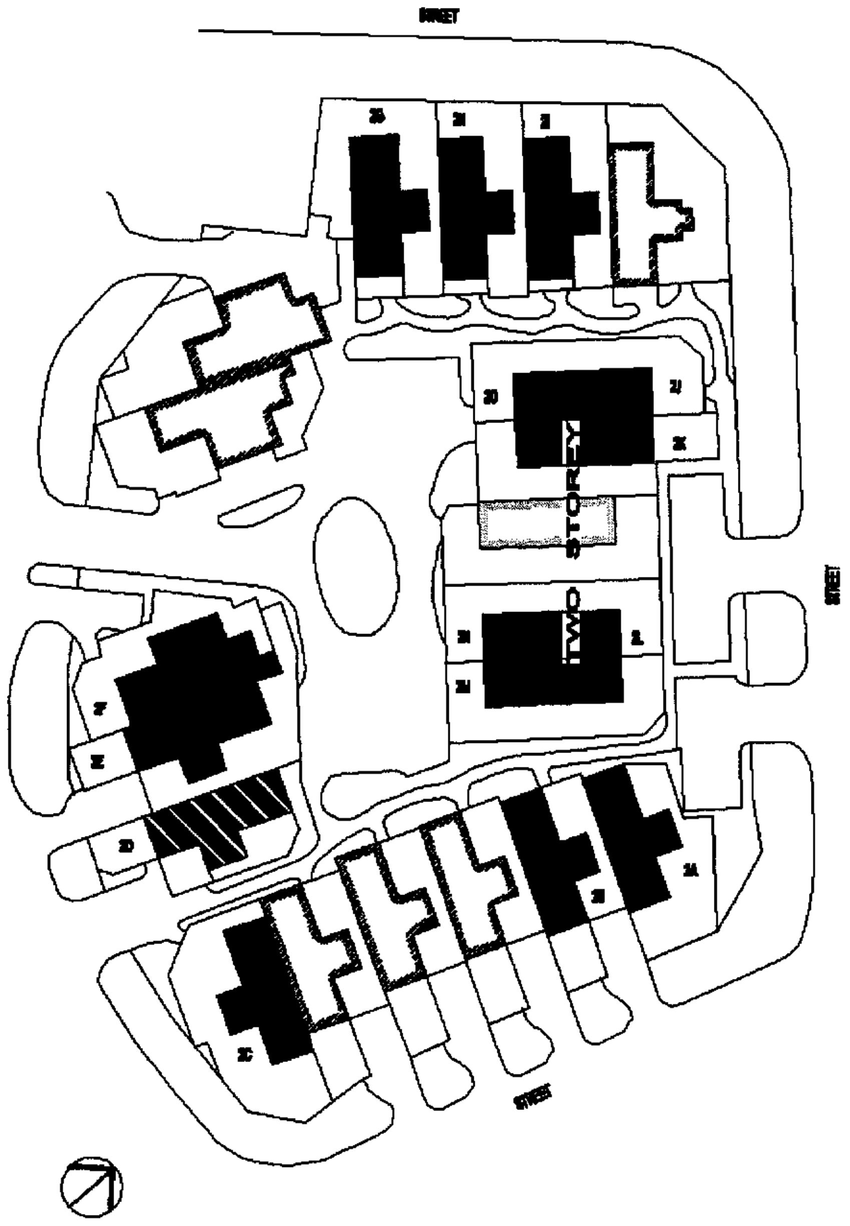


Figure A2-4 *Site Plan – Development 2*

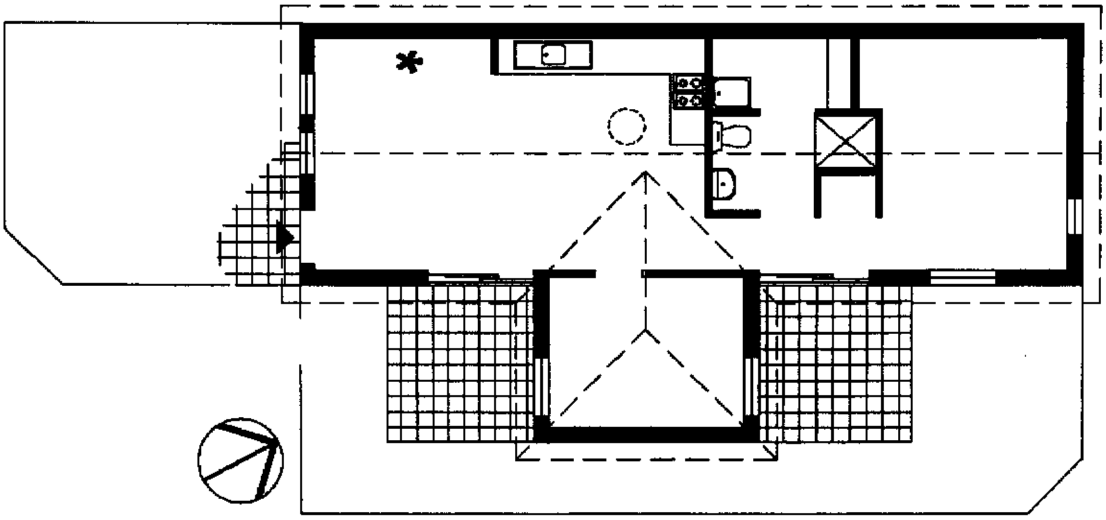
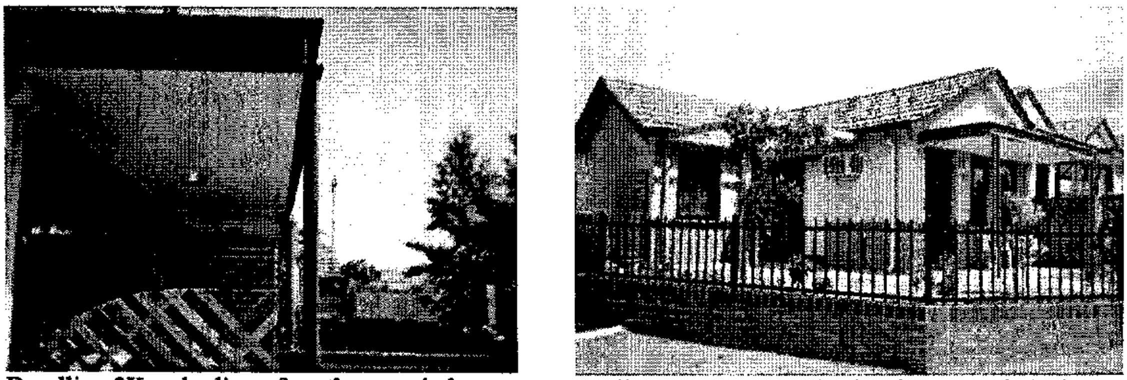
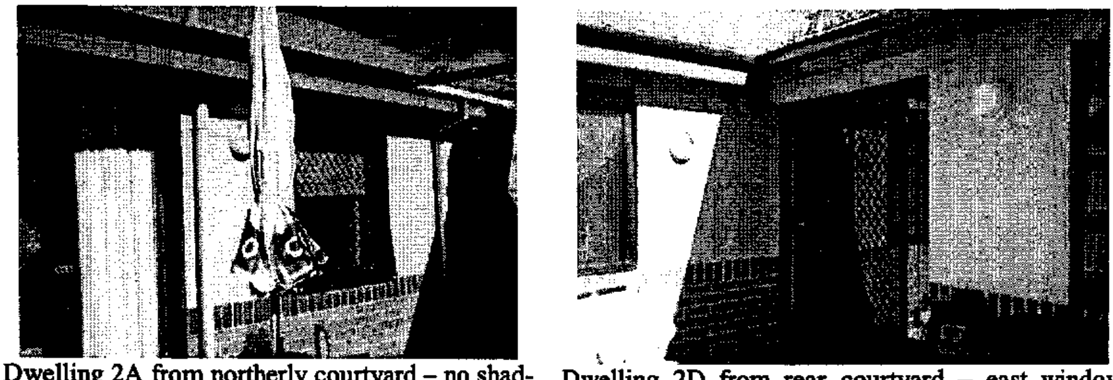


Figure A2-5 *Floor Plan Dwelling 2D - Monitored in summer and winter*



Dwelling 2K – shading of north east windows

Dwelling 2C – no northerly glazing and shading of most other glazing thus prohibiting direct solar gain in winter



Dwelling 2A from northerly courtyard – no shading to protect glazing from direct solar gain in summer

Dwelling 2D from rear courtyard – east window receives direct solar gain in summer and winter

Figure A2-6 *Images of Development 2*

A2.3 Development 3

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
62	7	3

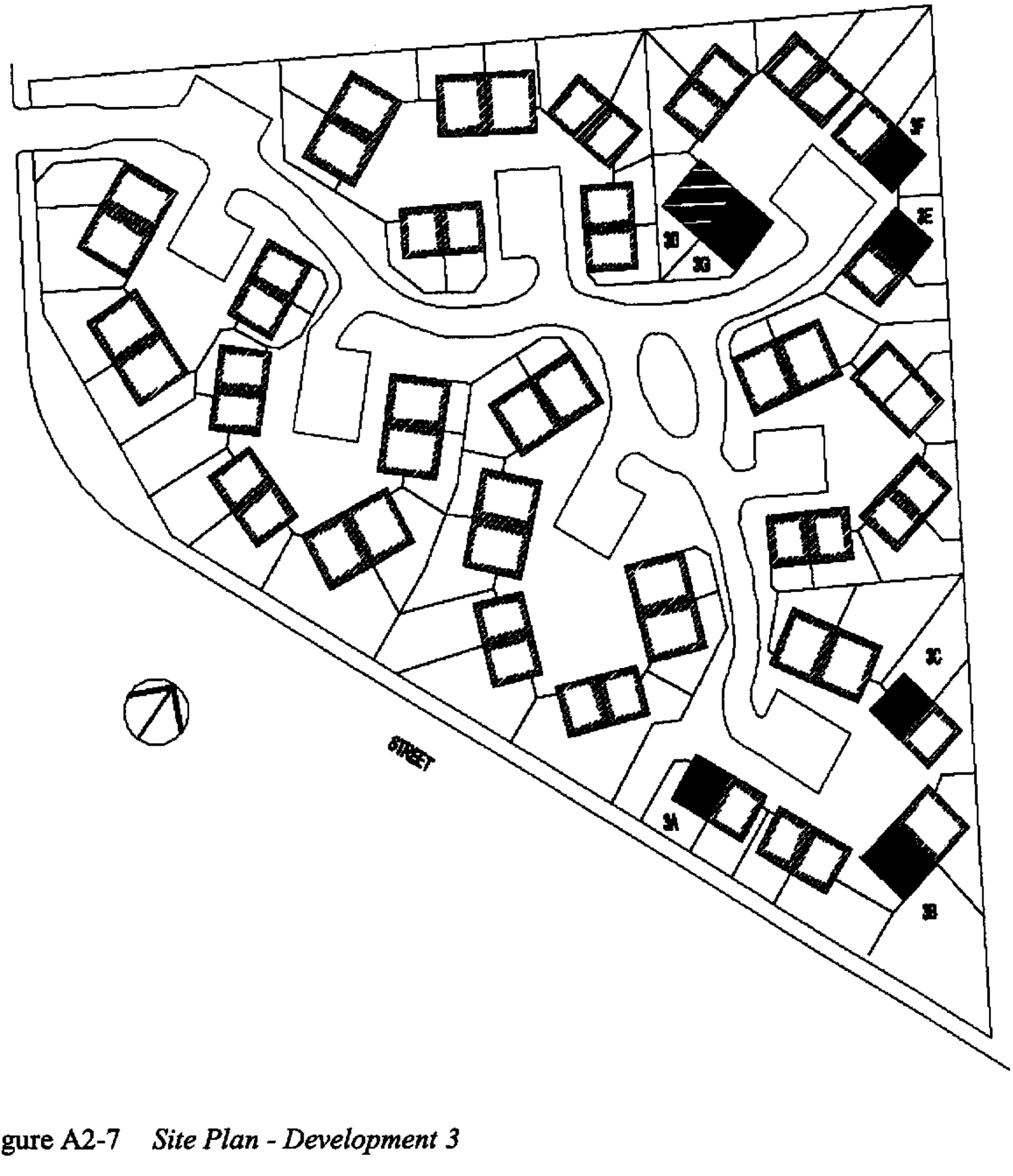


Figure A2-7 *Site Plan - Development 3*

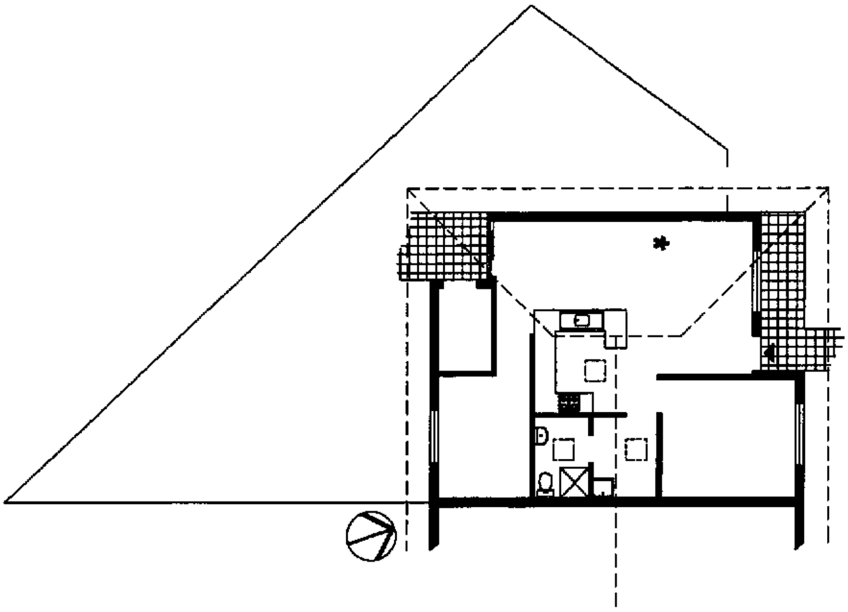
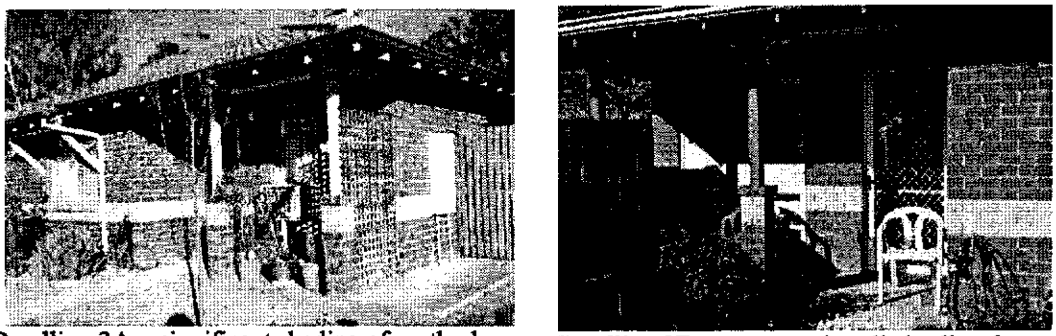


Figure A2-8 *Floor Plan Dwelling 3D - Monitored in summer and winter*

Dwelling 3D – only bedroom window exposed to winter solar gain on north elevation

Dwelling 3F – south elevation treated identically to north and west elevations



Dwelling 3A – significant shading of northerly glazing to living area in winter

Dwelling 3E – occupant installed roller shutter to protect from west sun

Figure A2-9 *Images of Development 3*

A2.4 Development 4

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
16	8	3

Figure A2-10 *Site Plan - Development 4*

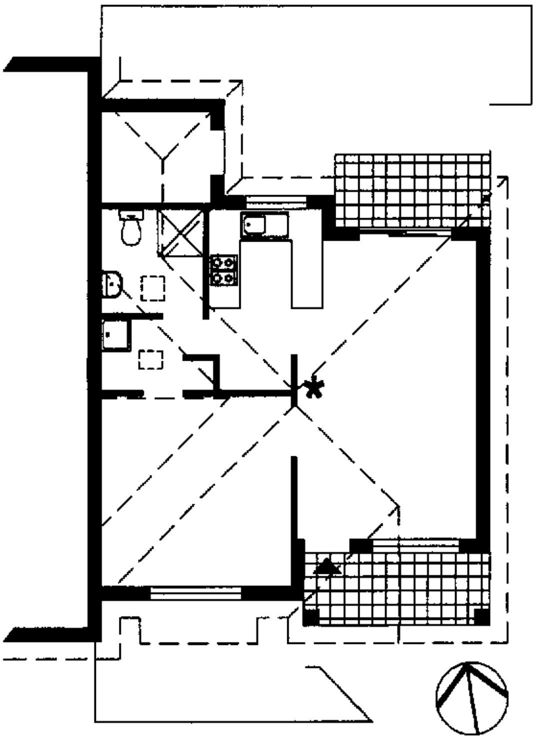
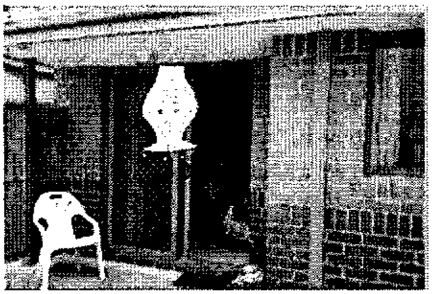
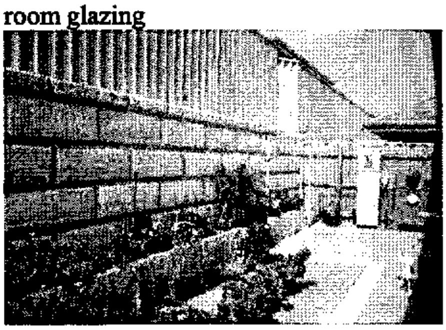
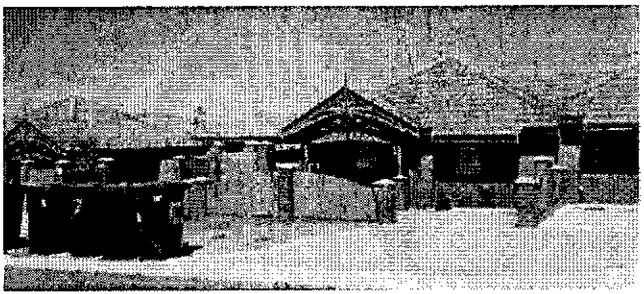


Figure A2-11 *Floor Plan - Dwelling 4A*



Dwelling 4A – eaves (above) and high boundary fence (below) shade living room glazing





Street frontage with Dwelling 4D to the right – no northerly windows provided

Carports shade northerly glazing to Dwellings 4C and 4H

Figure A2-12 *Images of Development 4*

A2.5 Development 5

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
9	6	3

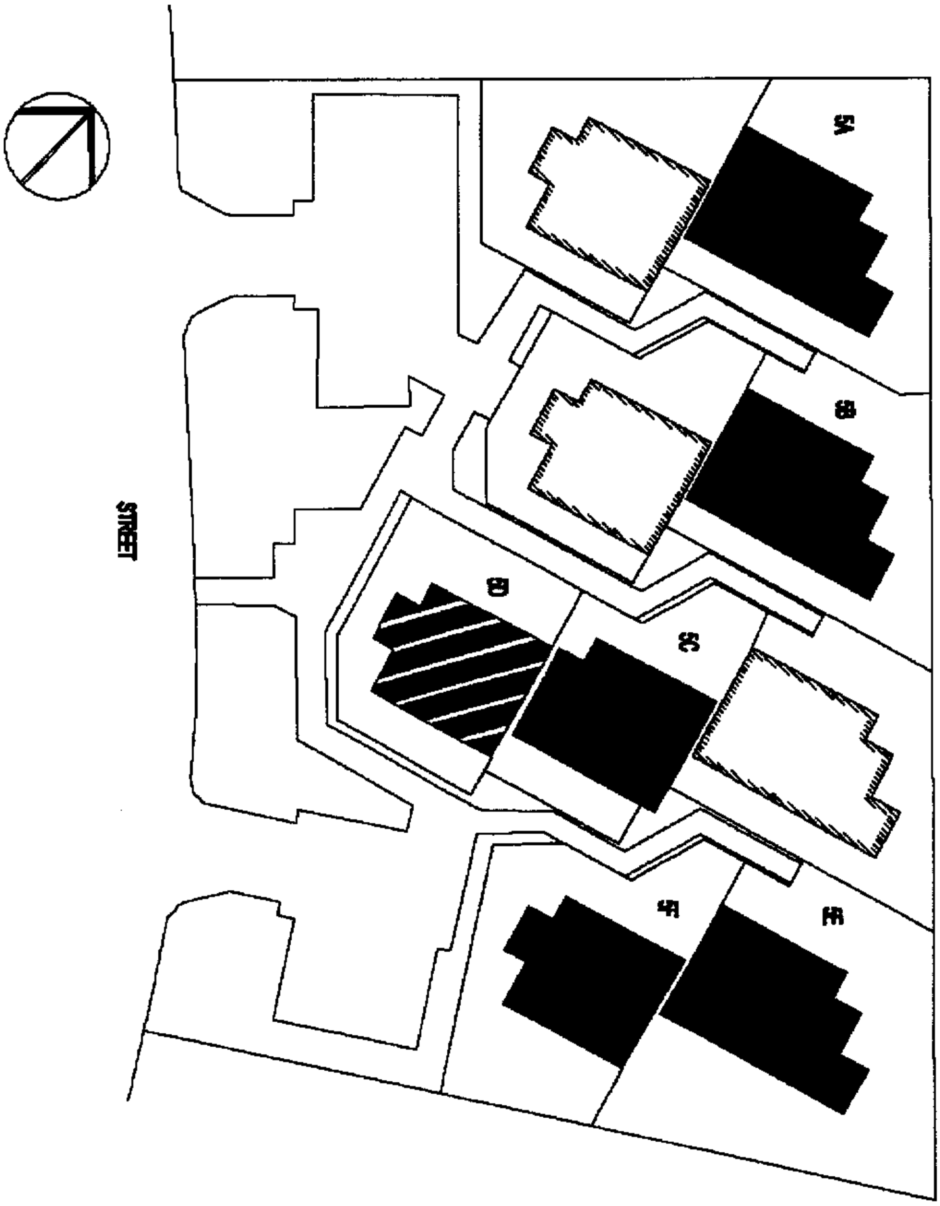


Figure A2-13 *Site Plan - Development 5*

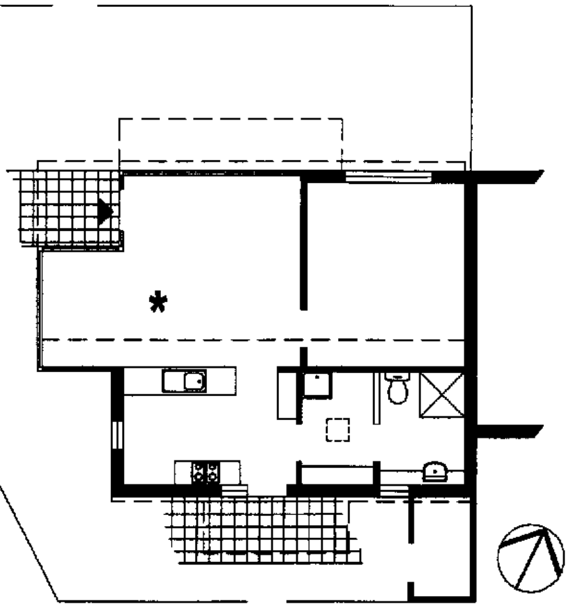
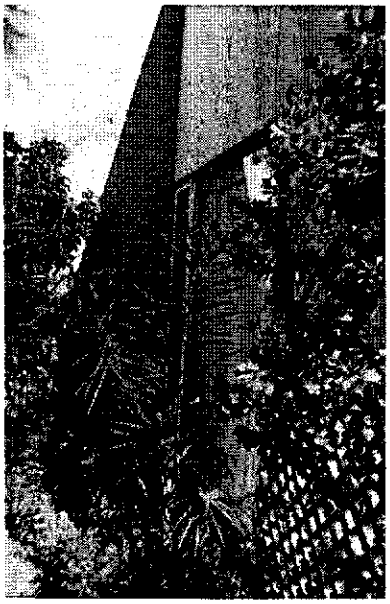


Figure A2-14 *Floor Plan - Dwelling 5D*


Dwelling 5E – no shading to east facing glazing


Dwelling 5D – no shading to northerly bed room window and significant shading to living room window


Dwelling 5C – shading to northerly windows close to pedestrian thoroughfare

Figure A2-15 *Images of Development 5*

A2.6 Development 6

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
17	8	4

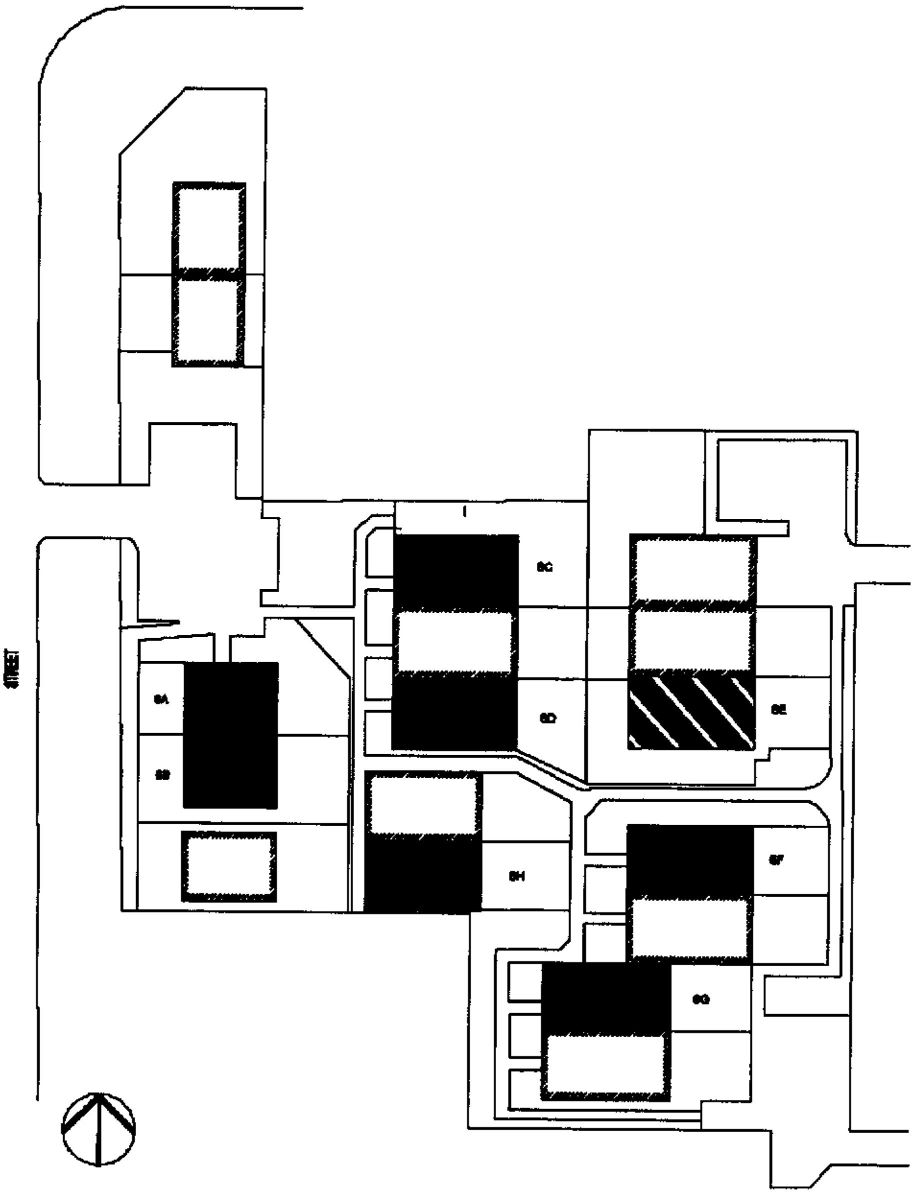


Figure A2-16 *Site Plan - Development 6*

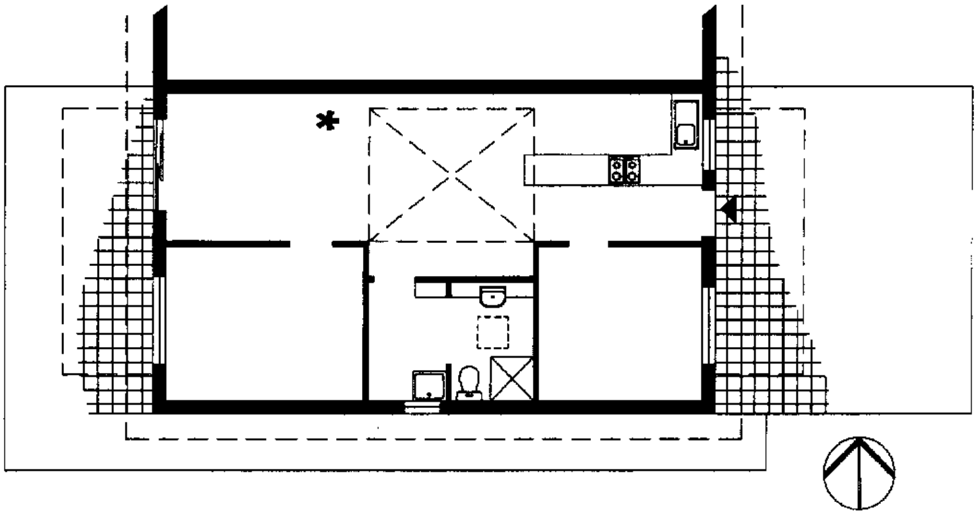
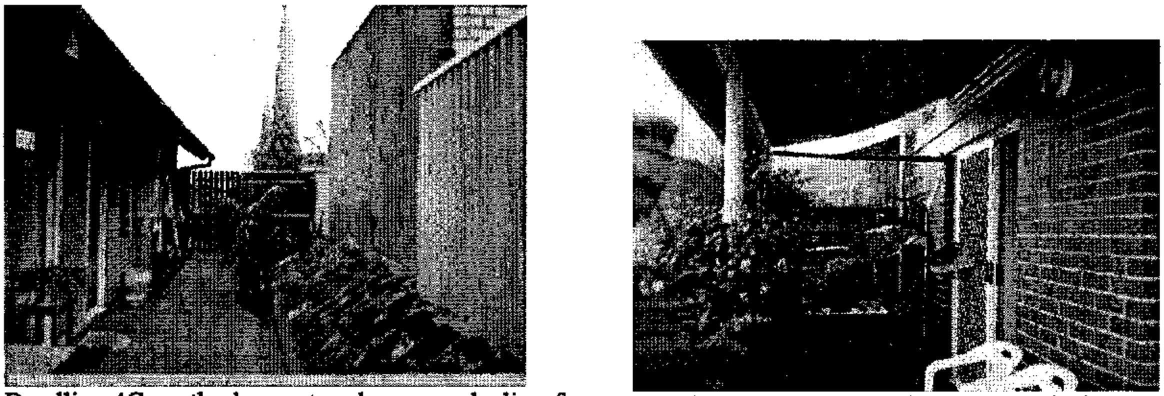


Figure A2-17 *Floor Plan Dwelling 6E*

Dwellings from the west including Dwelling 4C (left) – shading to try and minimise solar gain in summer

Dwelling 4A with northerly glazing and no roof glazing



Dwelling 4C northerly courtyard – some shading from high boundary wall

Dwelling 6E east verandah to provide shade

Figure A2-18 *Images of Development 6*

A2.7 Development 7

Total number of dwellings	Number of dwellings monitored in summer	Number of dwellings monitored in winter
8	6	2

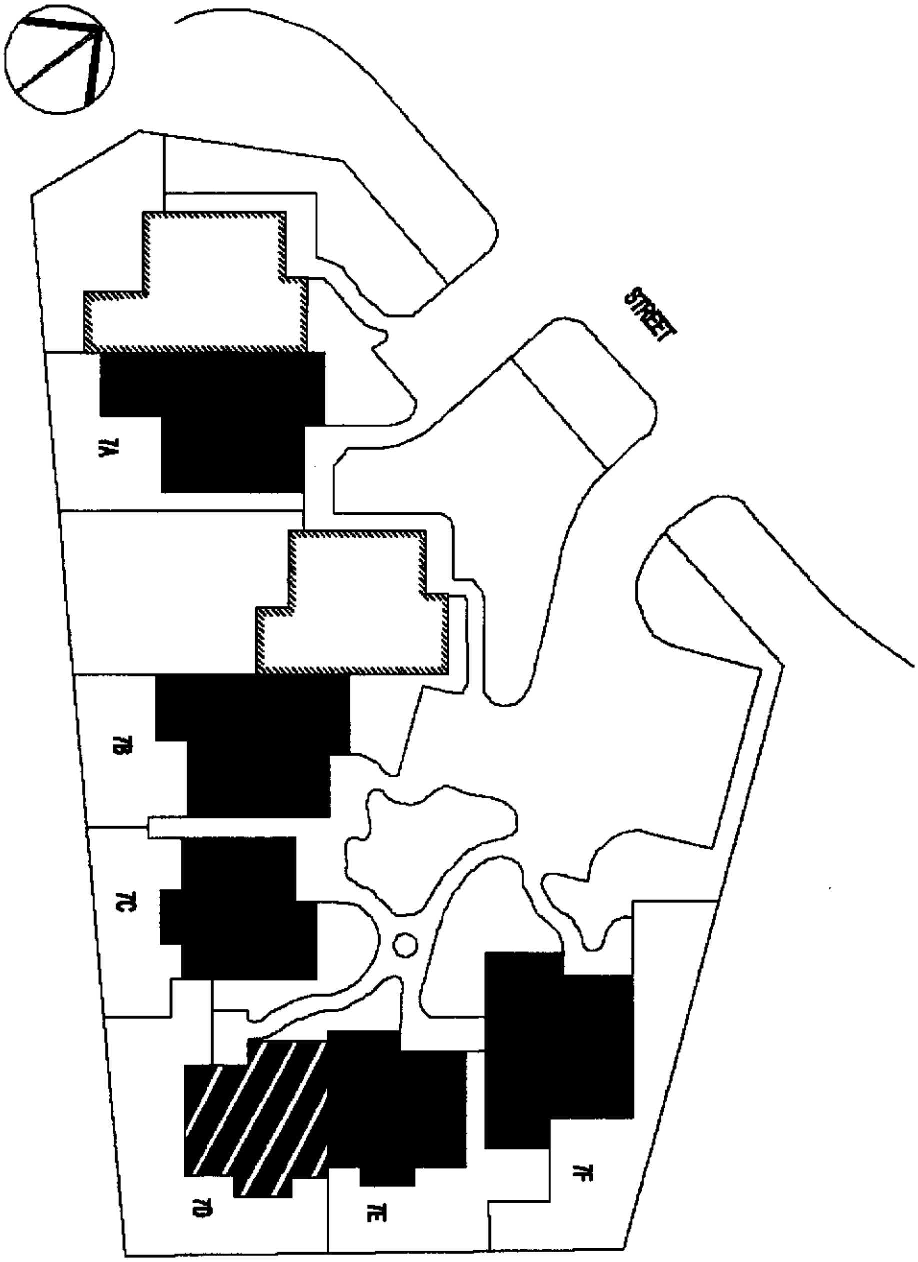


Figure A2-19 *Site Plan Development 7*

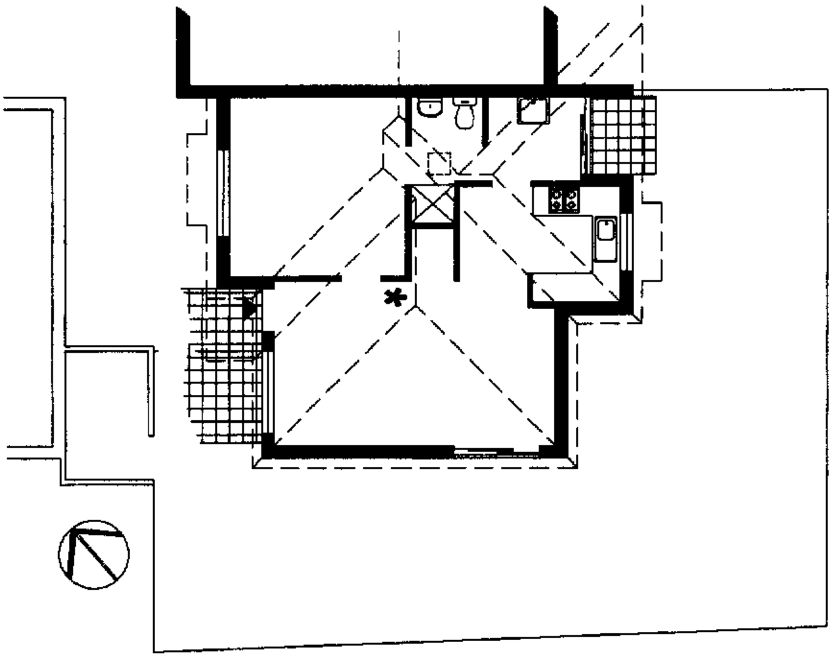
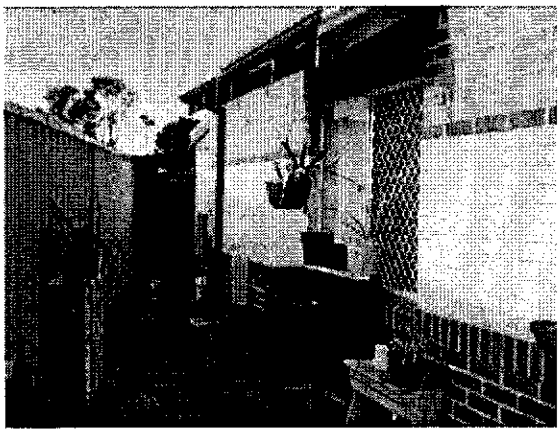


Figure A2-20 *Floor Plan Dwelling 7D*



Dwelling 7F with solitary northerly window

Dwellings 7D, 7E and 7F (Dwelling 7F left side) all with different degrees of exposure to solar radiation

Dwellings 7B and 7C have northerly orientation but eaves and plants block a significant amount of direct solar radiation

Figure A2-21 *Images of Development 7*

Appendix A3 - Outdoor/indoor thermal conditions during monitoring period

A3.1 Outdoor temperatures

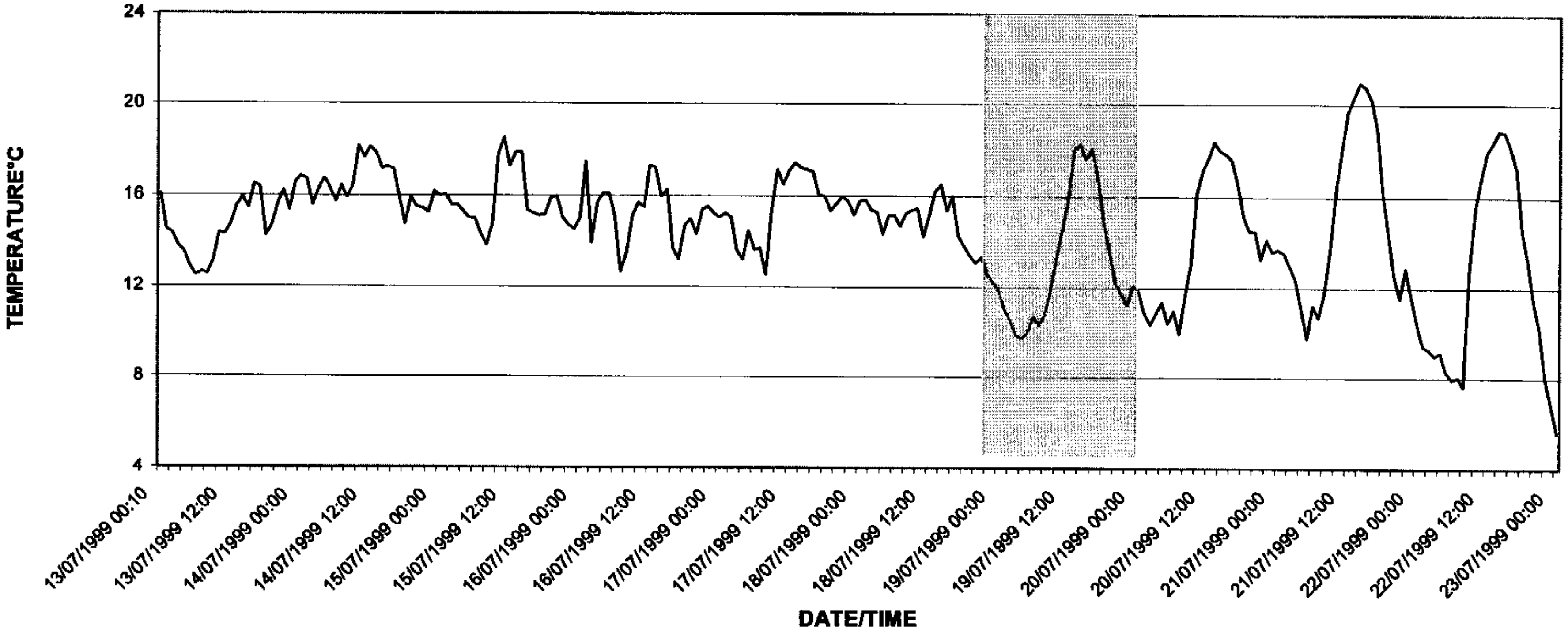


Figure A3-1 *Outdoor winter temperatures during monitoring period with design day indicated*

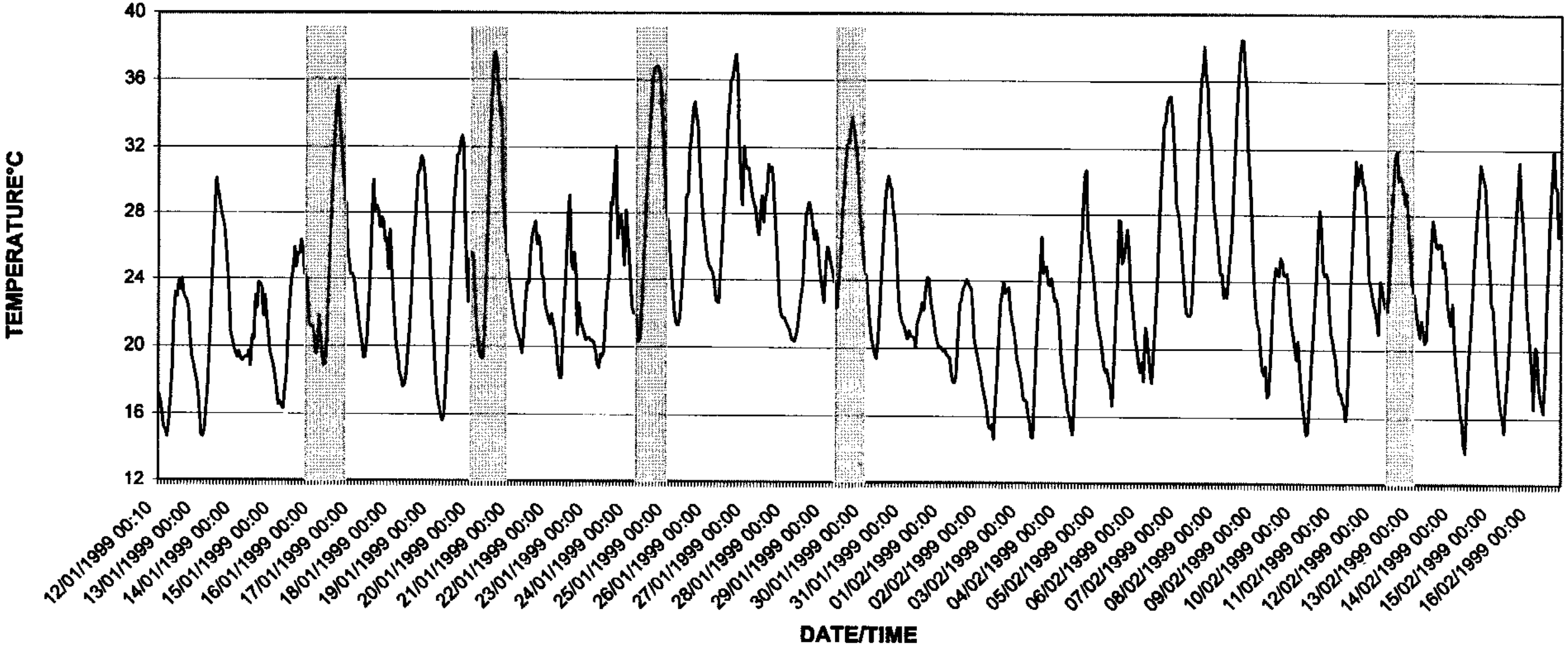


Figure A3-2 *Outdoor summer temperatures during monitoring period with design days indicated*

A3.2 Outdoor relative humidity

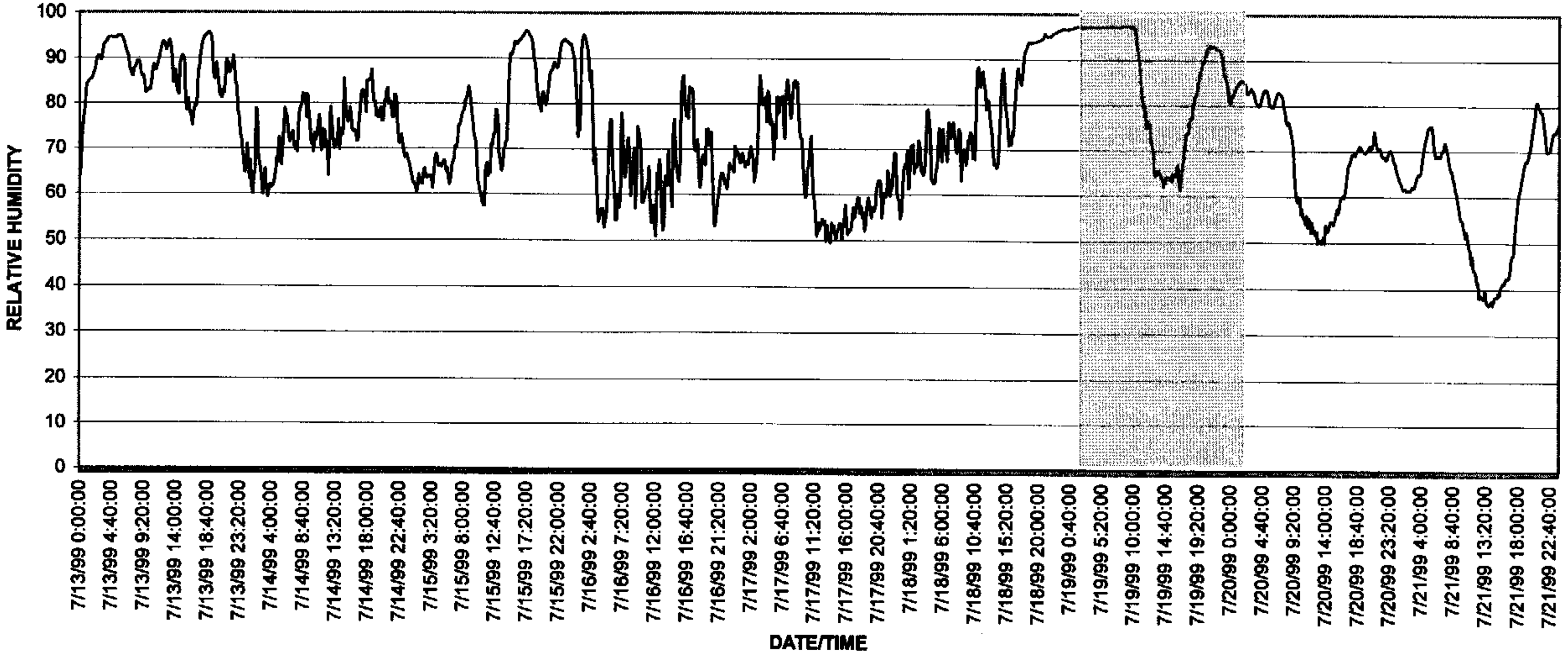


Figure A3-3 *Outdoor winter relative humidity during monitoring period with design day indicated*

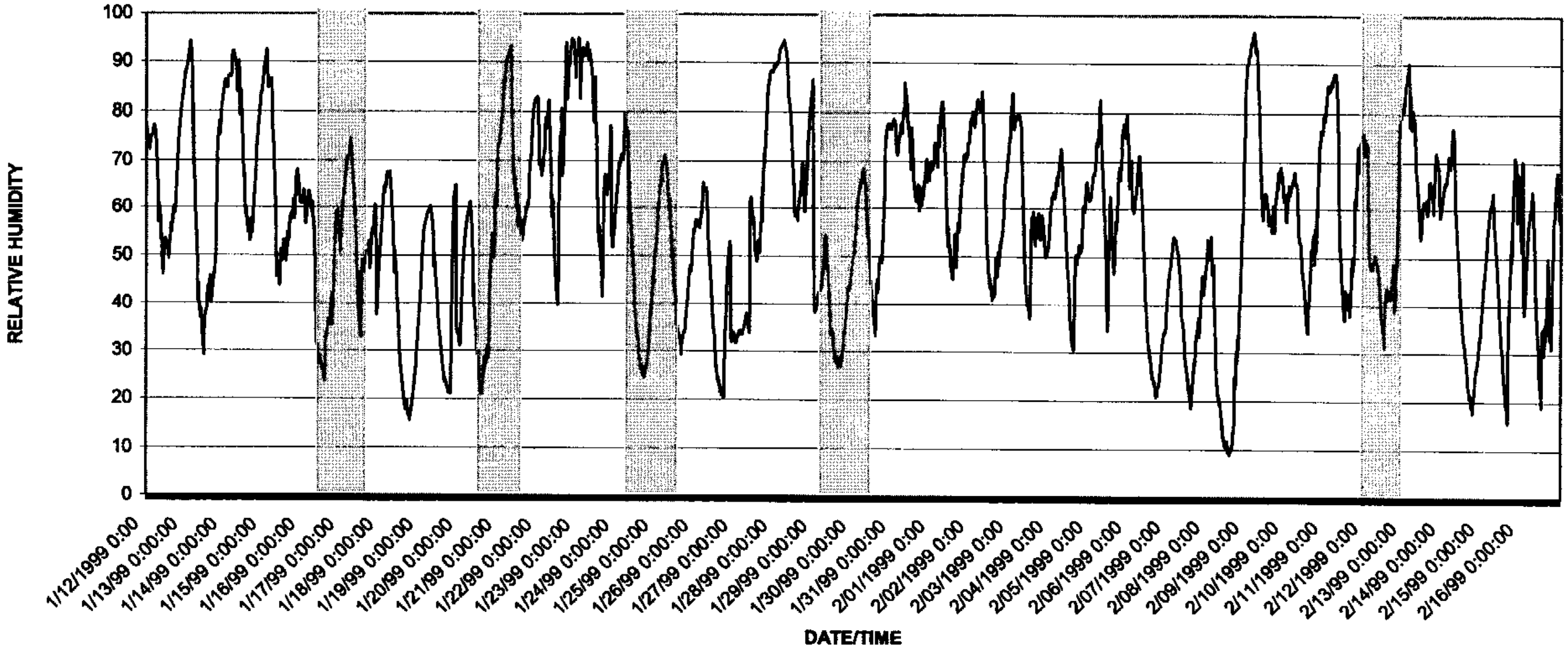


Figure A3-4 *Outdoor summer relative humidity during monitoring period with design days indicated*

A3.3 Example of monitored summer and winter temperatures in one dwelling (Dwelling 1C)

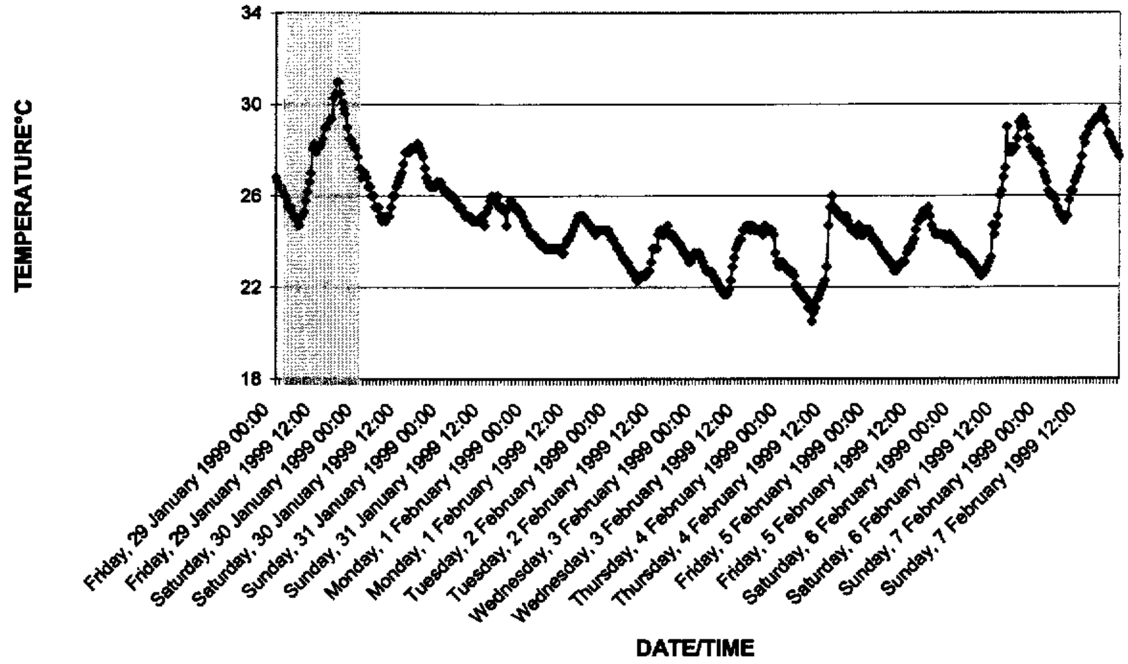


Figure A3-5 *Monitored summer temperatures with design day indicated*

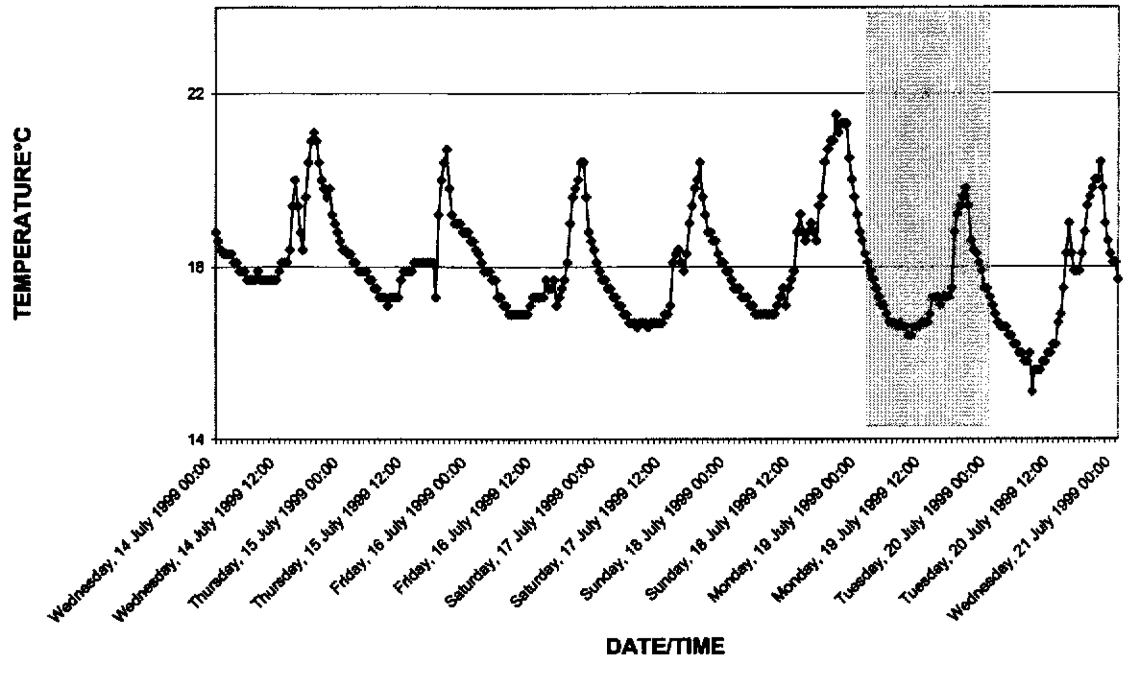


Figure A3-6 *Monitored winter temperatures with design day indicated*

A3.4 File names on CD for monitored temperatures in all dwellings

DEV. 1	DEV. 2	DEV. 3	DEV. 4	DEV. 5	DEV. 6	DEV. 7
DWELLING 1A SUMMER	DWELLING 2A SUMMER	DWELLING 3A SUMMER	DWELLING 4A SUMMER	DWELLING 5A SUMMER	DWELLING 6A SUMMER	DWELLING 7A SUMMER
DWELLING 1B SUMMER	DWELLING 2A WINTER	DWELLING 3A WINTER	DWELLING 4A WINTER	DWELLING 5B SUMMER	DWELLING 6B SUMMER	DWELLING 7B SUMMER
DWELLING 1C SUMMER	DWELLING 2B SUMMER	DWELLING 3B SUMMER	DWELLING 4B SUMMER	DWELLING 5C SUMMER	DWELLING 6C SUMMER	DWELLING 7C SUMMER
DWELLING 1C WINTER	DWELLING 2C SUMMER	DWELLING 3B WINTER	DWELLING 4B WINTER	DWELLING 5C WINTER	DWELLING 6C WINTER	DWELLING 7D SUMMER
DWELLING 1D SUMMER	DWELLING 2D SUMMER	DWELLING 3C SUMMER	DWELLING 4C SUMMER	DWELLING 5D SUMMER	DWELLING 6D SUMMER	DWELLING 7D WINTER
DWELLING 1E SUMMER	DWELLING 2D WINTER	DWELLING 3D SUMMER	DWELLING 4C WINTER	DWELLING 5D WINTER	DWELLING 6E SUMMER	DWELLING 7E SUMMER
DWELLING 1E WINTER	DWELLING 2E SUMMER	DWELLING 3D WINTER	DWELLING 4D SUMMER	DWELLING 5E SUMMER	DWELLING 6E WINTER	DWELLING 7F SUMMER
DWELLING 1F SUMMER	DWELLING 2F SUMMER	DWELLING 3E SUMMER	DWELLING 4E SUMMER	DWELLING 5E WINTER	DWELLING 6F SUMMER	DWELLING 7F WINTER
DWELLING 1G SUMMER	DWELLING 2G SUMMER	DWELLING 3E WINTER	DWELLING 4F SUMMER	DWELLING 5F SUMMER	DWELLING 6F WINTER	
DWELLING 1G WINTER	DWELLING 2H SUMMER	DWELLING 3F SUMMER	DWELLING 4G SUMMER		DWELLING 6G SUMMER	
DWELLING 1H SUMMER	DWELLING 2I SUMMER	DWELLING 3G SUMMER	DWELLING 4H SUMMER		DWELLING 6H SUMMER	
DWELLING 1I SUMMER	DWELLING 2J SUMMER				DWELLING 6H WINTER	
DWELLING 1J SUMMER	DWELLING 2J WINTER					
	DWELLING 2K SUMMER					
	DWELLING 2L SUMMER					
	DWELLING 2M SUMMER					
	DWELLING 2N SUMMER					
	DWELLING 2O SUMMER					

Table A3-1 *File names on CD for indoor monitored temperatures*

Appendix A4 - Questionnaire for multiple case study

Season 1) summer **Date** **Data logger no.**
2) winter

GENERAL

q1	Dwelling number	
q2	Gender	1) female 2) male
q3	How many occupants	1) 1 2) 2
q4	Age of occupant	1) 55-64 2) 65-74 3) 75+
q5	Years in this house	1) <1 2) 1-5 3) >5

DWELLING

q6	House Type	1) detached 2) semi-detached 3) terrace 4) semi-detached & common floor/roof
q7	Is there more than 2 sq metres of north facing glazing (between N30°E & N20°W)	1) yes 2) no
q8	Does sun shine on hard surface outside living room window in winter	1) yes 2) no
q9	Are there security grills on windows/doors to allow cross-ventilation	1) yes 2) no 3) partial
q10	Type of heating	1) gas 2) reverse cycle a.c 3) other electrical
q11	Type of cooling	0) fan 1) a.c. 2) evaporative cooling
q12	Type of hot water	1) gas instant 2) gas storage 3) elect instant 4) elect storage 5) solar
q13	Size of hot water heater [L]	1) <180 2) 180-200 3) >200
q14	Size of refrigerator [L]	1) <200

2) 200-350
3) >350
q15 Carpet 1) yes
2) no

q16 Furnishings 1) sparse
2) average
3) crowded
q17 Curtains 1) light
2) average
3) lined

OCCUPANT BEHAVIOUR

q18 Do you do anything to try and keep the house cool during the day in summer like close windows, close curtains, add external blinds
1) a little
2) a lot
3) no
q19 Do you leave windows and doors open at night in summer if it's hot inside
1) yes
2) no
q20 Do you feel a lack of privacy because of window placement
1) yes
2) no
q21 Do you have difficulty in opening/closing windows
1) yes
2) no
q22 Do windows have external sun control in summer like awning, effective pergola, effective trees/bushes, tinting 1) a little
2) adequate
3) none
q23 How many hours on average would you use your air conditioner in summer/week
0) no air conditioner
1) less than 14 hrs [2- hrs/day]
2) 14-28 hrs [2-4 hrs/day]
3) more than 28 hrs [4+ hrs/day]
q24 Hours /week use of oven 1) < 1
2) 1-2
3) 2-5
4) >5
q25 Do you know how much your last electricity bill was
1) yes
2) no
q26 Do you know how much your last gas bill was
1) no gas
2) yes
3) no
q27 How sensitive would you say you are to thermal conditions
1) very sensitive
2) sensitive
3) not so sensitive
q28 Do you do anything to try and reduce your heating needs in winter like open curtains for sun, draft stopper at doors, heavy curtains closed at night
1) a little

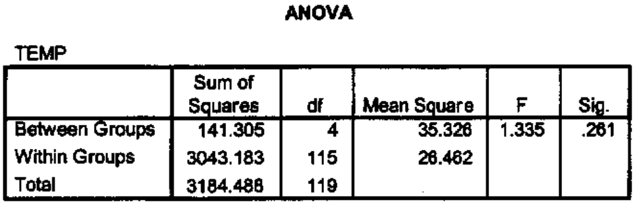
2) a lot
3) no
q29 If you feel cold in winter do you usually
1) turn on the heater
2) put on more clothes
3) become more active
4) other

q30. Living room window sun penetration in winter
1) substantial
2) a little
3) none
q31 How many hours on average would you use your heater in winter/week
1) less than 14 hrs [2- hrs/day]
2) 14-28 hrs [2-4 hrs/day]
3) more than 28 hrs [4+ hrs/day]

Appendix A5 - Statistical tests of data from multiple case study

A5.1 Typical statistical test

To determine if there was a significant difference between outdoor temperatures on the five summer design days, a one-way analysis of variance (ANOVA) was carried out using SPSS. The resulting output from SPSS is presented below.

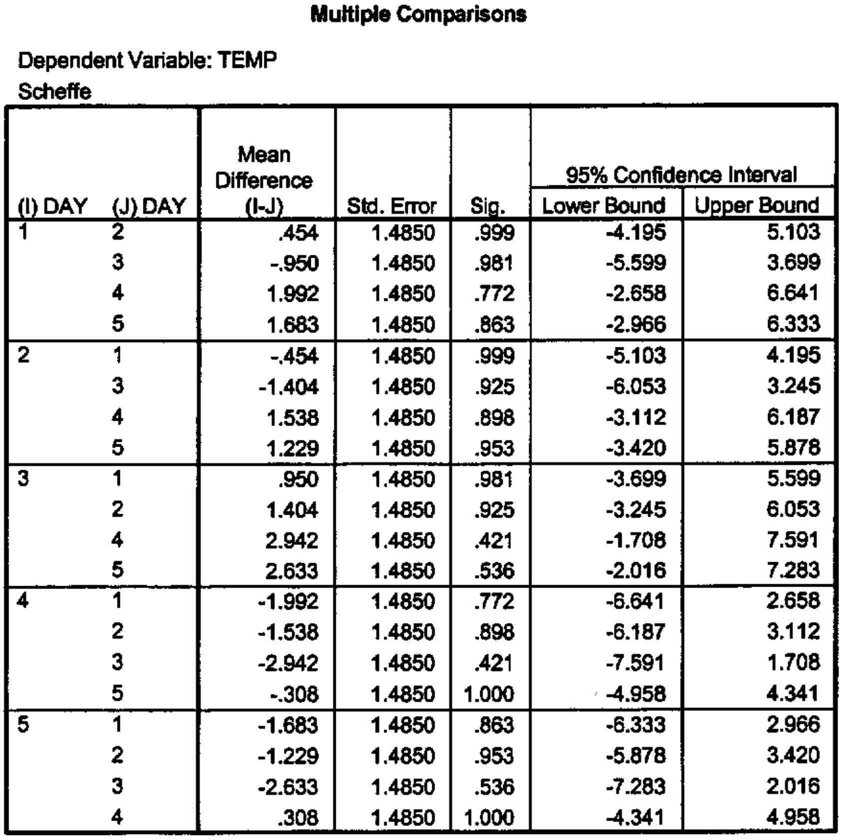


ANOVA

TEMP

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	141.305	4	35.326	1.335	.261
Within Groups	3043.183	115	26.462		
Total	3184.488	119			

Table A5-1 *One-way ANOVA indicating no significant difference between temperatures on the five summer design days*



Multiple Comparisons

Dependent Variable: TEMP
Scheffe

(I) DAY	(J) DAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	.454	1.4850	.999	-4.195	5.103
	3	-.950	1.4850	.981	-5.599	3.699
	4	1.992	1.4850	.772	-2.658	6.641
	5	1.683	1.4850	.863	-2.966	6.333
2	1	-.454	1.4850	.999	-5.103	4.195
	3	-1.404	1.4850	.925	-6.053	3.245
	4	1.538	1.4850	.898	-3.112	6.187
	5	1.229	1.4850	.953	-3.420	5.878
3	1	.950	1.4850	.981	-3.699	5.599
	2	1.404	1.4850	.925	-3.245	6.053
	4	2.942	1.4850	.421	-1.708	7.591
	5	2.633	1.4850	.536	-2.016	7.283
4	1	-1.992	1.4850	.772	-6.641	2.658
	2	-1.538	1.4850	.898	-6.187	3.112
	3	-2.942	1.4850	.421	-7.591	1.708
	5	-.308	1.4850	1.000	-4.958	4.341
5	1	-1.683	1.4850	.863	-6.333	2.966
	2	-1.229	1.4850	.953	-5.878	3.420
	3	-2.633	1.4850	.536	-7.283	2.016
	4	.308	1.4850	1.000	-4.341	4.958

Table A5-2 *Post hoc tests*

TEMP

Scheffe[a]

DAY	N	Subset for alpha = .050
		1
4	24	26.004
5	24	26.313
2	24	27.542
1	24	27.996
3	24	28.946
Sig.		.421

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 24.000.

Table A5-3 *Homogenous subsets*

A5.2 File names on CD for statistical tests

File name	Test used	Brief description
DATA FILE		-questionnaire responses -gas & electricity consumption -annual gas & electricity consumption/ dwelling -annual gas & electricity consumption/ dwelling/m^2 -winter gas consumption/ dwelling/m^2 -quartile gas & electricity consumption -summer & winter temperatures on design days -hourly monitored temperatures -mean daily monitored temperatures -mean night monitored temperatures -maximum monitored temperatures -minimum monitored temperatures -monitored diurnal temperature range -hourly outdoor temperatures
ANOVA OUTDOOR	ANOVA	To determine if there was a significant difference between outdoor temperatures on five summer design days
T-TEST-1	t-test	To determine if there was significant differences in mean temperatures between temperatures in 1 and 2 bedroom dwellings in summer or winter
NORMAL DISTRIBUTION-TEMPS	Shapiro-Wilk test of normality	To determine if monitored indoor temperatures on the design days displayed a normal distribution
ANOVA SUMMER-1	ANOVA	To determine if there was a significant difference in indoor temperatures on summer design day between dwellings within each development
ANOVA SUMMER-2	ANOVA	To determine if there was a significant difference in indoor temperatures on summer design days between the 7 developments
FACTOR ANALYSIS	Factor analysis	To facilitate the comparison of hourly temperatures on design days in summer between all 60 dwellings
ANOVA WINTER	ANOVA	To determine if there was a significant difference in indoor temperatures on the winter design day between all dwellings monitored
OCCUPANT BEHAVIOUR-2	Chi-square	To determine if there was a significant relationship between being a 2-person household and keeping the windows open on summer nights
OCCUPANT BEHAVIOUR-2	Chi-square	To determine if there was a significant correlation between age of the occupant and keeping the windows open on summer nights

OCCUPANT BEHAVIOUR-2	Chi-square	To determine if there was a significant relationship between a concern with privacy and keeping the windows open on summer nights
OCCUPANT BEHAVIOUR-1	Chi-square	To determine if being very sensitive to thermal conditions indicated taking positive steps to either keep a dwelling cool in summer or warm in winter
OCCUPANT BEHAVIOUR-1	Chi-square	To determine if there was a significant relationship between opening windows and age or gender of the occupant
OCCUPANT BEHAVIOUR-1	Chi-square	To determine if there was a significant association between the number of occupants in a household and the likelihood of the occupant taking an action other than turning on the heater if it was cold
ANOVA ENERGY-1	ANOVA	To determine if there were significant differences between the 7 developments in annual gas consumption/m^2, annual electricity consumption/m^2 and annual combined gas and electricity consumption/m^2
ENERGY-2	ANOVA	To determine if there was a significant difference between the 7 developments in winter gas consumption for heating
ENERGY-2	Chi-square	To determine if energy use was significantly related to being sensitive to thermal conditions
ENERGY-2	Chi-square	To determine if there were significant differences in annual electricity consumption/m^2 between air-conditioned and non-air-conditioned dwellings
T-TEST-2	t-test	To determine if there was a significant association between energy consumption/m^2 in terrace-type dwellings and in free standing dwellings
ENERGY-2	t-test	To determine if there was a significant difference between winter gas consumption/m^2 in the 3 developments where all dwellings having northerly window orientation and the other 4 developments
T-TEST-3	t-test	To determine if there was a significant relationship between indoor winter temperatures and mean winter gas consumption/m^2
ENERGY-2	t-test, Chi-square	To determine the relationships between energy consumption/m^2 and the number of occupants in a household

Table A5-4 *File names on CD for statistical tests*

Appendix A6 - Data base for detailed examination - Dwellings 4A, 4B, 5D & 5E

A6.1	Plans
A6.2	Questionnaire results
A6.3	Monitored temperatures
A6.4	Computer simulated temperatures on design days

A6.1 Plans

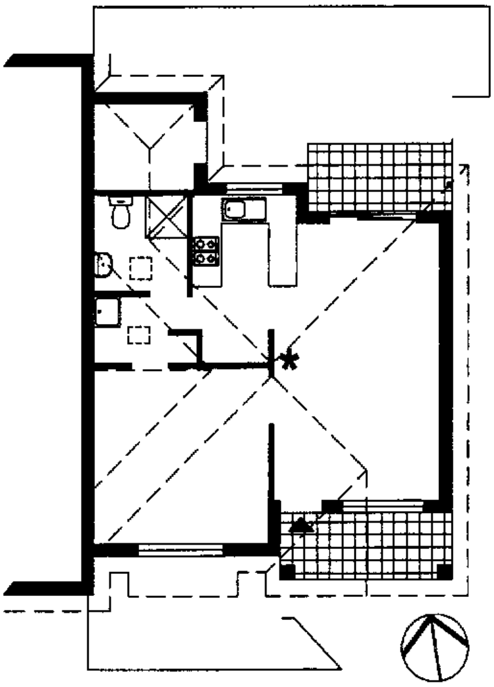


Figure A6-1 *Plan of Dwelling 4A*

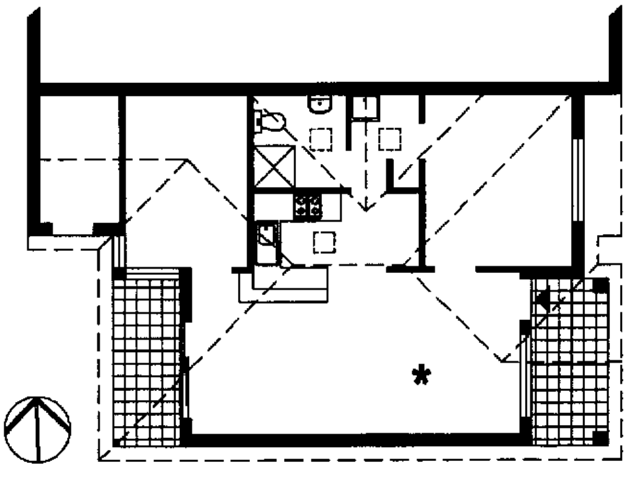


Figure A6-2 *Plan of Dwelling 4B*

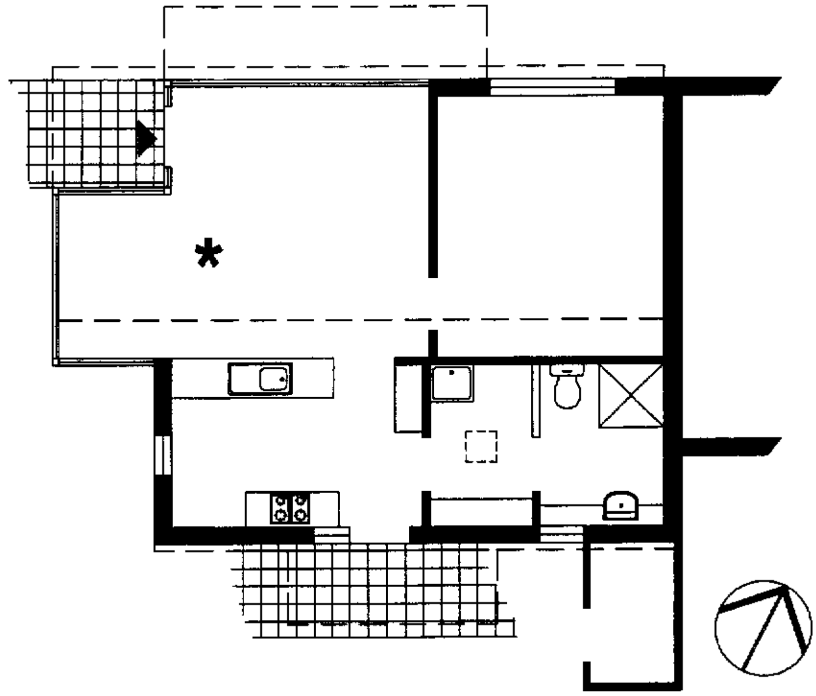


Figure A6-3 *Plan of Dwelling 5D*

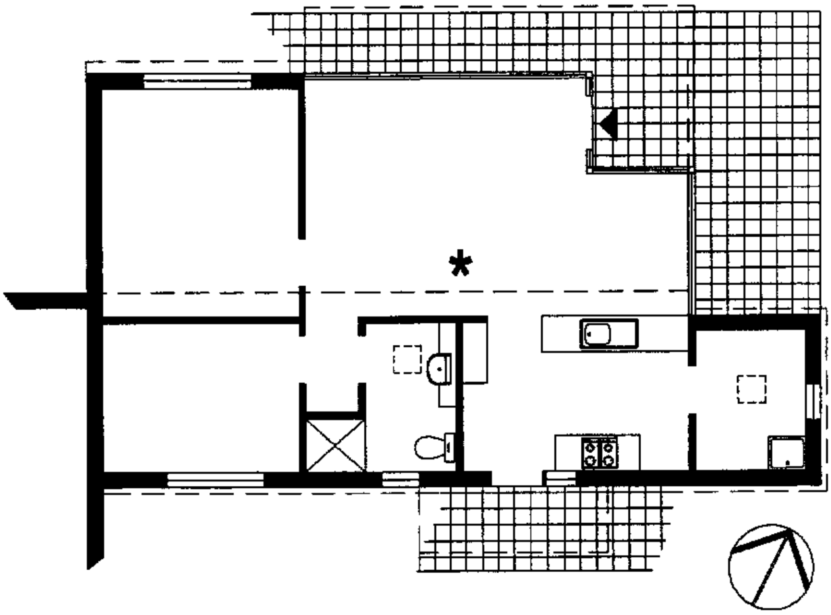


Figure A6-4 *Plan of Dwelling 5E*

A6.2 Questionnaire results

Q1 Dwelling number	**Dwelling 4A**	**Dwelling 4B**	**Dwelling 5D**	**Dwelling 5E**
Q2 Gender	Female	Female	Male	Couple
Q3 Number of occupants	1	1	1	2
Q4 Age of occupant (years)	55-64	75+	55-64	65-74
Q5 Years in this dwelling	< 1	< 1	1-5	1-5
Q6 Dwelling type	Semi-detached	Semi-detached	Semi-detached	Semi-detached
Q7 Substantial north glazing	Yes	No	Yes	Yes
Q8 Outdoor winter solar heat gain	Yes	No	Yes	Yes
Q9 Security grills	Yes	Yes	Yes	Yes
Q10 Type of heating	Gas	Gas	Gas	Gas
Q11 Type of cooling	Fan	Fan	Fan	Fan
Q12 Type of hot water service	Gas storage	Gas storage	Gas storage	Gas storage
Q13 Size of hot water tank (l)	180-200	180-200	180-200	180-200
Q14 Size of refrigerator (l)	200-350	200-350	200-350	> 350
Q15 Carpet/many rugs on floor	No	No	No	Yes
Q16 Quantity of furnishings	Average	Sparse	Sparse	Crowded
Q17 insulation properties of curtains	Average	Poor	Average	Poor
Q18 Action to keep house cool in summer	A little	A little	A little	A little
Q19 Leave windows open on summer nights	No	Yes	Yes	Yes
Q20 Concern with privacy	No	No	Yes	No
Q21 Difficulty in opening/closing windows	No	Yes	No	No
Q22 External shading of glazing in summer	A little	A little[1]	A little	A little
Q23 Average weekly use of air-con. in summer	No air-con.	No air-con	No air-con	No air-con
Q24 Average daily use of oven (hours)	1-2	<1	2-5	<1
Q25 Knowledge of cost of electricity usage	Yes	Yes	No	Yes
Q26 Knowledge of cost of gas usage	Yes	Yes	No	Yes
Q27 Sensitivity to thermal conditions	Very sensitive	Not very sens.	Not very sens	Not very sens
Q28 Action to reduce heating needs in winter	A little	A little	A little	A little
Q29 Action if feeling cold in winter	Turn on heater	Wear more clothes	Become more active	Turn on heater
Q30 Amount of sun penetration in winter	A little	None	A little	Substantial
Q31 Average weekly use of heater in winter (hrs)	< 14	14-28	< 14	14-28

Table A6-1 *Occupant responses to questionnaire*

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[1] Although there were no particular considerations given to shading on east and west glazing in Dwelling 4B, the neighbouring buildings provide significant shading.

A6.3 Monitored temperatures

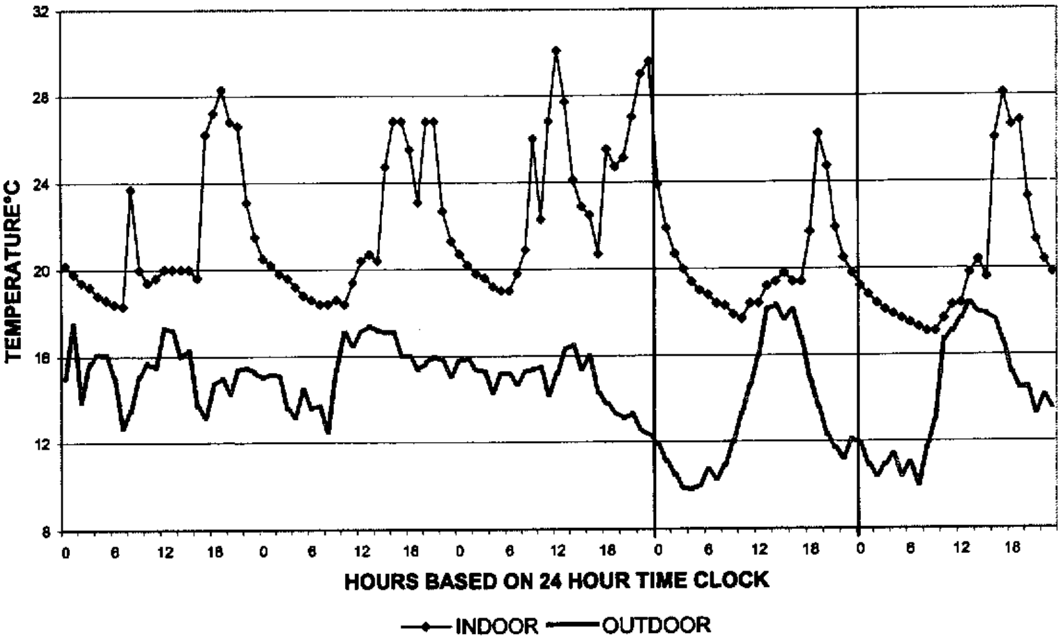

Figure A6-5 *Monitored winter temperatures in Dwelling 4A 16th –20th July (design day 19th July)*

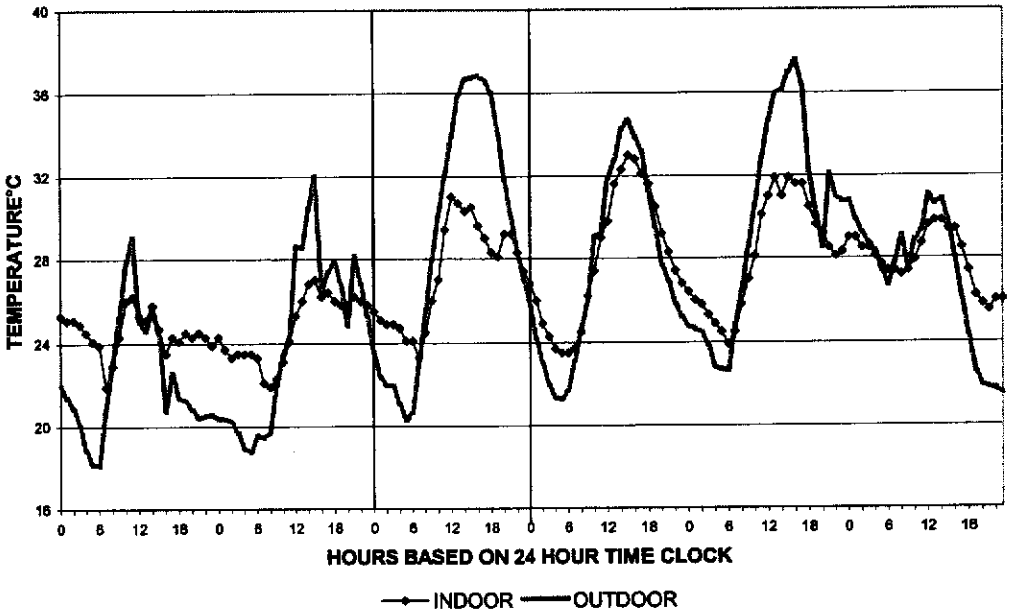

Figure A6-6 *Monitored summer temperatures in Dwelling 4A 22nd –27th January (design day 24th January)*

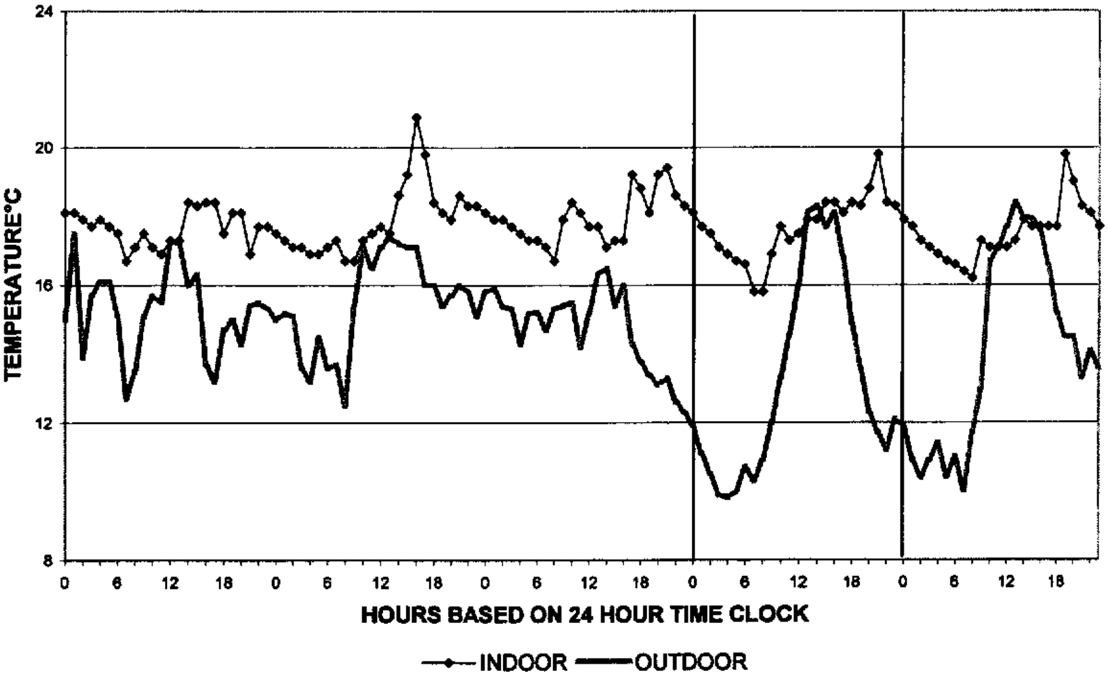

Figure A6-7 *Monitored winter temperatures in Dwelling 4B 16th –20th July (design day 19th July)*

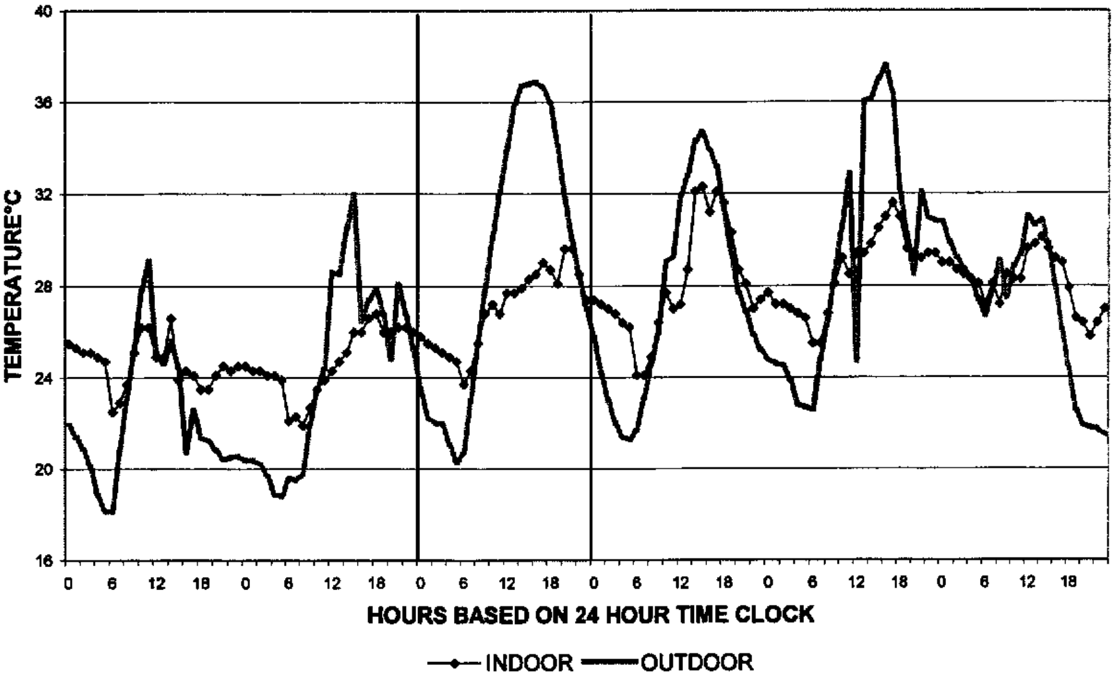

Figure A6-8 *Monitored summer temperatures in Dwelling 4B 22nd –27th January (design day 24th January)*

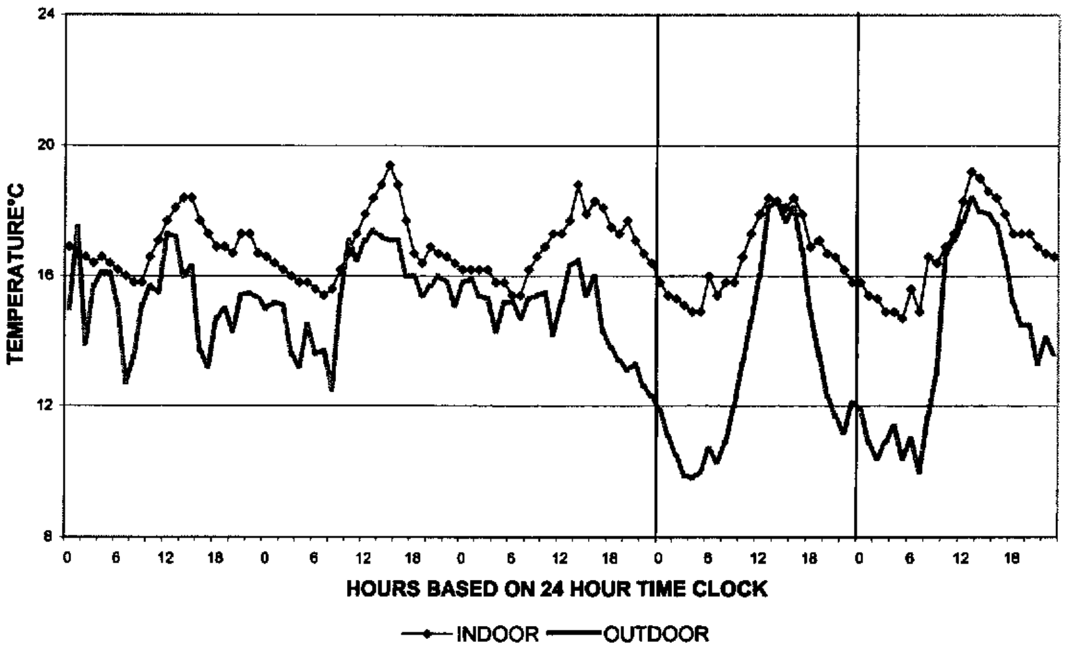

Figure A6-9 *Monitored winter temperatures in Dwelling 5D 16th –20th July (design day 19th July)*

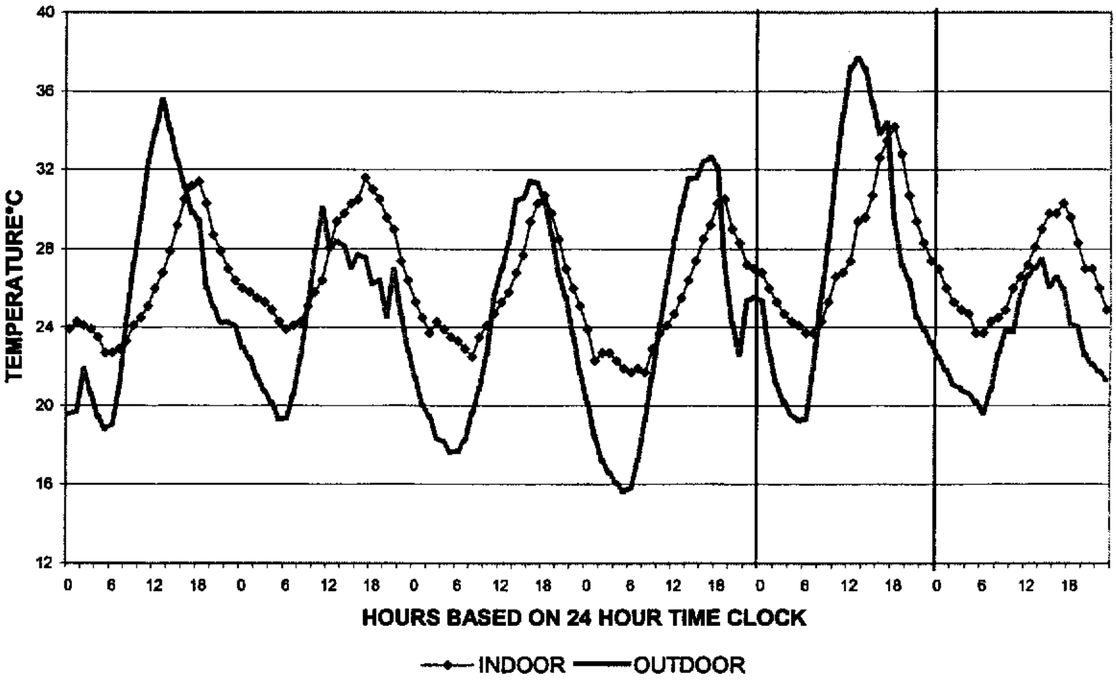

Figure A6-10 *Monitored summer temperatures in Dwelling 5D 16th –21st January (design day 20th January)*

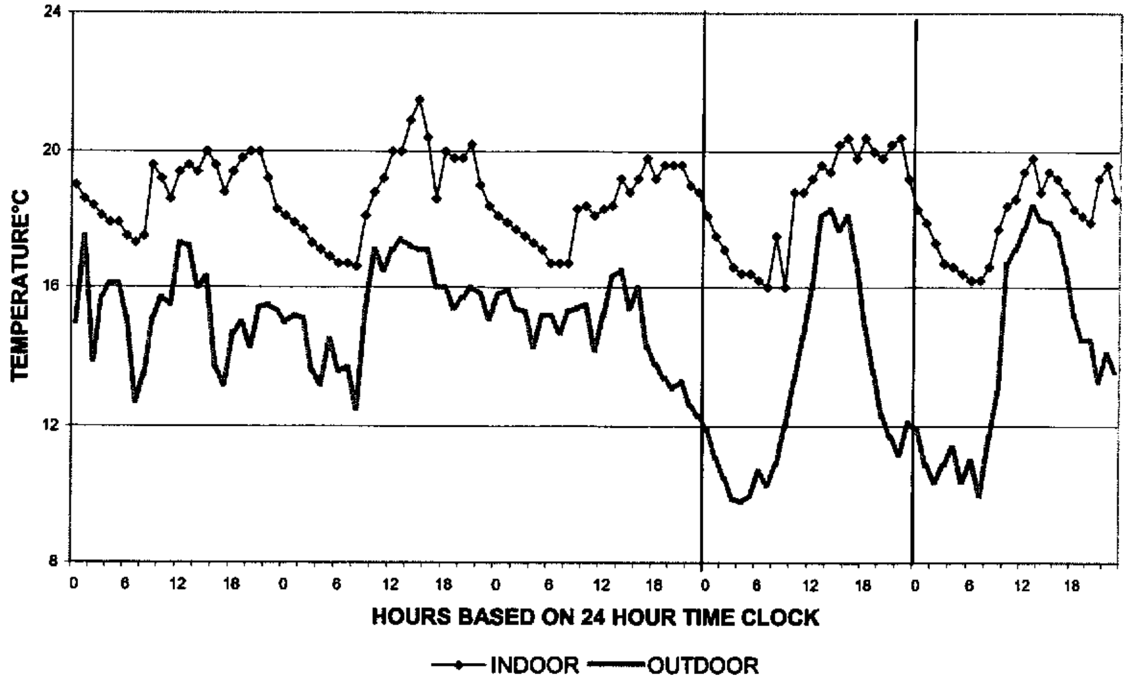

Figure A6-11 *Monitored winter temperatures in Dwelling 5E 16th –20th July (design day 19th July)*

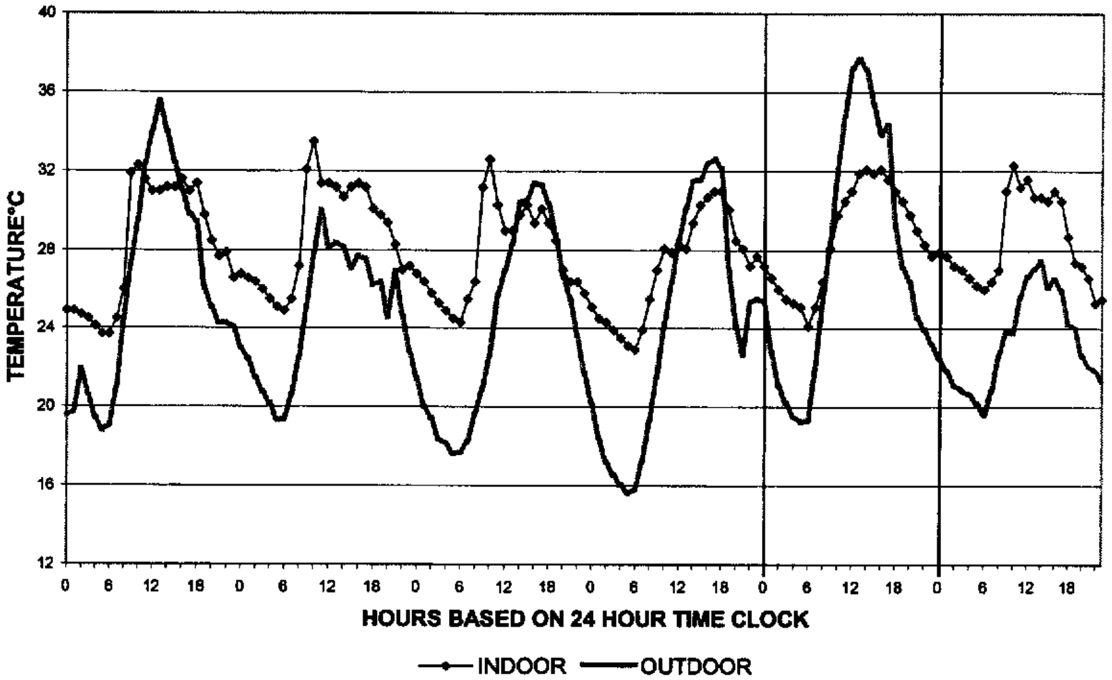

Figure A6-12 *Monitored summer temperature in Dwelling 5E 16th –21st January (design day 20th January)*

A6.4 Computer simulated temperatures on design days

Month	Day	Hour	Outdoor	Living	BedRms	RoofSp	Monitored
1	7	0	23.5	26.1	25.7	22	25.5
1	7	1	22.3	25.5	25.5	21	25.1
1	7	2	22	25.1	25.3	20.6	24.9
1	7	3	22	24.9	25.1	20.7	24.9
1	7	4	21.1	24.5	24.9	20.2	24.7
1	7	5	20.3	24	24.6	19.5	24.1
1	7	6	20.7	23.9	24.5	19.7	24.1
1	7	7	23	24.4	24.8	22.4	23.3
1	7	8	25.5	25.6	25	26.4	24.5
1	7	9	27.9	26.4	25.2	30.2	26
1	7	10	30.1	26.6	25.4	34.4	27
1	7	11	32.1	27.1	25.6	39	29.4
1	7	12	34	27.6	25.9	43.9	31
1	7	13	35.9	28.3	26.2	46.7	30.7
1	7	14	36.7	28.8	26.4	46.9	30.3
1	7	15	36.8	29.2	26.6	45.5	30.5
1	7	16	36.9	29.5	26.8	43.9	29.6
1	7	17	36.6	29.6	26.9	41.9	29
1	7	18	36	29.8	27	39.2	28.3
1	7	19	34.1	30.7	27	35.8	28.1
1	7	20	31.8	29.5	27	32.2	29.2
1	7	21	30	29.1	27	29.6	29.2
1	7	22	28.4	28.9	27	27.8	28.3
1	7	23	27	28.1	27.2	26.3	27.4
7	27	0	11.9	17.8	18.4	11.7	23.9
7	27	1	11.1	17.7	18.4	10.3	21.9
7	27	2	10.5	17.5	18.3	9.1	20.7
7	27	3	9.9	17.4	18.3	7.9	20
7	27	4	9.8	17.3	18.2	7.4	19.4
7	27	5	10	17.2	18.2	7.5	19
7	27	6	10.7	17.1	18.2	8.2	18.8
7	27	7	10.3	17	18.2	8.4	18.4
7	27	8	10.9	17.7	17.9	9.5	18.3
7	27	9	12	17.4	17.9	14.2	17.9
7	27	10	13.3	17.5	18	20.3	17.7
7	27	11	14.6	18	18.1	24.8	18.4
7	27	12	16	18.4	18.3	27.5	18.4
7	27	13	18.1	18.9	18.4	28.7	19.2
7	27	14	18.3	19.1	18.5	27.9	19.4
7	27	15	17.7	19.2	18.6	25.3	19.8
7	27	16	18.1	19.3	18.6	23.3	19.4
7	27	17	16.8	19.1	18.6	19.9	19.4
7	27	18	14.9	19	18.5	15.2	21.7
7	27	19	13.6	20	18.5	12.2	26.2
7	27	20	12.3	19	18.5	10.6	24.7
7	27	21	11.7	18.9	18.4	9.7	21.9
7	27	22	11.2	18.7	18.4	9.1	20.5
7	27	23	12.1	18.3	18.6	9.4	19.8

Table A6-2 *Design days for typical existing one-bedroom dwelling (Dwelling 4A)*

Month	Day	Hour	Outdoor	Living	BedRms	RoofSp	Monitored
1	7	0	23.5	26.1	26	22	25.8
1	7	1	22.3	25.5	25.7	20.9	25.5
1	7	2	22	25.1	25.5	20.6	25.3
1	7	3	22	24.9	25.3	20.6	25.1
1	7	4	21.1	24.5	25.1	20.2	24.9
1	7	5	20.3	24	24.8	19.5	24.7
1	7	6	20.7	23.9	24.7	19.7	23.7
1	7	7	23	24.7	24.9	22.4	24.3
1	7	8	25.5	25.9	25.2	26.4	25.5
1	7	9	27.9	26.7	25.4	30.3	26.8
1	7	10	30.1	26.9	25.6	34.4	27.2
1	7	11	32.1	27.3	25.9	39	26.8
1	7	12	34	27.7	26.2	44	27.7
1	7	13	35.9	28.3	26.5	46.7	27.7
1	7	14	36.7	28.7	26.7	47	27.9
1	7	15	36.8	29.1	26.9	45.6	28.3
1	7	16	36.9	29.4	27.1	44	28.5
1	7	17	36.6	29.8	27.2	41.9	29
1	7	18	36	30.1	27.3	39.3	28.7
1	7	19	34.1	30.4	27.3	35.8	28.1
1	7	20	31.8	29.4	27.4	32.2	29.6
1	7	21	30	29.1	27.4	29.6	29.6
1	7	22	28.4	28.8	27.4	27.8	28.5
1	7	23	27	28.1	27.6	26.3	27.4
7	27	0	11.9	17.4	18	11.7	17.9
7	27	1	11.1	17.3	17.9	10.3	17.7
7	27	2	10.5	17.2	17.9	9.1	17.3
7	27	3	9.9	17	17.8	7.9	17.1
7	27	4	9.8	16.9	17.8	7.4	16.9
7	27	5	10	16.8	17.8	7.5	16.7
7	27	6	10.7	16.8	17.7	8.2	16.6
7	27	7	10.3	16.7	17.7	8.4	16.4
7	27	8	10.9	17.3	17.5	9.5	16.2
7	27	9	12	17.4	17.5	14.2	17.3
7	27	10	13.3	17.5	17.6	20.3	17.1
7	27	11	14.6	17.7	17.7	24.9	17.1
7	27	12	16	17.8	17.9	27.5	17.1
7	27	13	18.1	18.1	18	28.7	17.3
7	27	14	18.3	18.2	18.1	27.9	17.9
7	27	15	17.7	18.3	18.2	25.3	17.7
7	27	16	18.1	18.5	18.2	23.3	17.7
7	27	17	16.8	18.6	18.1	19.8	17.7
7	27	18	14.9	18.4	18.1	15.2	17.7
7	27	19	13.6	19.1	18	12.2	19.8
7	27	20	12.3	18.3	18	10.6	19
7	27	21	11.7	18.1	18	9.7	18.3
7	27	22	11.2	18	17.9	9.1	18.1
7	27	23	12.1	17.7	18.1	9.3	17.7

Table A6-3 *Design days for typical existing two-bedroom dwelling (Dwelling 4B)*

Month	Day	Hour	Outdoor	Living	BedRms	RoofSp	Monitored
1	17	0	25.3	27.4	27.4	24.1	26.8
1	17	1	22.8	26.4	26.9	22	26
1	17	2	21.1	25.4	26.3	20.3	25.3
1	17	3	20.2	24.7	25.9	19.4	24.7
1	17	4	19.6	24.3	25.7	18.6	24.3
1	17	5	19.2	24.1	25.5	17.9	24.1
1	17	6	19.3	24.1	25.4	17.8	23.7
1	17	7	22	24.7	25.6	21.8	23.7
1	17	8	25.6	26.3	26	26.7	24.3
1	17	9	28.5	27.6	26.8	30.5	25.3
1	17	10	32.1	28.6	26.8	35	26.6
1	17	11	34.8	29.7	27.1	39	26.8
1	17	12	37.2	30.7	27.4	42.5	27.4
1	17	13	37.7	31.4	27.7	43.7	29.4
1	17	14	37.2	31.9	28	43.1	29.6
1	17	15	35.4	32.2	28.2	40.9	30.7
1	17	16	33.9	32.3	28.3	38.2	32.6
1	17	17	34.4	32.5	28.5	36.9	33.5
1	17	18	29.3	31.8	28.5	30.8	34.2
1	17	19	27.2	31.2	28.5	26.8	32.8
1	17	20	26.4	29.4	28.3	25	30.7
1	17	21	24.6	28.6	28	23	29.4
1	17	22	24	28.1	27.8	22.3	28.3
1	17	23	23.2	27.3	27.7	21.5	27.4
7	27	0	11.9	19.3	19.9	11.1	15.8
7	27	1	11.1	19	19.8	9.4	15.4
7	27	2	10.5	18.8	19.7	8.2	15.3
7	27	3	9.9	18.5	19.6	6.8	15.1
7	27	4	9.8	18.3	19.5	6.9	14.9
7	27	5	10	18.2	19.4	7.1	14.9
7	27	6	10.7	18.1	19.4	8.2	16
7	27	7	10.3	18	19.3	7.9	15.4
7	27	8	10.9	18.5	19	9.4	15.8
7	27	9	12	18.6	19	13.9	15.8
7	27	10	13.3	19.2	19	17.9	16.6
7	27	11	14.6	20	19.1	20.8	17.3
7	27	12	16	21	19.2	22.5	17.9
7	27	13	18.1	22.1	19.3	23.9	18.4
7	27	14	18.3	23.1	19.5	23.3	18.3
7	27	15	17.7	23.8	19.6	21.2	18.1
7	27	16	18.1	24.7	19.8	20.1	18.4
7	27	17	16.8	23.5	20	16.5	17.9
7	27	18	14.9	22.5	20.1	12.6	16.9
7	27	19	13.6	22.8	20.2	11	17.1
7	27	20	12.3	21.3	20.3	9.7	16.7
7	27	21	11.7	21.2	20.3	9	16.6
7	27	22	11.2	20.9	20.3	8.5	16.2
7	27	23	12.1	20.4	20.5	9.2	15.8

Table A6-4 *Design days for existing one-bed-room dwelling (Dwelling 5D)*

Month	Day	Hour	Outdoor	Living	BedRms	RoofSp	Monitored
1	17	0	25.3	27.7	28.3	24.2	27.2
1	17	1	22.8	26.7	27.7	22	26.6
1	17	2	21.1	25.7	27.1	20.3	26
1	17	3	20.2	25	26.6	19.4	25.5
1	17	4	19.6	24.7	26.3	18.6	25.3
1	17	5	19.2	24.4	26.1	17.9	25.1
1	17	6	19.3	24.6	26.2	18	24.1
1	17	7	22	25.5	26.8	23.3	25.1
1	17	8	25.6	27.2	27.5	29.3	26.4
1	17	9	28.5	28.5	28.7	33.7	28.1
1	17	10	32.1	29.5	29.6	39.5	29.8
1	17	11	34.8	30.3	29.4	44.7	30.5
1	17	12	37.2	31	29.5	49.5	31
1	17	13	37.7	31.6	29.7	51.2	31.9
1	17	14	37.2	31.9	29.9	50.4	32.1
1	17	15	35.4	31.9	30.1	47.5	31.9
1	17	16	33.9	31.7	30.2	43.6	32.1
1	17	17	34.4	31.8	30.4	40.9	31.6
1	17	18	29.3	31.2	30.2	33.1	31
1	17	19	27.2	30.5	29.7	27.6	30.5
1	17	20	26.4	29.4	29.5	25.1	29.8
1	17	21	24.6	28.7	29.1	23.1	29
1	17	22	24	28.3	28.8	22.3	28.3
1	17	23	23.2	27.6	28.9	21.5	27.7
7	27	0	11.9	19.2	19.2	11	18.1
7	27	1	11.1	18.9	19	9.4	17.5
7	27	2	10.5	18.7	18.9	8.2	17.1
7	27	3	9.9	18.4	18.8	6.7	16.6
7	27	4	9.8	18.3	18.6	6.9	16.4
7	27	5	10	18.1	18.5	7.1	16.4
7	27	6	10.7	18.1	18.4	8.1	16.2
7	27	7	10.3	17.9	18.3	7.9	16
7	27	8	10.9	18.8	18.3	10.3	17.5
7	27	9	12	19.6	19	18.4	16
7	27	10	13.3	20.5	19.5	25.3	18.8
7	27	11	14.6	21.3	19.7	29.7	18.8
7	27	12	16	21.9	19.7	31.6	19.2
7	27	13	18.1	22.4	19.6	32.2	19.6
7	27	14	18.3	22.8	19.7	30	19.4
7	27	15	17.7	22.9	19.9	26.1	20.2
7	27	16	18.1	23.1	20.1	23.8	20.4
7	27	17	16.8	22.8	20.2	18.1	19.8
7	27	18	14.9	22.1	20.2	12.8	20.4
7	27	19	13.6	22.3	20.2	11	20
7	27	20	12.3	21.3	20.3	9.7	19.8
7	27	21	11.7	21	20.3	9	20.2
7	27	22	11.2	20.7	20.2	8.5	20.4
7	27	23	12.1	20.3	20.5	9.2	19.2

Table A6-5 *Design days for typical existing two-bedroom dwelling (Dwelling 5E)*

Appendix A7 - NatHERS simulations - input and output data

A7.1 Typical SCRATCH file and hourly temperatures on the design days

A7.2 File names on CD

A7.1 Typical SCRATCH file and hourly temperatures on the design days

```
SCRATCH FILE - TYPICAL TWO-BEDROOM DWELLING -BENCHMARK COMPLIANT
0C:\NATHERS\CLIMATE\CLIMAT13
0C:\NATHERS\SCRATCH.OUT
0STDWIN.DAT
0 -31.9 115.9 120.0
0
C  16/5/03 9:5
N 1WINDOW1:  4mm single-glazed clear, Al frame, standard
1 1  21  4                         1
N 3SKYLIGHT: Double Glazed, Opal
1 3  21  450  021  4               10          0.300
N 5WALL: Cavity Brick/Insul: R 1.0
1 5  14 11043  034  5014 11024  10
N12ROOF: Roofing Tiles/Insul: None
112  26  20
N20FLOOR ON GROUND: Ground under slab
120  41   059  0
N23FLOOR: Concrete Slab/Insul: None/Cover: Vinyl
123  59  018 10032  3
N24FLOOR: Concrete Slab/Insul: None/Cover: Ceramic Tiles
124  59  018 10016  8
N27FLOOR: for Roofspace
127  24  1334 100
N31CEILING: Plasterboard/Insul: R 2.0
131  34 10024  13
N35CEILING: Above Ground
135  32   318 10059  0
N36CEILING: Above Ground
136  16   818 10059  0
N39PARTITION: Brick, plastered
139  24  1014 22024  10
N47INTERNAL: Brick, plastered
147  24  1014 22024  10
C Roof  Abs  Emit
160   0.50  0.9
C Wall  Abs   HSR  Azim  HSRP  HSDP Sched
161   0.50   20   10    0    0    0
161   0.50   20  100    0    0    0
161   0.50   20  190    0    0    0
162    65   31  0.3
C Curtain data (AddedR, Trans, Abs)*3 and terrain wind factor
163   0.030 0.250 0.350 0.030 0.250 0.350 0.030 0.250 0.350  0.63
C Outdoor blinds shading factor (up to 3)
164   1.000 1.000 1.000
C Pergola Schedules
165 1  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
165 2  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
165 3  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
165 4  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
165 5  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
165 6  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
C  Living Area
C     Area  Azim  HSRP  HSDP  HSR  HSD  VSR  VSD  Pos Curtn Blind PSched
2 1 1  10.5   10    0    0   26    5    0    0    0    1    0    0
2 1 1   5.4   10    0    0   37    7    0    0    0    1    0    0
2 1 1   0.9  100    0    0   37    7    0    0    0    1    0    0
2 1 1   3.8  190    0    0   26    5    0    0    0    1    0    0
C     Area  Azim  AdjZ                    Tilt      Skylt
2 1 5  15.3   10
2 1 5  11.1  100
2 1 5  17.8  190
2 123  57.0        4
2 131  57.0        3
2 139  12.0        2
2 147  24.0
```

```
C Bed Rooms
2 2 1  0.5  190   0   0  138   25   0   0   0   1   0   0
C     Area  Azim  AdjZ                   Tilt     Skylt
2 2 3  0.2  190                      68        99
2 2 5  9.1  190
2 224  8.0        4
2 231  8.0        3
2 239 12.0        1
2 247  2.4
C RoofSpace
C     Area  Azim  AdjZ                   Tilt     Skylt
2 312 77.3
2 327 57.0        1
2 327  8.0        2
C Ground
C     Area  Azim  AdjZ                   Tilt     Skylt
2 420 65.0
2 435 57.0        1
2 436  8.0        2
300    3   1   2   3
301  LivingBedRmsRoofSpGround
C  Curtain Closing Times
401     18   18
C  Curtain Opening Times
402      7    7
C  Curtains Drawing Temps
403     28   28
C  Curtains Drawing Solar
404    200  200
C  External Blinds Drawing Temps
405     24   24
C  External Blinds Drawing Solar
406     75   75
C  Summer Vent, On Times
407     18   18
C  Summer Vent, Off Times
408      9    9
C  Summer Vent, On Temps
409   25.0  25.0
C  Summer Vent, Off Temps
410   17.0  17.0
C  Summer Vent, A Factor, AirChanges = A + B*sqrt(V)
411   20.0  3.0
C  Summer Vent, B Factor
412    1.0  10.0
C      Sensible then latent internal heat gain (watts), [hour]          HIGHLIGHTED MANUAL ADJUSTMENTS
5 1 1  100  100  100  100  100  100  100  233  233  135  135  135
5 1 2  135  135  135  135  135  258  408  408  408  408  100  100
5 1 3    0    0    0    0    0    0    0   95   95   48   48   48
5 1 4   48   48   48   48   48   71   71   71   71   71    0    0
5 2 1   50   50   50   50   50   50   50    0    0    0    0    0
5 2 2    0    0    0    0    0    0    0   12   12   12   62   50
5 2 3   25   25   25   25   25   25   25    0    0    0    0    0
5 2 4    0    0    0    0    0    0    0    0    0   25   25
C   Volume Infilt
6 1    137 0.30 0.39
6 2     19 0.30 0.10
6 3     81 6.00 2.50
6 4      0 0.00 0.00
700
800 1   0   1
800 2   0   0
C     On1  Off1 Tstat  On2  Off2 Tstat  On3  Off3 Tstat
802 1   7  24 26.0
9
```

Hourly temperatures on summer and winter design days (°C)						
Month	**Day**	**Hour**	**Outdoor**	**Living**	**BedRms**	**RoofSp**
1	7	0	23.5	25.7	25.8	22
1	7	1	22.3	25	25.3	20.9
1	7	2	22	24.5	24.9	20.6
1	7	3	22	24.3	24.8	20.6
1	7	4	21.1	23.8	24.4	20.2
1	7	5	20.3	23.3	24	19.5
1	7	6	20.7	23.2	23.8	19.7
1	7	7	23	24.1	24.4	22.4
1	7	8	25.5	25.6	25	26.4
1	7	9	27.9	26.8	25.2	30.3
1	7	10	30.1	27.1	25.5	34.4
1	7	11	32.1	27.7	25.8	39
1	7	12	34	28.3	26.1	44
1	7	13	35.9	29.1	26.5	46.8
1	7	14	36.7	29.7	26.8	47
1	7	15	36.8	30.1	27	45.6
1	7	16	36.9	30.3	27.3	44
1	7	17	36.6	30.5	27.4	41.9
1	7	18	36	30.6	27.6	39.3
1	7	19	34.1	31	27.6	35.8
1	7	20	31.8	29.8	27.6	32.2
1	7	21	30	29.3	27.6	29.6
1	7	22	28.4	29	27.6	27.8
1	7	23	27	28	27.8	26.3
7	27	0	11.9	20.8	21.5	11.9
7	27	1	11.1	20.6	21.4	10.5
7	27	2	10.5	20.4	21.3	9.2
7	27	3	9.9	20.2	21.2	8
7	27	4	9.8	20	21.1	7.5
7	27	5	10	19.9	21.1	7.7
7	27	6	10.7	19.8	21	8.3
7	27	7	10.3	19.7	20.9	8.5
7	27	8	10.9	20.7	20.6	9.6
7	27	9	12	21.9	20.6	14.4
7	27	10	13.3	23.2	20.7	20.5
7	27	11	14.6	24.3	20.9	25.1
7	27	12	16	22.9	21.2	27.7
7	27	13	18.1	23.4	21.5	29
7	27	14	18.3	23.4	21.7	28.1
7	27	15	17.7	22.9	21.9	25.5
7	27	16	18.1	22.9	22	23.5
7	27	17	16.8	22.5	22.1	20
7	27	18	14.9	22.3	22.1	15.4
7	27	19	13.6	22.5	22	12.4
7	27	20	12.3	21.4	22	10.8
7	27	21	11.7	22	21.9	9.8
7	27	22	11.2	21.9	21.8	9.3
7	27	23	12.1	21.5	22	9.5

Table A7-1 *Hourly temperatures on design days for benchmark-compliant two-bedroom dwelling*

A7.2 File names on CD

File name	Brief description
EXISTING 4A HOURLY	Annual simulated temperatures with design days extracted
EXISTING 4A SCRATCH	Text file containing the building description for simulation
EXISTING 4B HOURLY	Annual simulated temperatures with design days extracted
EXISTING 4B SCRATCH	Text file containing the building description for simulation
EXISTING 5D HOURLY	Annual simulated temperatures with design days extracted
EXISTING 5D SCRATCH	Text file containing the building description for simulation
EXISTING 5E HOURLY	Annual simulated temperatures with design days extracted
EXISTING 5E SCRATCH	Text file containing the building description for simulation
BENCHMARK COMPLIANT HOURLY	Annual simulated temperatures with design days extracted
BENCHMARK COMPLIANT SCRATCH	Text file containing the building description for simulation
REGS COMPLIANT HOURLY	Annual simulated temperatures with design days extracted
REGS COMPLIANT SCRATCH	Text file containing the building description for simulation
PM1 HOURLY	Annual simulated temperatures with design days extracted
PM1 SCRATCH	Text file containing the building description for simulation
PM2 HOURLY	Annual simulated temperatures with design days extracted
PM2 SCRATCH	Text file containing the building description for simulation
PM3 HOURLY	Annual simulated temperatures with design days extracted
PM3 SCRATCH	Text file containing the building description for simulation
M1 HOURLY	Annual simulated temperatures with design days extracted
M1 SCRATCH	Text file containing the building description for simulation
M1A HOURLY	Annual simulated temperatures with design days extracted
M1A SCRATCH	Text file containing the building description for simulation
M2 HOURLY	Annual simulated temperatures with design days extracted
M2 SCRATCH	Text file containing the building description for simulation
M3 HOURLY	Annual simulated temperatures with design days extracted
M3 SCRATCH	Text file containing the building description for simulation
M4 HOURLY	Annual simulated temperatures with design days extracted
M4 SCRATCH	Text file containing the building description for simulation
M5 HOURLY	Annual simulated temperatures with design days extracted
M5 SCRATCH	Text file containing the building description for simulation
M6 HOURLY	Annual simulated temperatures with design days extracted
M6 SCRATCH	Text file containing the building description for simulation
M7 HOURLY	Annual simulated temperatures with design days extracted
M7 SCRATCH	Text file containing the building description for simulation
M8 HOURLY	Annual simulated temperatures with design days extracted
M8 SCRATCH	Text file containing the building description for simulation
M9 HOURLY	Annual simulated temperatures with design days extracted
M9 SCRATCH	Text file containing the building description for simulation
M10 HOURLY	Annual simulated temperatures with design days extracted
M10 SCRATCH	Text file containing the building description for simulation
M11 HOURLY	Annual simulated temperatures with design days extracted
M11 SCRATCH	Text file containing the building description for simulation
M12 HOURLY	Annual simulated temperatures with design days extracted
M12 SCRATCH	Text file containing the building description for simulation
M13 HOURLY	Annual simulated temperatures with design days extracted
M13 SCRATCH	Text file containing the building description for simulation
M14 HOURLY	Annual simulated temperatures with design days extracted
M14 SCRATCH	Text file containing the building description for simulation
M15 HOURLY	Annual simulated temperatures with design days extracted
M15 SCRATCH	Text file containing the building description for simulation
M16 HOURLY	Annual simulated temperatures with design days extracted
M16 SCRATCH	Text file containing the building description for simulation
M1-LS HOURLY	Annual simulated temperatures with design days extracted
M1-LS SCRATCH	Text file containing the building description for simulation
M1-AERATED BLOCKS HOURLY	Annual simulated temperatures with design days extracted

M1-AERATED BLOCKS SCRATCH	Text file containing the building description for simulation
M1-CARPET HOURLY	Annual simulated temperatures with design days extracted
M1-CARPET SCRATCH	Text file containing the building description for simulation
M3-50 HOURLY	Annual simulated temperatures with design days extracted
M3-50 SCRATCH	Text file containing the building description for simulation
M3-80 HOURLY	Annual simulated temperatures with design days extracted
M3-80 SCRATCH	Text file containing the building description for simulation

Table A7-2 *File names on CD for NatHERS simulations*