renewable energy

$P_o = \frac{1}{2} \rho \upsilon^3$

$P = G \times A \times \eta$

$Q = m \times c_p \times \Delta T$

$U_n = \frac{k}{d}$

Energy Efficient Building Design

Resource Book

Renewable Energy Centre
Brisbane Institute of TAFE

Australian CRC for
Renewable Energy Ltd

one of a series of modules in the Nationally Accredited Course
Certificate IV in Renewable Energy Technologies

BRISBANE
INSTITUTE OF TAFE

Energy Efficient Building Design

Resource Book

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CORRECTIONS

RET 209 RESOURCE BOOK

UNIT	PAGE	CORRECTION
2	1	Fig 1- replace "Absorbed and re-radiated as heat" with; "Absorbed and re-radiated"
2	2	2.3 - last sentence should read; "The Australian Government, under the Kyoto Accord, has agreed to limit the increase in CO_2 emissions for the period 1996 – 2004 to 8%".
2	5	2.6 - last sentence under General should read; "The overheating is not as great as in hot-arid areas, but conditions can be uncomfortable.........."
2	7	Table 1- the caption should read; "Heating degree days per year".
2	8	2.8 - last sentence should read; "Heating degree days can be derived for a particular month using the formula: $HDD = N \times (T_b - T_a)$ [if $T_a<T_b$] or, $HDD = 0$ [if $T_a>T_b$] And cooling degree days from: $CDD = N \times (T_a - T_b)$ [if $T_a>T_b$] or, $CDD = 0$ [if $T_a<T_b$]
2	23	3.7 – para 1 last sentence should read; "The chart shown in Figure 22, for example is for a person engaged in sedentary activity, wearing a normal lightweight suit and acclimatised to Brisbane conditions".
2	26	3.8 (continued) – para 4 should read; "**Thermal Neutrality** is the DBT at 50% RH which, averaged over a large sample of people, is found by them to be neither too hot nor too cold. This takes into account climate and habits and depends on the outdoor mean temperature as follows: $T_n = 17.6 + 0.31 \times T_{av}$ (provided that T_{av} is between 3^0C and 35^0C)
3	2	Figure 2 - the latitude angle on these diagrams is given as L, on p4, and in the List of Symbols, latitude angle is given the symbol ϕ.
3	4	2.2 (continued) - under **declination (δ)** the last section should read; "At solar noon the angle between the zenith and the sun is: $Z = (\delta - \phi)$" *Note; this formula is valid for both Northern and Southern hemispheres.*
3	6	2.4 sub-heading 1, last sentence should read; "The sun takes 4 minutes to traverse 1^0 of longitude (approximately 111km)".
3	7	2.4 (continued) sub-heading 3 should read; "**Daylight saving correction** is required if clocks have been advanced. "To convert from **local to solar time** use the following rule: solar time = local time + 4($long_{loc}$ – $long_{st}$) – E where longloc - longitude of the location

		longst - longitude of standard meridian E - equation of time correction If DST is effective at the time in question then the standard meridian must be adjusted by adding 15^0 E (one hour)".
3	7	2.5 - formula for declination should read; "$\delta = 23.45 \sin (360 \times (n - 81)/365)$"
3	9	2.7 - the equation given for azimuth (ψ) will have two possible solutions, meaning that the sun could be in either of two quadrants of the sky. In most cases this is not important, since there is only one logical solution. However, in the tropics it may not be clear which solution is correct and a second equation would need to be used as well.
3	25	3.5.1 (continued) para between Table 5 and Table 6, second sentence - Figure 20 should read; "Figure 11". Last sentence should read; "A sample table for North facing vertical planes for Brisbane is given in Table 6".
3	27	4.1 second sentence - "$\delta\theta$" should be "$d\theta$"
3	29	4.3 - the first term of the equation for I (hourly irradiance) should read; $H\pi/24$ not $H\pi/180$
3	30	4.4 - under type of surface the definition of β should read; "β - plane tilted at an angle β to the horizontal".
4	10	3.5 - the equation for T_{sky} should read; "$T_{sky} = 0.0552\ T_a^{1.5}$" *Note that in this equation both temperatures are in Kelvin.*
4	14	4.1.2 Table 5 - third column heading should read; "High emittance surfaces"
5	18	Figure 23 – u and v should be interchanged.
5	19	Top of page under SOLPOS – third line tan a should read; "tan α"
6	5	Table 2 – this is from the 1983 version of the standard; AS 2627 – Part 1, 1993 has a revised table.
8	1	**2 DESIGN FOR CLIMATE** para 2 middle of line 2 – cosequently should read; "consequently"
8	17	2.10 para 2, first line – If a glazed area of…. Should read; "If a north facing glazed area of…."
8	22	3.3 para 2 line three - …of the edge of an obstruction….. should read; "…. Of the sun in relation to the edge of an obstruction…"
10	15	8.8 – equation $Q_R = (U \times A)\ [\alpha R_o \times 11.57 - T_{sky}]$ should read; "$Q_R = (U \times A)\ [\alpha R_o \times H_o \times 11.57 - T_{sky}]$"
11	8	Table 3 – conductivities are not in SI units; multiply values by 10^2 to give W/mK
11	19	Figure 12 – the angle L (the slope of the collector to the horizontal) should be the same as the zenith angle of the sun, not the altitude angle of the sun as shown.
12	21	3.2 – the first term of the equation should be; "η_{camot} = "

Student Notes

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Preface

Solar efficient buildings use sun and shade to best heating and cooling advantage through the use of passive solar design and active solar systems. Important passive design variables include orientation, window positioning, ventilation, insulation, shading, construction materials and layout of the building. Design characteristics most applicable to a particular location depend on site considerations such as topography, solar access and landscaping. More fundamentally, appropriate design characteristics depend on prevailing climate type. Active solar systems, which include solar water and space heating devices, use collector panels and heat storage in combination with pipework or ducts for energy delivery.

This preface briefly examines the development of solar architecture, its importance, and the extent of its application in Australia today. The format of this education manual and its rationale is also discussed.

HISTORICAL BACKGROUND

Solar energy is not an exotic new energy source needing decades of further research and development before it can be practically proven. On the contrary, solar efficient building design has evolved over thousands of years.

Passive Solar Design

Excavations of ancient Greek cities show that solar architecture flourished. Entire cities were planned to allow their citizens equal access to the winter sun. Individual homes were orientated to face south. Because the Greeks worshipped the sun, there were few cultural barriers to solar architecture.

New scientific knowledge and better materials contribute to improved passive solar design today. However, the steady evolution of solar architecture has been interrupted by the discovery of seemingly plentiful and cheap fossil fuels.

The 1970's was the decade of several energy "crises" where concerns over high energy prices and depletion of non-renewable energy sources (based on fossil fuels) re-emerged. One of the solar design success stories during this period was that of the "Village Homes" project in Davis, California. Here sympathetic local government councillors paved the way for an energy efficient housing estate based on an innovative building code which resulted in significant energy savings in buildings.

Such innovative building regulations have been absent in Australia. However, during the late 1970's many-solar designed buildings appeared in the southern states of Australia. The GMI (Glass, Mass and Insulation) Council of Australia was formed in 1983 to promote energy efficient house design and construction though a process of education. Funding was provided by various private organisations, the Federal Government and State Governments in New South Wales, South Australia, Tasmania and Victoria. The GMI Council developed the "Five Star Design Rating" award for high efficiency through excellence in design and construction. This award was the result of a certification procedure which aimed to assist builders to market energy efficient home designs which passed a certain standard. The rating scheme was designed in conjunction with the CSIRO Division of Building Research.

Most of the buildings which have successfully incorporated passive solar design have been of the direct gain type. They generally incorporate thermal mass in the form of a concrete slab floor and masonry internal walls. Insulation is usually installed in the walls as well as the roof. This type of design has been proven in the temperate regions of Australia.

Active Solar Buildings

Heating and cooling systems which use separate solar collection and storage are often referred to as being active systems. Many active solar systems for space heating have been installed into buildings in Europe and North America. In Australia the climate is generally much milder and the simpler and cheaper direct gain systems have been much more popular than active systems. There are however examples of active systems in Australia which have worked well.

Perhaps the simplest and most cost effective water-based system uses low density polyethylene pipe embedded in a concrete slab floor as the heat emitter. Conventional solar hot water collectors are used to heat an in-ground concrete storage tank. Hot water is circulated from this tank through the floor slab.

Air-based heating systems have also been built. The simplest and most cost effective designs use a shallow pebble bed storage system under the concrete slab floor as both heat storage and heat emitter. An air collector running the full length of the roof provides the heat which is delivered to the storage.

Several solar air-conditioning systems have been trialled in Australia. They generally use high temperature collectors to provide the heat needed to operate Lithium Bromide absorption chillers. Although technically most have been successful, the economics of even the best designed systems have discouraged their use at present.

Solar Water Heating

Probably the best known active solar energy system is the solar water heater. Rudimentary solar water heaters were produced over one hundred years ago and used extensively in California. Between 25 and 65 per cent of homes in Cyprus, Israel and Jordan presently use solar water heating. All new buildings in Israel must install solar water heaters.

In terms of the Australian solar manufacturing industry, factory production of solar water heaters commenced in 1957 based on CSIRO research started in 1952. By 1974 there were six manufacturers developing products, and in 1988/89 35,200 units worth $70 million were built. Today both technology and complete units are being exported.

BENEFITS OF SOLAR EFFICIENT BUILDINGS

Comprehensively assessing the costs and benefits of solar efficient buildings is a complex matter. It is widely accepted however, that for a limited extra initial cost a solar efficient building accrues financial and other benefits over its lifetime. These benefits, such as fuel bill reductions and thermal comfort improvement, may accrue directly to the building occupants. There are also benefits relating to "bigger issues" such as environmental degradation which affect society in general. Some of these benefits are discussed briefly with a view to providing a rationale for more solar efficient buildings (especially housing) in Australia.

Thermal Comfort Improvement

Figure 1 shows a comparison of temperature swings in a conventional house and solar efficient house in the south-west of Western Australia. Figure 1(a) shows that temperature swings inside the conventional house are very pronounced. Figure 1(b) shows that temperature swings in the solar house are shown to be far less and generally within a comfort zone of between 18 and 25°C. However, the comfort zone is somewhat atypical in that it does not account for seasonal acclimatisation.

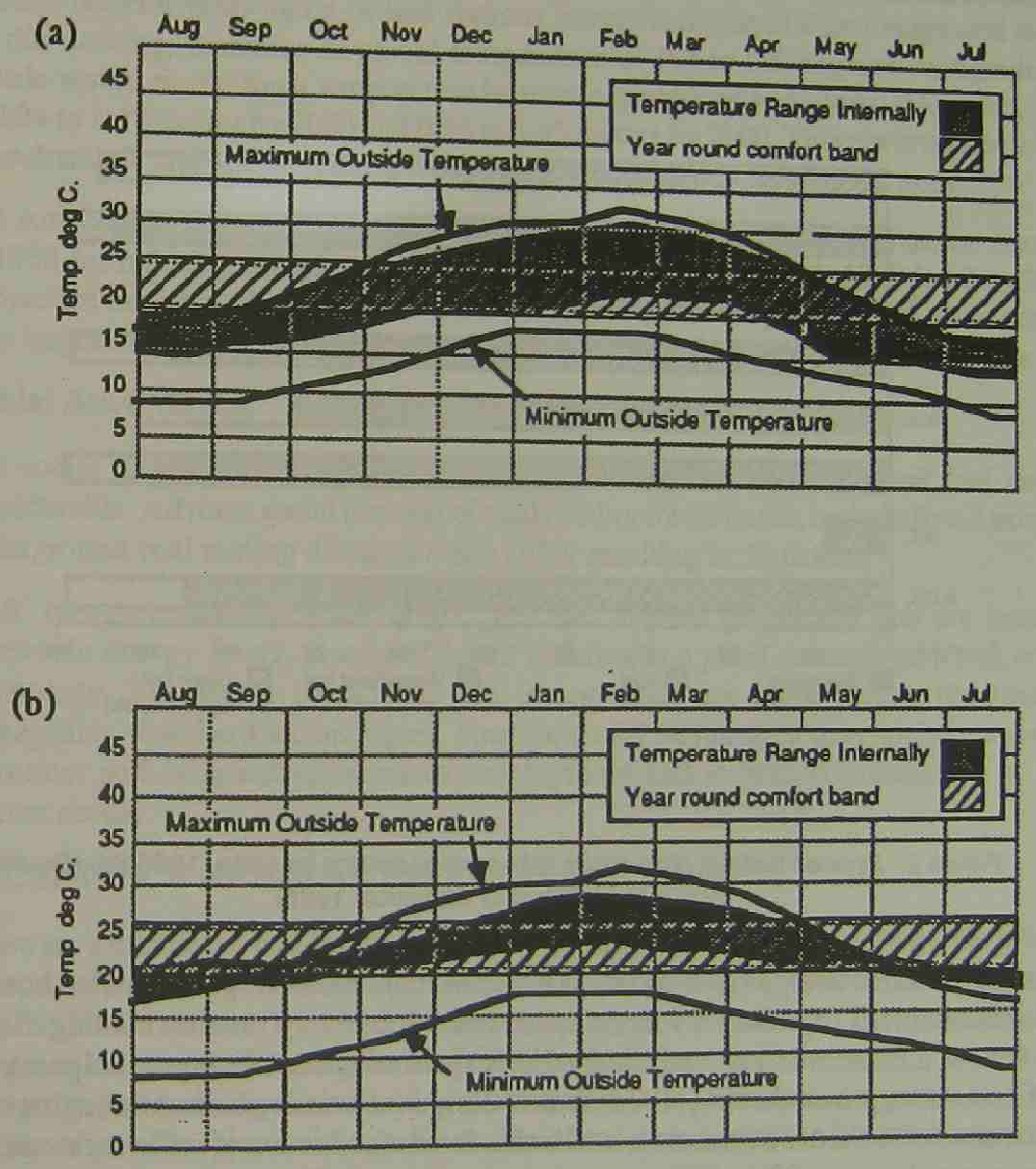


Figure 1 - (a) Graph based on temperatures documented for a conventional house monitored at Forrestfield, W.A. (b) Graph based on readings obtained from a solar efficient home in Perth. (Source: Baverstock and Paolino, 1986).

Energy Savings and Lower Fuel Bills

The residential sector accounts for about 12 per cent of final energy use in Australia. Two-thirds of this is for space and water heating.

Figure 2 shows that in 1985/86, the vast majority of Australian households had some form of space heating from non-renewable energy. Electric space heating was most commonly used, with over 58% of households in N.S.W. and the A.C.T. having electricity as the main heating source. In Victoria, about 60% of households used gas for their main heating. In Tasmania, over 50% of households used wood or other solid fuel. Less than 10% of homes in the N.T. had space heating from non-renewable fuels.

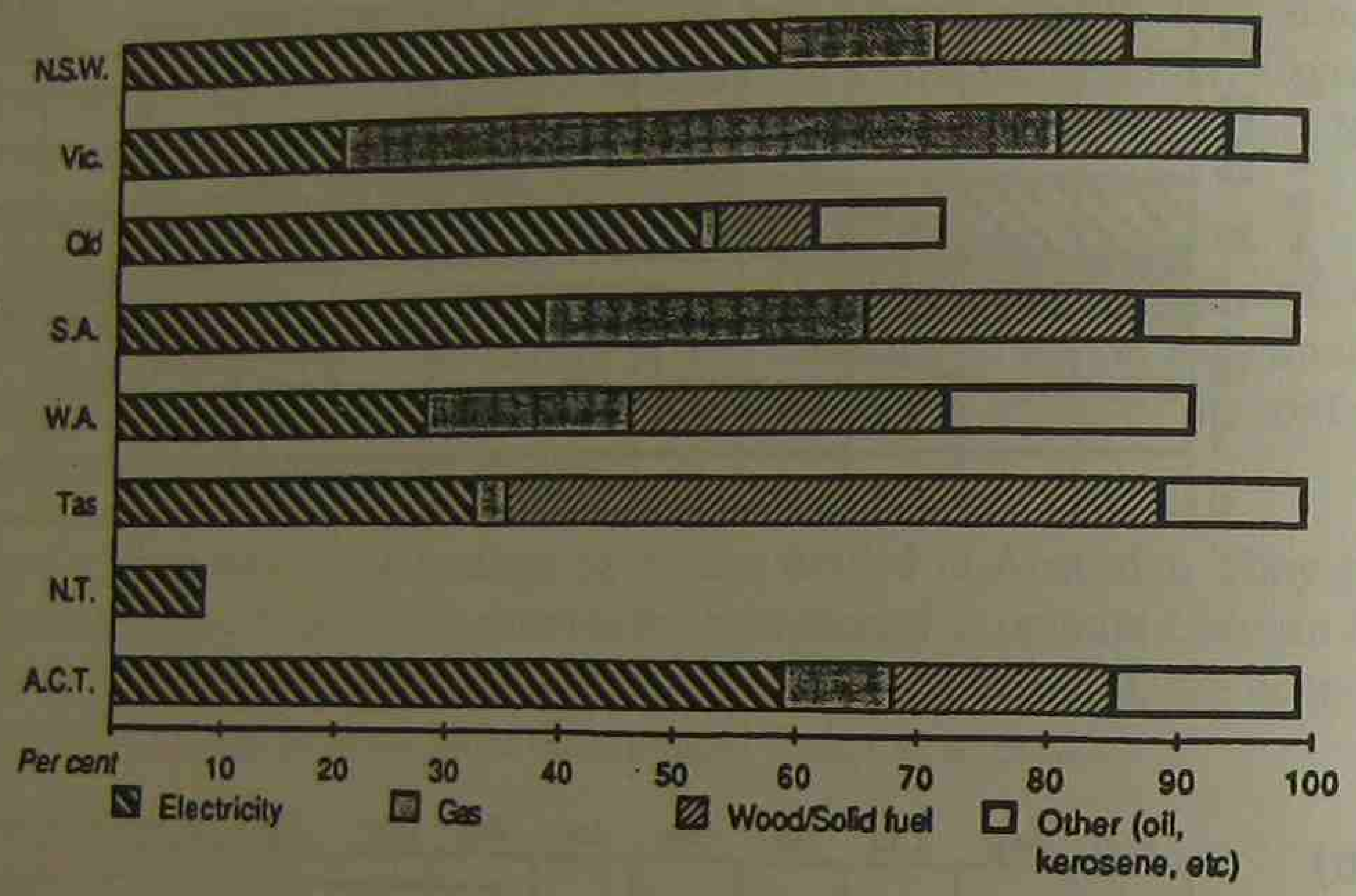


Figure 2 - Space Heating: Non-renewable energy source by state, 1985/86. (Source: Australian Bureau of Statistics, 1988).

Despite different energy types and costs between states the average Australian household spends hundreds of dollars a year on space heating but very little on cooling. Some 40 to 60% of a household's annual energy bill is spent on space heating in temperate areas. It has been suggested that improved thermal design (at little or no cost) through measures such as sensible house orientation, roof insulation and reduction of infiltration can reduce these costs by some 30 to 40%.

Space heating costs may be reduced by a further 20% through the additional use of heavy insulation in floors, walls and roof. Purpose-built houses incorporating passive solar systems can contribute much of the remaining heat requirement. In practical terms, South Australian Housing Trust experiments proved that it was possible for a solar efficient house to reduce heating bills by 60 to 70% when compared to a conventional house. However, some of these energy savings may be foregone if the householder choses to increase the number of rooms heated.

Less Pollution and Fossil Fuel Use

Most of the non-renewable energy used in buildings is in the form of electricity (from coal) or gas. These fossil fuels are finite and contribute to a range of environmental problems which are now being seen as considerable liabilities rather than as local nuisances. The World Commission on Environment and Development (1987) identified several major risks associated with fossil fuel combustion. These include urban/industrial air pollution, acidification of the environment and climate change due to the so-called greenhouse effect of carbon dioxide and other gases.

Fossil fuel combustion releases over half of the greenhouse gases that threaten the earth's climate. Several years ago a United Nations Intergovernmental Panel suggested that if we did nothing, increases in global temperature of 0.2 to 0.5 degrees centigrade per decade would result. Such temperature increases could lead to a global rise in sea level of 0.24 to 1.17 metres by 2050 and 0.56 to 3.45 metres by 2100. This sea level rise would have dramatic and adverse impacts on Australia's coastal cities.

The Australian Government has endorsed in principle, the goals of the Toronto Accords of 1988 for reducing greenhouse gas emissions by 20% from their 1988 level by 2005. In practice however, the government has indicated that it may not pursue these goals if they impose unfavourable economic impacts on Australia relative to other nations.

Social Advantages

The social disadvantages of 'hard' energy technologies based on fossil fuel use are considerable. Adverse social impacts of coal mining for example, include five Australian underground coal mining disasters since 1970, resulting in 50 deaths.

'Soft' energy technologies are simple, flexible, applied decentrally and are based on renewable energy flows. A solar efficient building is a good example of a soft energy technology. The social impacts of soft technologies are more gentle, pleasant and manageable than hard technologies. Specific social advantages may include increased consumer self-sufficiency, increased employment and increased satisfaction of basic human needs.

ACCEPTANCE OF SOLAR EFFICIENT BUILDINGS

There are a number of buildings in Australia that have been designed along solar efficient lines. *Australian Solar Houses* by Parnell and Cole (1983) included 68 case studies and was the first major work to describe solar housing in this country. The magazine *Solar Progress* has featured descriptions of 90 solar buildings over the years. *Passive Solar Design in Australia* by Greenland and Szokolay (1985) presented a series of 42 case studies of passive solar buildings. Several hundred new Australian houses have received a 5-star design rating certificate.

The extent to which solar efficient principles are used in new buildings depends fundamentally on several non-technical factors. In the broadest sense these may be seen to be associated with public policies of government and electricity authorities, and with the private sector policies of building companies, equipment suppliers and designers. Public policies of relevance may relate to building codes, energy pricing, energy education and institutional structures. Private sector policies may relate to pricing of materials, information provision, marketing of new buildings and established building practice. Consumer awareness or choice of innovative buildings is often constrained by these factors. Another constraint relates to whether or not the building is to be occupied by the owner or leased out. Typically little consideration is given to the solar design of rented buildings.

It is clear that solar design principles are not a major concern for most builders, especially those building project homes to a standard floor plan. There is some evidence that householders wanting an advanced solar efficient building have met with opposition from builders. However, some builders (of non-project houses) have recommended the use of roof and wall insulation to clients.

The most recent National Energy Survey of the Australian Bureau of Statistics showed that about 50% of Australian homes had roof insulation, although significant differences in level of use between States was evident - from a low of 18% in Queensland to a high of 79% in the A.C.T. Only about 15% of homes had wall insulation, which was most commonly used in Victoria and least commonly used in Western Australia. Interstate differences in the level of use of both roof and wall insulation are graphically presented in Figure 3.

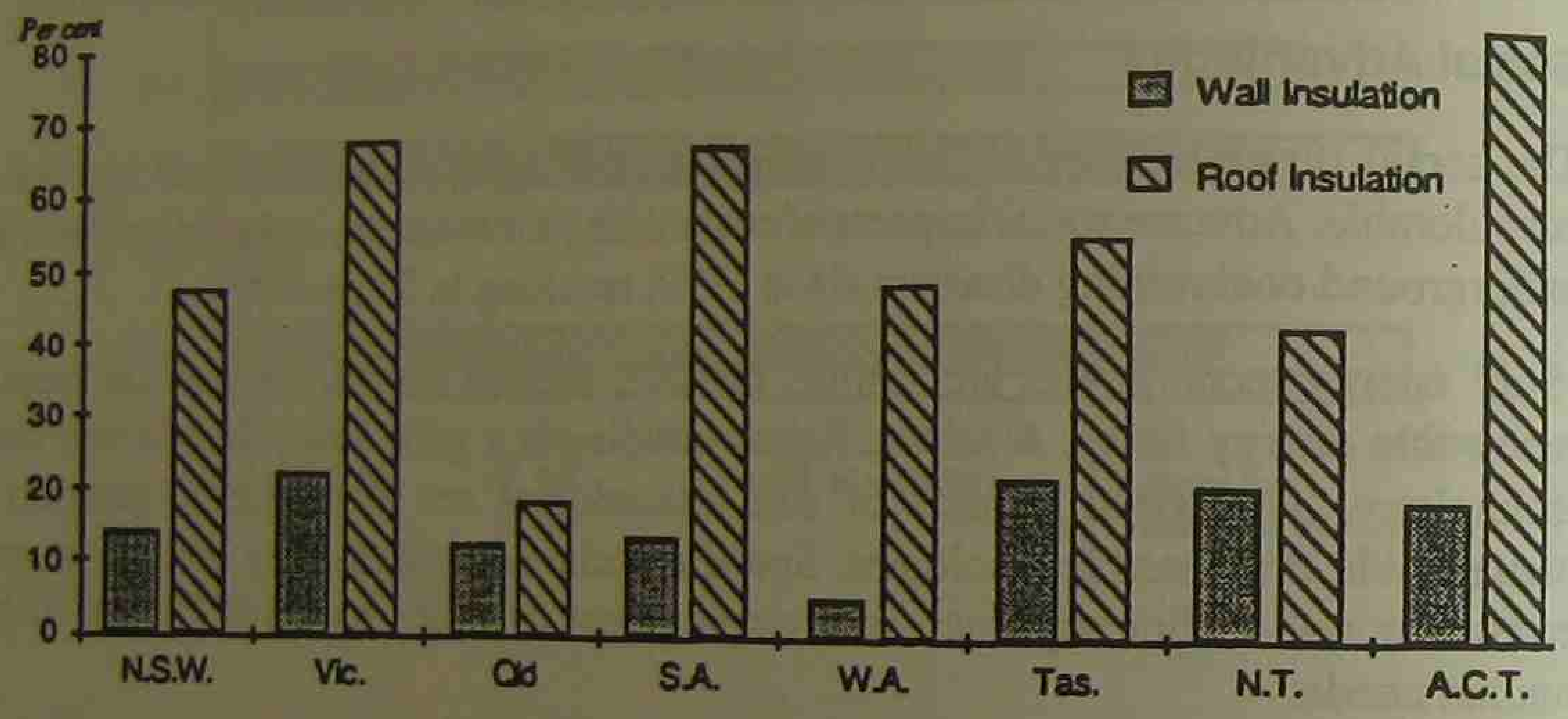


Figure 3 - Roof and wall insulation by state, 1985/86.
(Source: Australian Bureau of Statistics, 1988).

It has been suggested that the new Parliament House in Canberra is a good example of a modern building constructed without sufficient regard to solar efficiency. Most of its glazing faces east-west and has no external shading. So, although it is double-glazed to retain heat in winter the building is subject to excess heat from the sun in summer.

BOOKS ON SOLAR EFFICIENCY

Very little has been written on solar efficient design for commercial buildings, although the basic principles are the same as those for housing. Usually, however, there are more constraints and other considerations in the commercial setting.

There are a number of general and readable books on solar efficient and energy efficient housing in Australia. A number of texts have drawn together and presented case studies on solar housing. To date, however, a detailed training manual for designers and technologists has not been readily available. It is this gap that this manual is designed to fill. General texts of relevance and the plan of this manual are briefly described below.

General Texts

The following general Australian texts should be readily available for reference or purchase:

Drysdale, J.W., (1975). *Designing Houses for Australian Climates*, Canberra: AGPS.

Szokolay, S.V., and Sale, R., (1979). *The Australia and New Zealand Solar Home Book*, Sydney: Australia and New Zealand Book Co.

Kay, M., Ballinger, J.A., Hora, U., and Harris, S., (1982). *Energy Efficient Site Planning Handbook*, Sydney: Housing Commission of N.S.W.

Parnell, M and Cole, G., (1983). *Australian Solar Houses*, Sydney: Second Backrow Press.

Australian Construction Services, (1983). *Energy Efficient Australian Housing*, Canberra: AGPS.

Greenland, J., and Szokolay, S.V., (1985). *Passive Solar Design in Australia*, Red Hill, ACT: Royal Australian Institute of Architects.

The following items examine general aspects of solar efficient housing in N.S.W., Victoria and Queensland respectively:

Ballinger, J.A., Prasad, D.K., and Cassell, D.J., (1992). *Energy Efficient Housing in New South Wales*, Sydney: N.S.W. Office of Energy.

Gregory, J., and Darby, F., (Eds.) (1990). *Solar Efficient Design for Housing: A Manual for Architects and Designers*, Melbourne: Victorian Solar Energy Council.

Szokolay, S.V., (1991). *Climate, Comfort and Energy: Design of Houses for Queensland Climates*, Brisbane: University of Queensland Architectural Science Unit. (Booklet)

Plan of this Manual

Unlike most of the above texts, this manual draws together discussion of both active and passive solar systems for use in buildings. The basic purpose of this manual is to provide the technical information necessary to understand and design solar efficient buildings, with special reference to housing.

The contents of the manual are divided into largely self-contained Units (modules) ordered in sequence, as follows:

- ☐ introduction to solar efficient housing (Unit 1)
- ☐ solar theory and physical principles (Units 2 to 4)
- ☐ glazing, thermal mass and insulation (Units 5 to 7)
- ☐ advanced design issues (Units 8 to 10)
- ☐ solar water heating and other active systems (Units 11 and 12)
- ☐ building codes, economics and consumer acceptance (Unit 13).

An extensive bibliography of sources of information used is presented at the end of the manual. The detailed content of each Unit of this manual is outlined in the Table of Contents which follows.

Unit 1

Solar Efficient Housing: An Overview

1 INTRODUCTION

Solar efficient houses use sun and shade to best heating and cooling advantage. They provide a comfortable indoor environment with only minimal use of other energy sources. Solar efficient houses are in tune with the environment in terms of site and climate.

This unit discusses basic passive solar design principles and the two broad approaches relating to solar energy systems often used in solar efficient housing. These approaches involve "passive solar systems" and "active solar systems".

2 DESIGN FOR SITE AND CLIMATE

Site considerations relate fundamentally to allotment orientation, topography and landscaping. Climatic considerations relate to prevailing weather patterns, both at the macro (general) and micro (local) level.

For the purposes of design, there are three macro-climatic zones in Australia. In the **hot-humid zone** extending across far northern Australia and down the Queensland coast, temperatures remain high all year and their daily range is small. In the **hot-arid zone** covering the majority of sparsely populated Australia, both daily and seasonal ranges of temperature are wide. In the **temperate zone** covering south-eastern Australia (including Victoria and Tasmania) and south-western Australia, average temperatures are lower than for the hot-arid zone, but again wide temperature ranges occur.

3 PASSIVE SOLAR DESIGN PRINCIPLES

Among other things, houses should modify the climate to provide comfortable living conditions. A number of different design issues need to be considered in order to best achieve this goal. These "passive design" issues relate to orientation, zoning, thermal mass, glass, insulation, sun control, ventilation and landscaping. Each of these is discussed in turn below. Houses which include appropriate features relating to these issues are termed "passive solar" or "solar efficient".

3.1 Orientation

Solar house design begins with careful consideration of house orientation with respect to the site. A "true north" orientation allows maximum sun entry in winter and easiest sun exclusion in summer. If a true north orientation is not possible due to site restrictions, it is acceptable to orientate northern windows between approximately 30 degrees east of north and 15 degrees west of north. Different block orientations and acceptable house plan layouts are shown in Figure 1.

3.2 Zoning

The temperature range in each room of the house is determined by its exposure to the elements. The north side will be the warmest all year since (in the southern hemisphere) the sun is in the northern sky. The west side will be colder in winter and hotter in summer. The south side will be the coolest throughout the year.

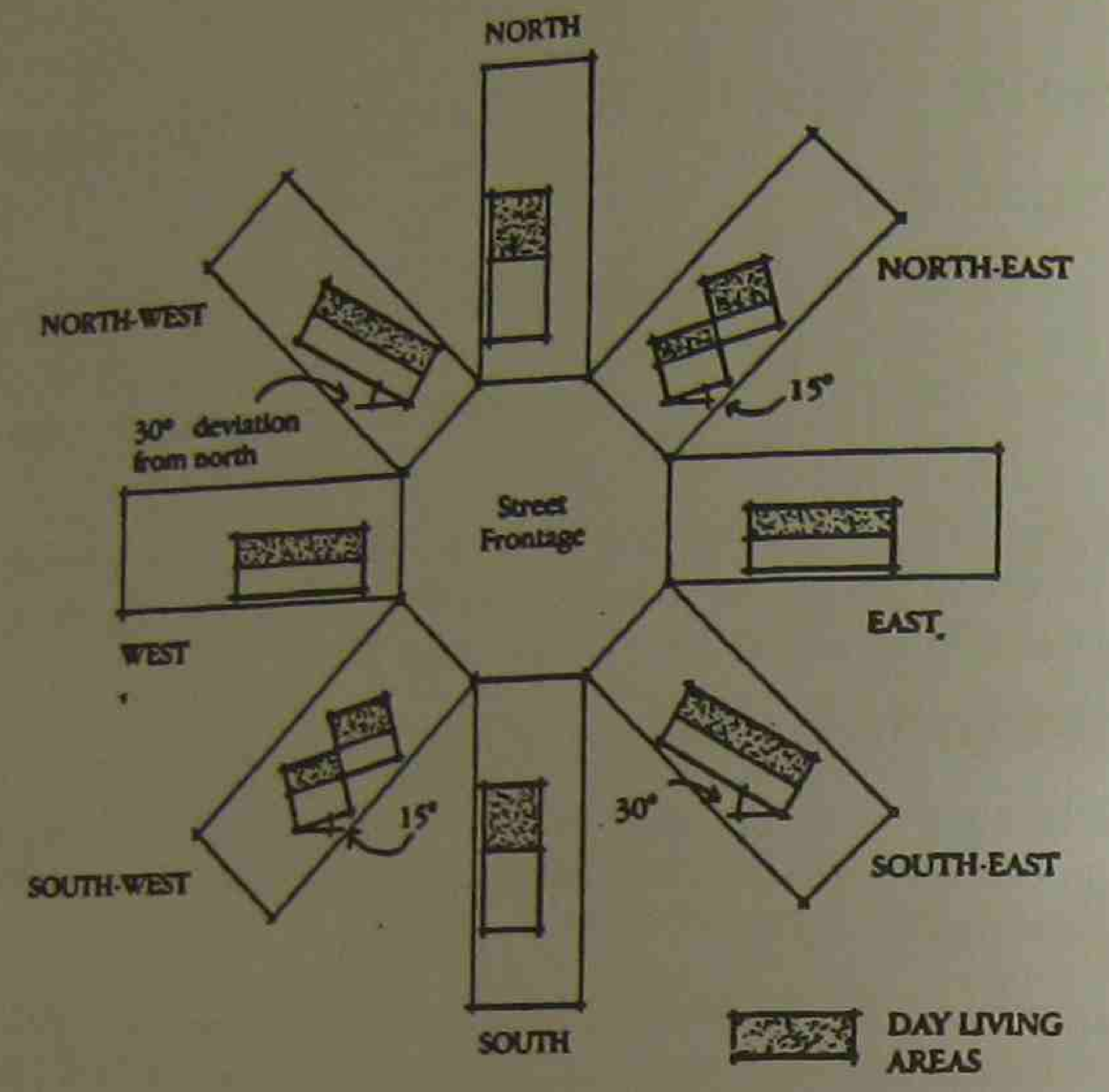


Figure 1 - Different block orientations showing acceptable plan layouts. (Source: Energy Victoria, 1991).

Day-use living areas benefit most from northern exposure. East-facing and more particularly west-facing rooms are likely to be hot. South-facing rooms are likely to be cool. Service and sleeping areas are therefore best located in the south. Living and dining areas are best located to the north (see Figure 2).

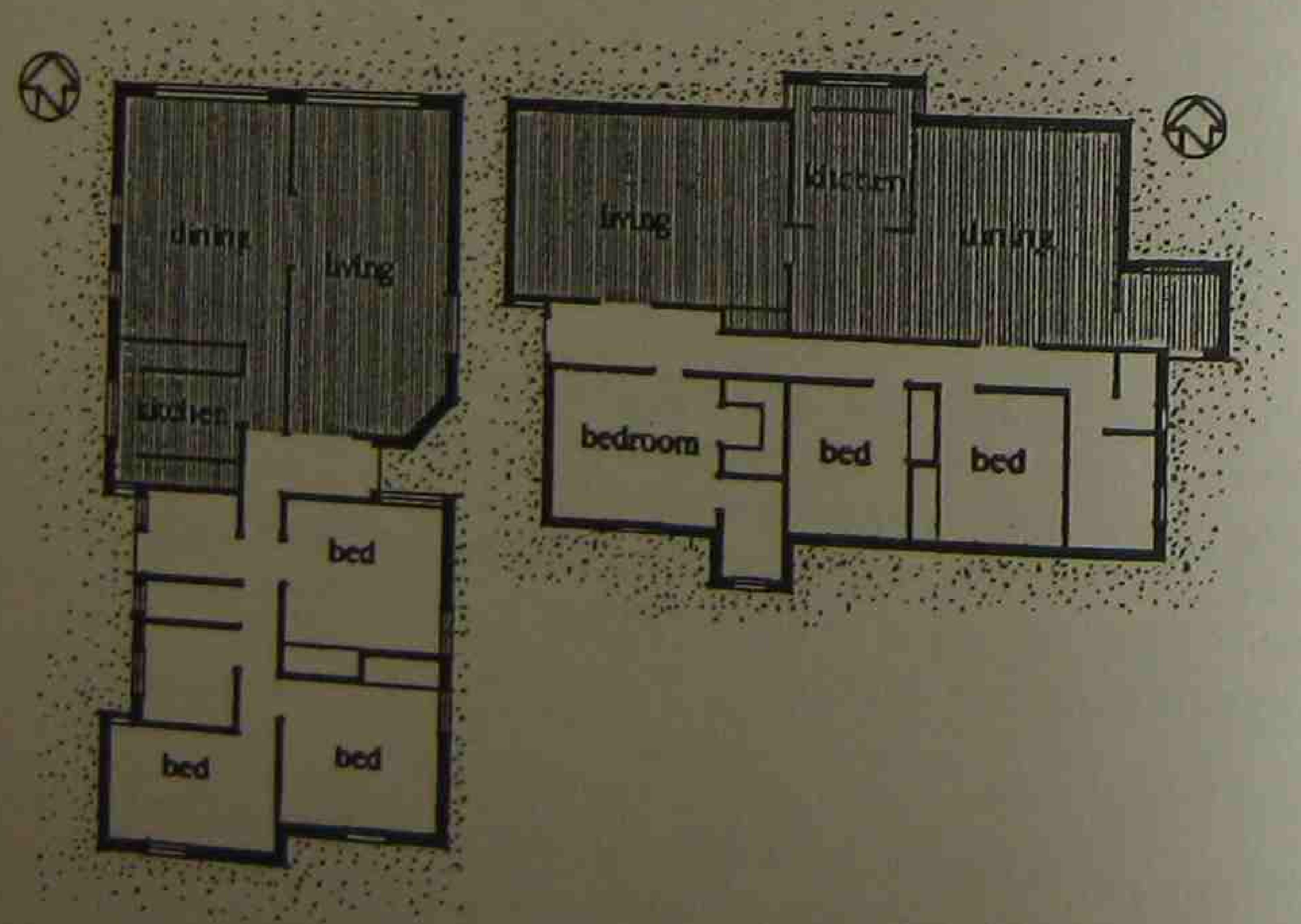


Figure 2 - Acceptable zoning for two basic plan shapes. (Source: Energy Victoria, 1991).

3.3 Thermal Mass

Heavyweight construction involves the use of massive building materials such as concrete floors and masonry walls. Such materials absorb daytime warmth from the sun then release it back into the room at night. This acts to even out temperature variations between day and night. In the temperate climatic zone thermal mass is generally a desirable feature which makes the house more comfortable.

In a hot-humid climate however, outdoor temperatures are normally high and thermal mass is generally not desirable. In this situation buildings are generally built using lightweight materials such as timber and brick veneer. These materials have low thermal mass and heat up and cool down quickly.

Houses in the hot-arid climatic zone may be built using composite construction, as shown in Figure 3. In this case, heavyweight construction would be desirable for living areas occupied by day and lightweight frame construction desirable for bedrooms and service areas.

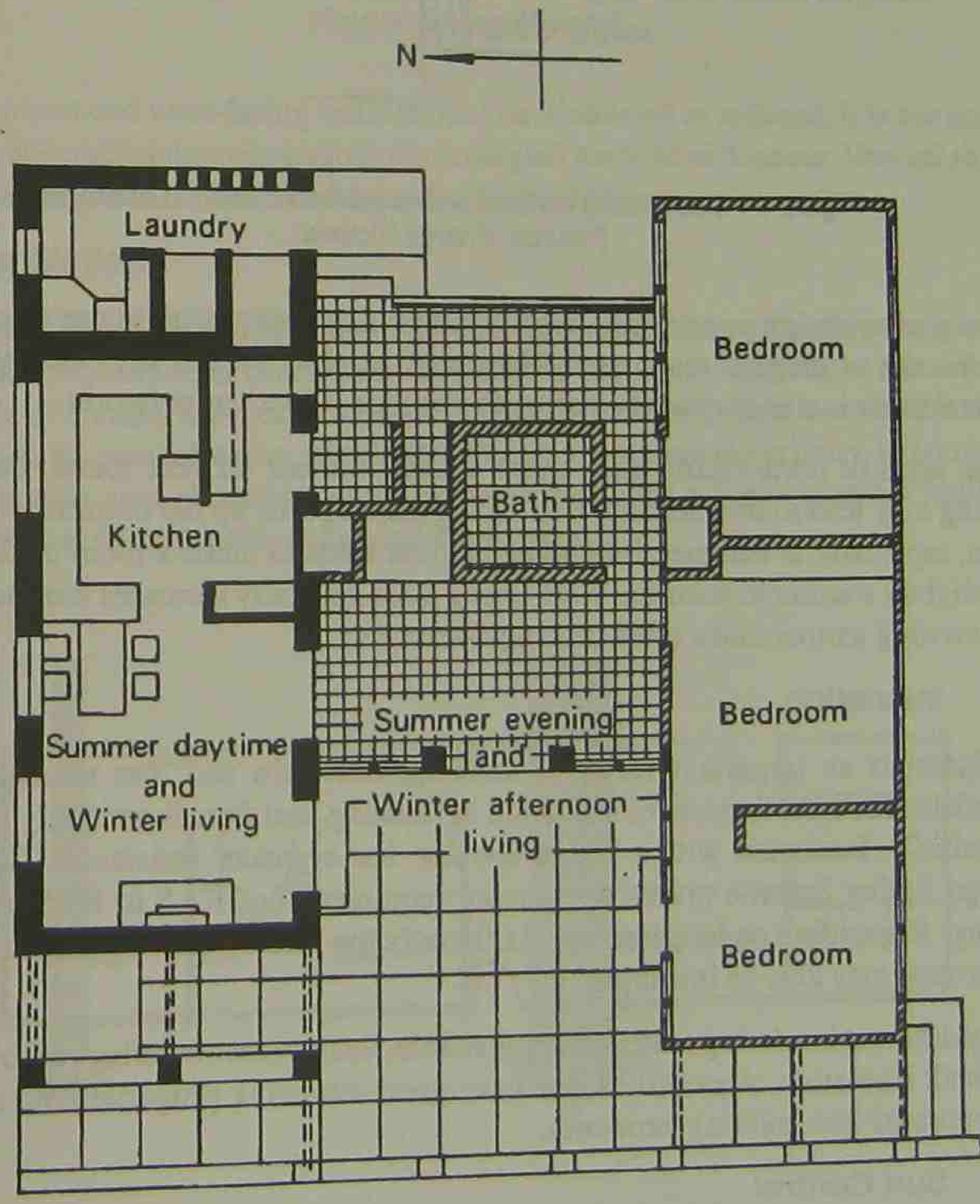


Figure 3 - House design for hot-arid climate combining heavy and light construction. (Source: Drysdale, 1975).

3.4 Glass

In energy terms, windows are the weak spot in any home. Double-glazing can reduce winter heat loss but does little to lessen direct summer sun. The use of pelmets and heavy close-fitting curtains, shown in Figure 4, also help to reduce heat loss and to lessen the extent of heat gain.

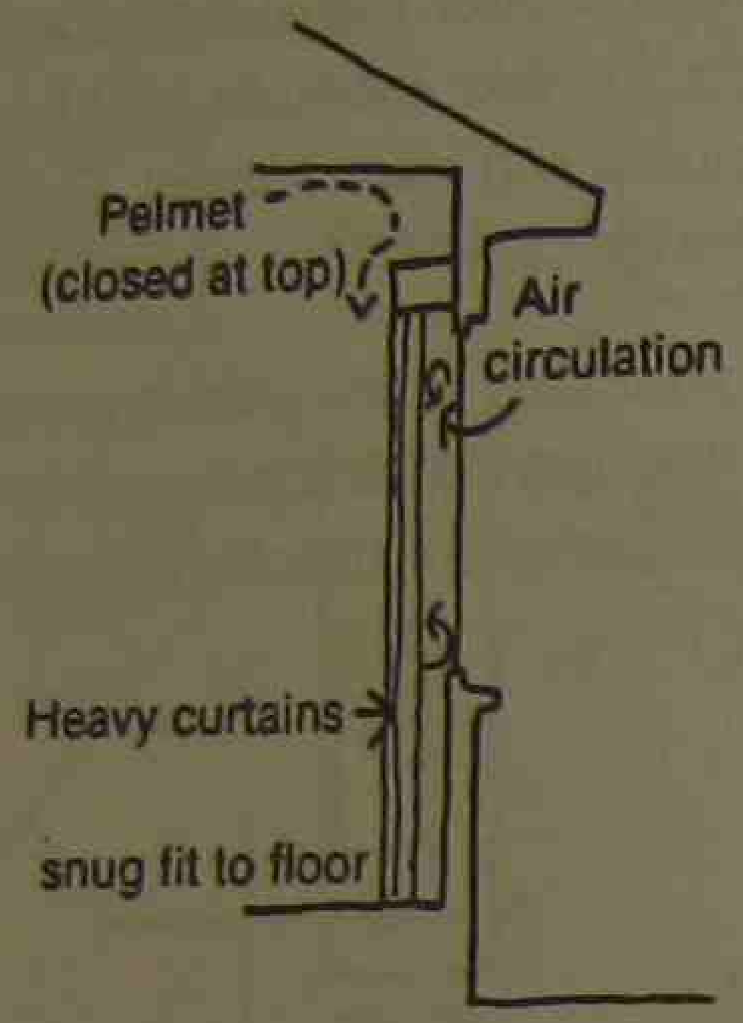


Figure 4 - Close-fitting curtains with a pelmet blocked in at the top.
(Source: Energy Victoria).

From a solar design perspective, ideal window size depends on house orientation and the amount of thermal mass used. Generally, as glass area is increased the need for thermal mass is also increased in order to stabilise indoor temperatures.

Large areas of north-facing glass make a room warmer all year round, but too much glazing may lead to overheating. East-facing glass speeds up the morning warming of a room, especially in summer. South-facing glass tends to make a room colder in winter and slightly warmer in summer. West-facing glass generally increases summer afternoon and evening temperatures often causing discomfort.

3.5 Insulation

Insulation is an important factor in reducing heat gain and loss through non-glass materials. The effectiveness of insulation in resisting heat flow is generally known as its "R-value". Insulation with a higher R-value has a greater resistance. The Five Star Design Rating Scheme places a minimum requirement of R1.5 to R3.5 insulation on ceilings (depending on location) and R1.0 insulation on external walls. Floors raised off the ground may also be insulated.

Many different insulating materials are available. Basic types are reflective foil insulation and bulk insulation. Air cavities also have good insulating properties and are usefully incorporated into building structures.

3.6 Sun Control

The sun is high in the sky during summer and low during winter. An ideal design lets in the winter sun but excludes the hotter summer sun. North-facing windows can easily be protected from the rays of the high summer sun by eaves or slatted pergolas. When correctly designed, these fixtures will still allow for winter sun penetration (see Figure 5).

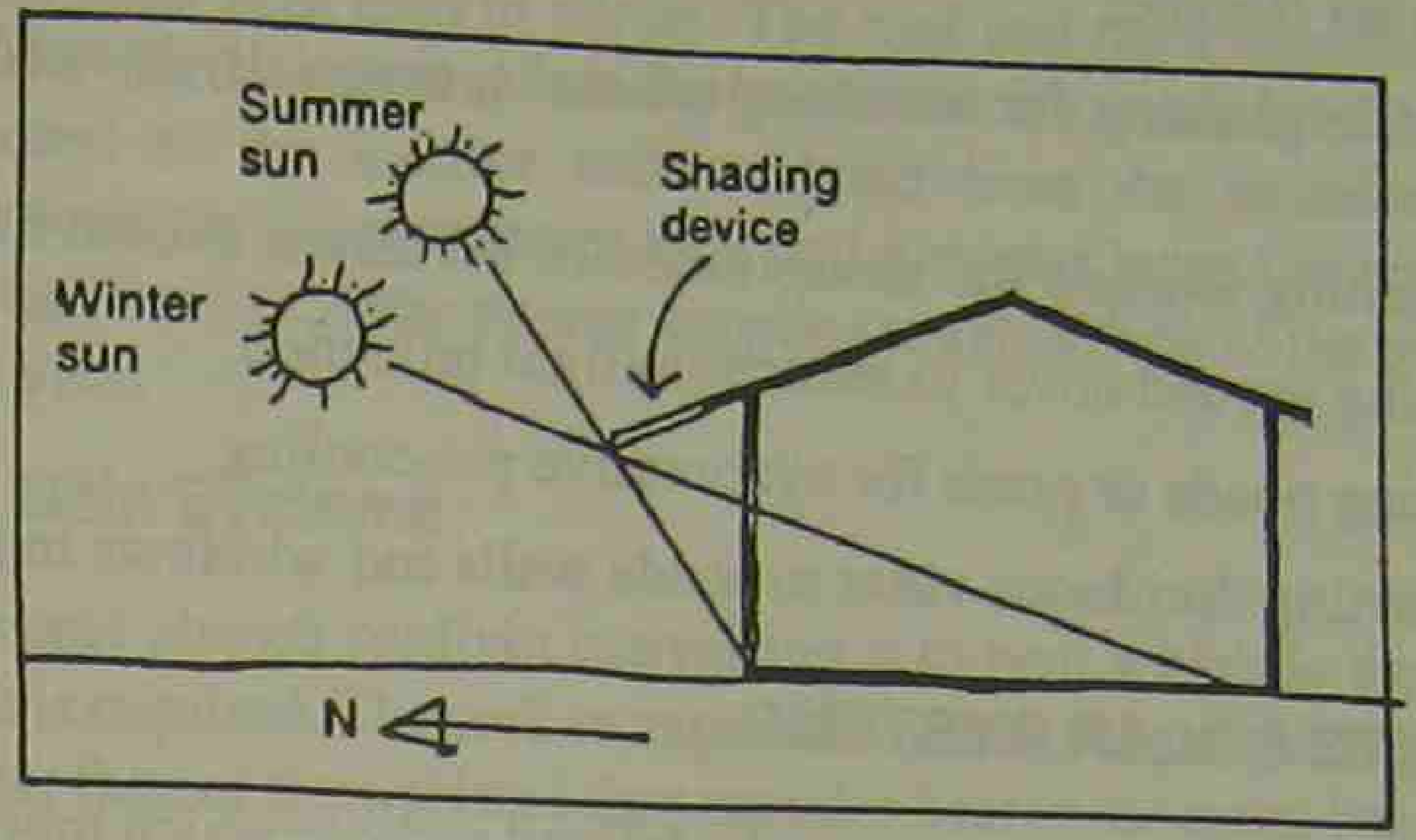


Figure 5 - Shading of north-facing windows using eaves or slatted pergolas.
(Source: Energy Victoria).

Glazing on east and west-facing walls should be eliminated or reduced. It is not possible to effectively control the penetration of low-angled sunlight with eaves. Vertical shading devices are important for east and west-facing glazing.

3.7 Ventilation

Ventilation is particularly important in hot-humid climates during summer at night when the outside temperature is cooler than the inside. Functional design must allow full use to be made of cooling breezes. Windows extending down to ground level on the air inlet side provide the most effective ventilation. Where ventilation is a priority, windows with 100% openable area should be used. Figure 6 illustrates a house plan for hot-humid climates which allows for flow-through ventilation.

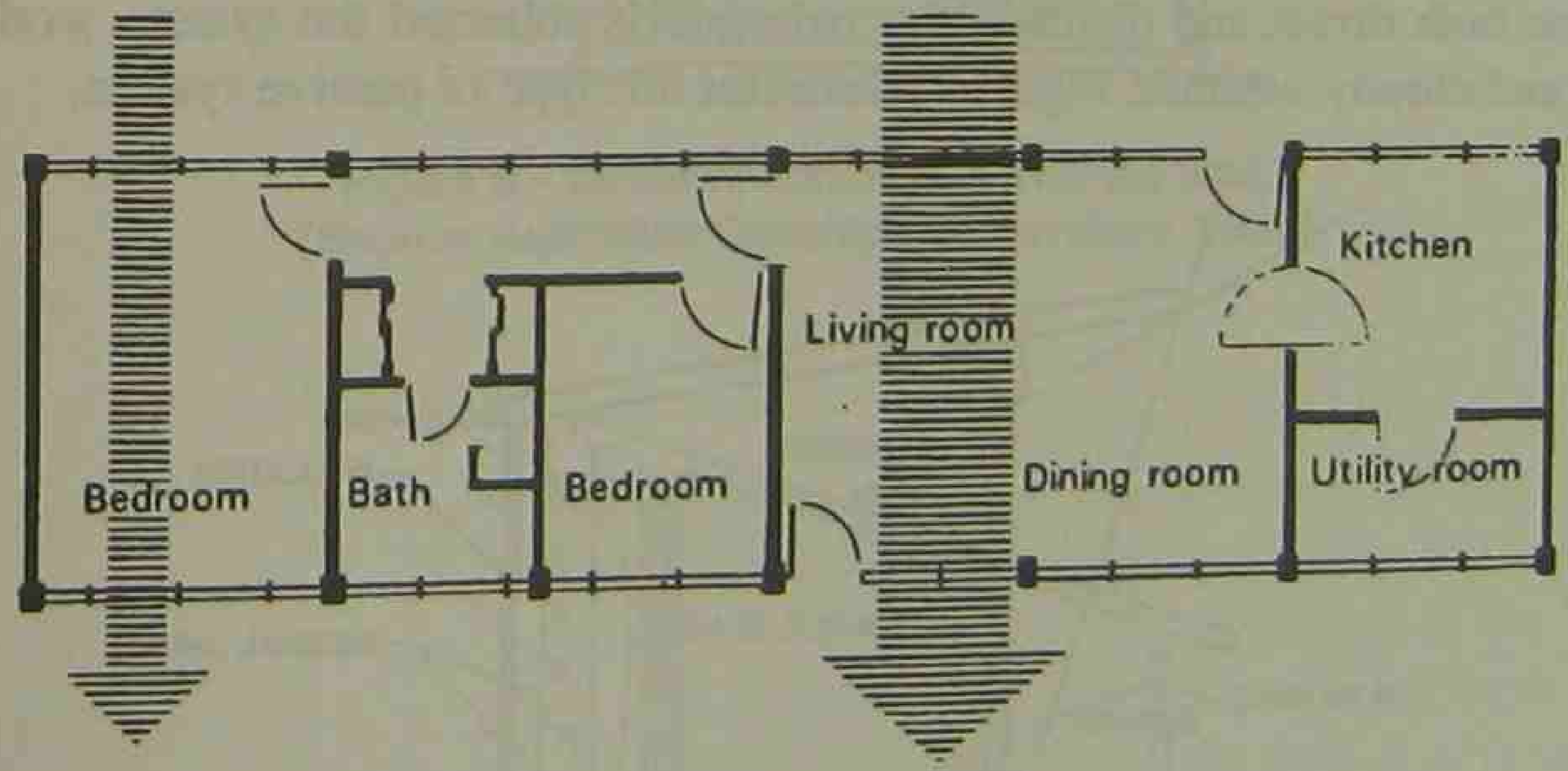


Figure 6 - House design for hot-humid climates which allows for flow-through ventilation.
(Source: Drysdale, 1975).

3.8 Landscaping

Appropriate landscaping can improve summer and winter conditions inside the home. Basic techniques include:

- dense planting for winter windbreaks, especially towards the south of the house
- planting to allow the transpiration of the leaves to cool hot summer winds
- using ground cover to reduce sunlight reflection
- using ponds or pools for evaporative pre-cooling
- planting deciduous vines to shade walls and windows in summer.

4 PASSIVE SOLAR SYSTEMS

Passive solar systems are most commonly defined as those which involve thermal energy flows by natural means such as radiation, conduction and natural convection. In essence, the system is comprised of the building structure or some elements within it.

The basic elements of a passive solar heating system are:

- equator-facing glass for solar collection
- thermal mass for heat absorption, storage and heat emission
- insulation to reduce heat transmission
- weather-stripping to minimise the infiltration of air from outside

The two predominant approaches to passive solar heating are direct gain and indirect gain systems.

4.1 Direct Gain Systems

Direct gain, where the living space is directly heated by sunlight, is the simplest approach to passive solar heating. The living space is used as a solar collector and contains thermal mass for absorbing and storing daytime heat for the colder nights. Typically between one-half and two-thirds of the total internal surface area is constructed of masonry. Because both direct and diffuse solar radiation is collected the system works in both sunny and cloudy weather. Figure 7 illustrates this type of passive system.

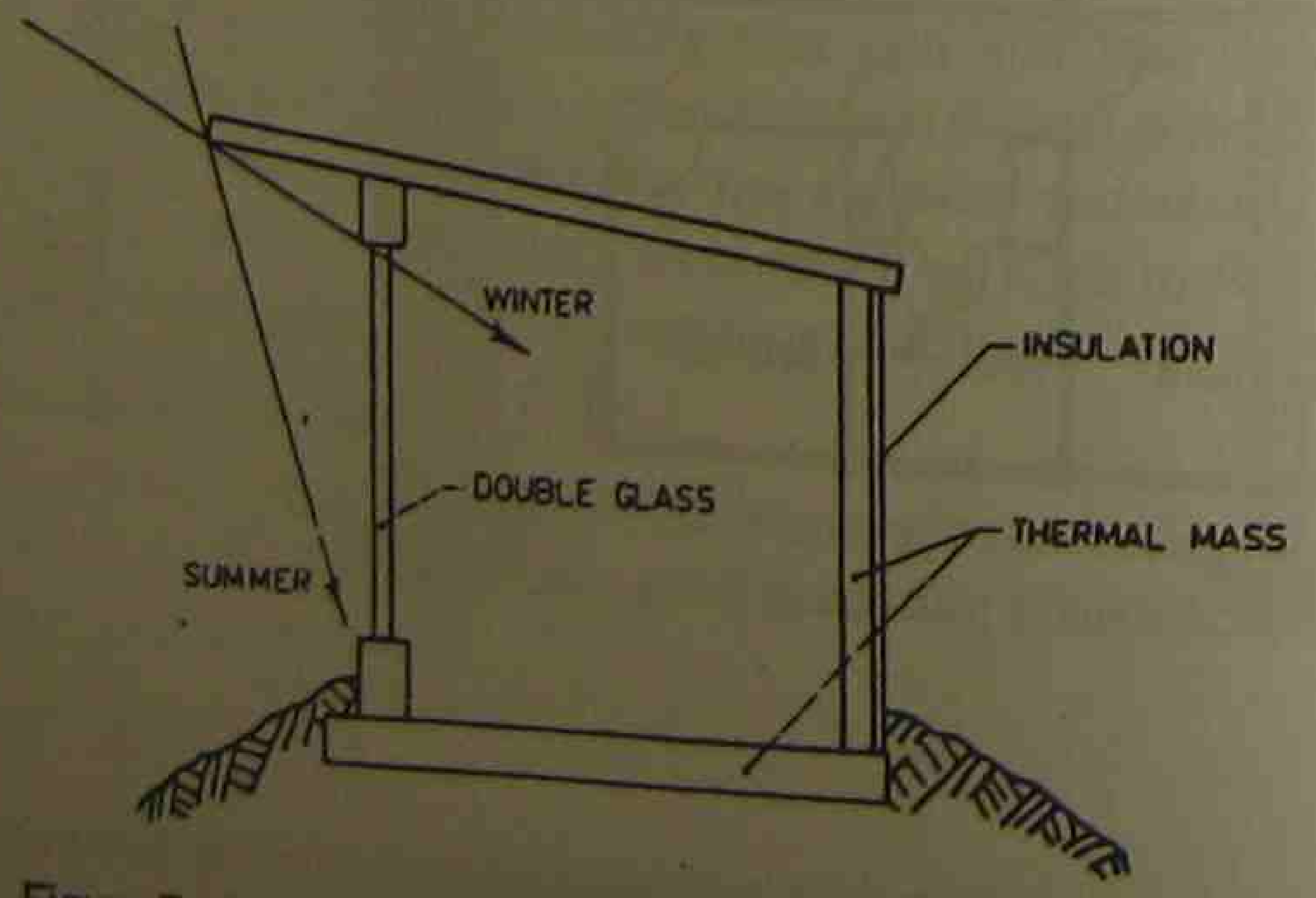


Figure 7 - A direct gain system. (Source: Baker, et. al., 1984).

One of the earliest and largest contemporary examples of a direct gain system is the St. George's County Secondary School in Wallasey, England, completed in 1962. The two-storey building, constructed of masonry, has a transparent equator-facing (south) wall for maximum solar heat gain in winter. The roof and floor consist of 16 to 25 cm thick concrete. The north wall and interior partitions are made of 20 cm brick. The masonry is exposed to the interior and insulated from the exterior by 12 cm of polystyrene. The masonry interior stores heat and prevents large fluctuations of indoor temperature through the day. Solar energy supplies roughly 50% of the buildings heating needs during the year.

4.2 Indirect Gain Systems

Indirect gain systems absorb sunlight converting it to heat which is then transferred to the space where it is required. Thermal storage wall systems absorb sunlight on the glazed and darkened outer face of the wall and then transfer heat to the room behind. This occurs via conduction through the wall. If top and bottom vents have been provided in the wall, heat transfer takes place primarily via natural convection from the heated wall to the space behind. The **Trombe wall** has the convection air flow taking place between the glazing and the solid wall and then through the vents to the room behind. The expelled heated air is replaced with cooler air from the room. The **Lawrance wall** uses a cavity brick construction with the convection taking place within the cavity which is vented to the room behind. The air space between the glazing and the black outer surface remains sealed. The operation of a Trombe wall is shown in Figures 8 and 9 for winter and summer respectively. One problem with this system is that the massive wall impedes the view through the window.

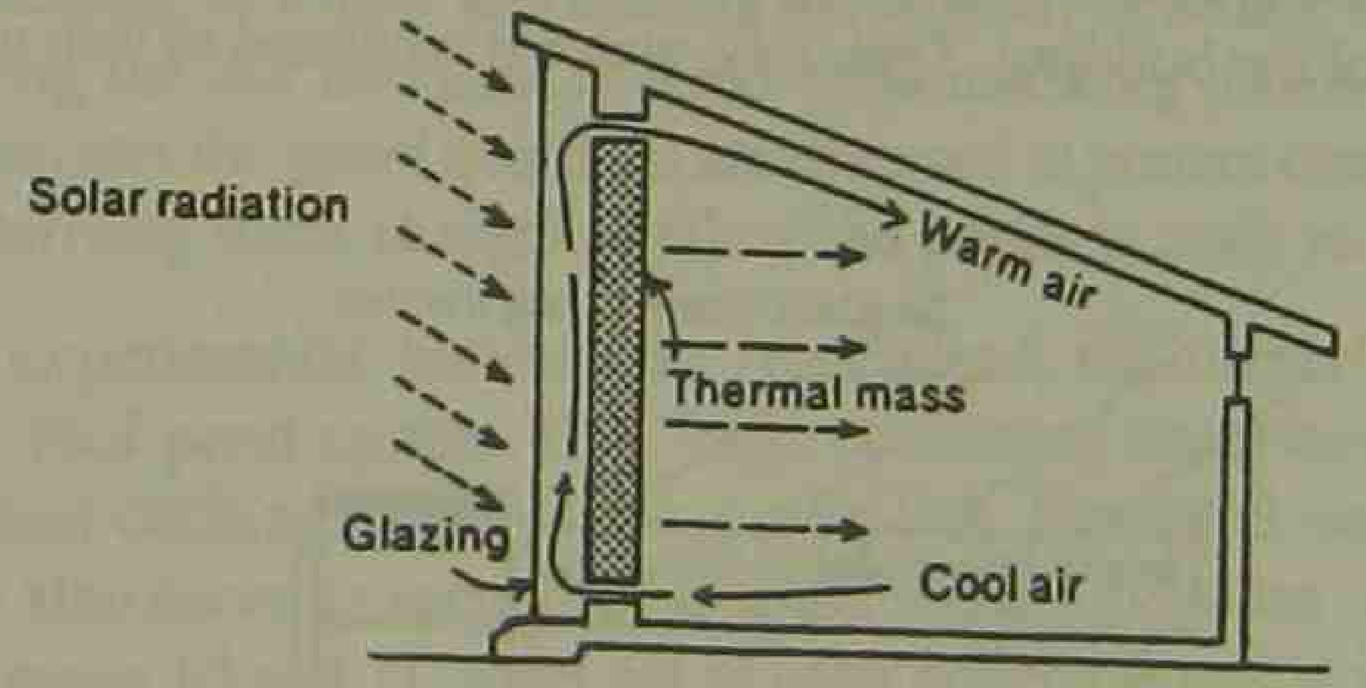


Figure 8 - Winter operation of a Trombe wall.
(Source: Australian Construction Services, 1983).

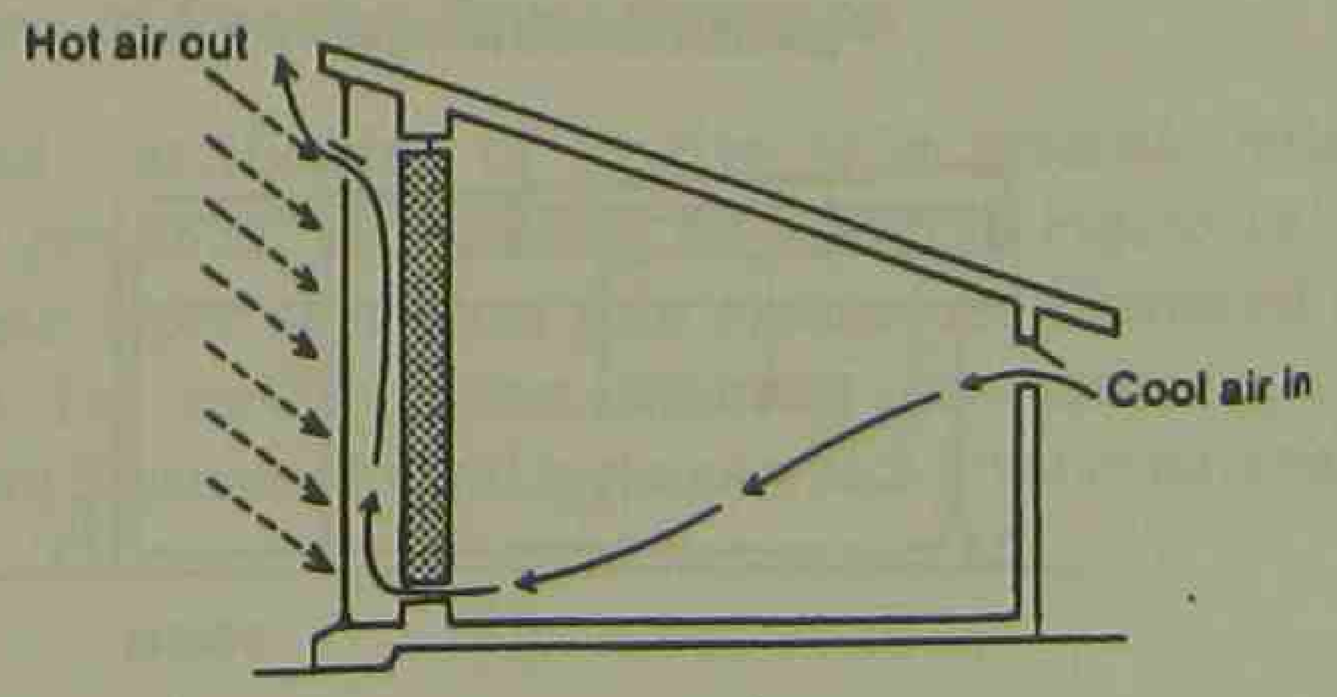


Figure 9 - Summer operation of a Trombe wall.
(Source: Australian Construction Services, 1983).

A well known example of this system is the Trombe-Michel house in Odeillo, France. The house, built in 1967, uses a double-glazed thermal wall constructed of concrete approximately 60cm thick and painted black to absorb sunlight that passes through the glass. It takes between 10 and 15 hours for heat to travel through the wall, so instantaneous heating is made possible by circulating room air in the gap between the glass and the wall. Approximately 70% of the yearly heating needs of this building are supplied by solar energy. In summer, the roof overhang completely shades the equator-facing wall and glazing vents can be opened for cross-ventilation. However, indoor overheating after clear days in spring and autumn has been reported.

Water storage walls operate on the same principle as masonry storage walls except a **water wall** transfers heat through the wall by convection rather than by conduction. Convection distributes heat gains quickly and so water walls may provide thermal storage with greatly reduced surface temperatures. Convection also helps to overcome spring and autumn overheating of the space. Water is also attractive because it is cheap, easy to install and has a high thermal capacity per unit volume, when compared to concrete. Problems with water are those of containment, corrosion and water damage risk.

The classic example of a water wall system is the Baer residence in Corrales, New Mexico. Here, equator-facing walls contain water-filled drums, stacked horizontally in a metal support frame behind single-glazed windows. The windows are covered at night by insulating panels. These panels fold down during the day and act as reflectors in winter. The operation reverses in summer to provide night-time radiant cooling and day-time insulation and shading from the sun. The heat flow from the drums to the rooms is controlled in winter by curtains.

Another indirect gain system is the roof pond or **water roof**, where the thermal mass is located in the roof of the building. Typically, water is enclosed in thin plastic bags which are supported by a roof which serves as the ceiling of the room below. The system is suited to both heating in winter and cooling in summer. In winter, the ponds are exposed to sunlight during the day and then covered with insulating panels at night, as shown in Figure 10. In summer the panel positions are reversed to protect them from the sun during the day and removing them at night to allow the ponds to cool, as shown in Figure 11.

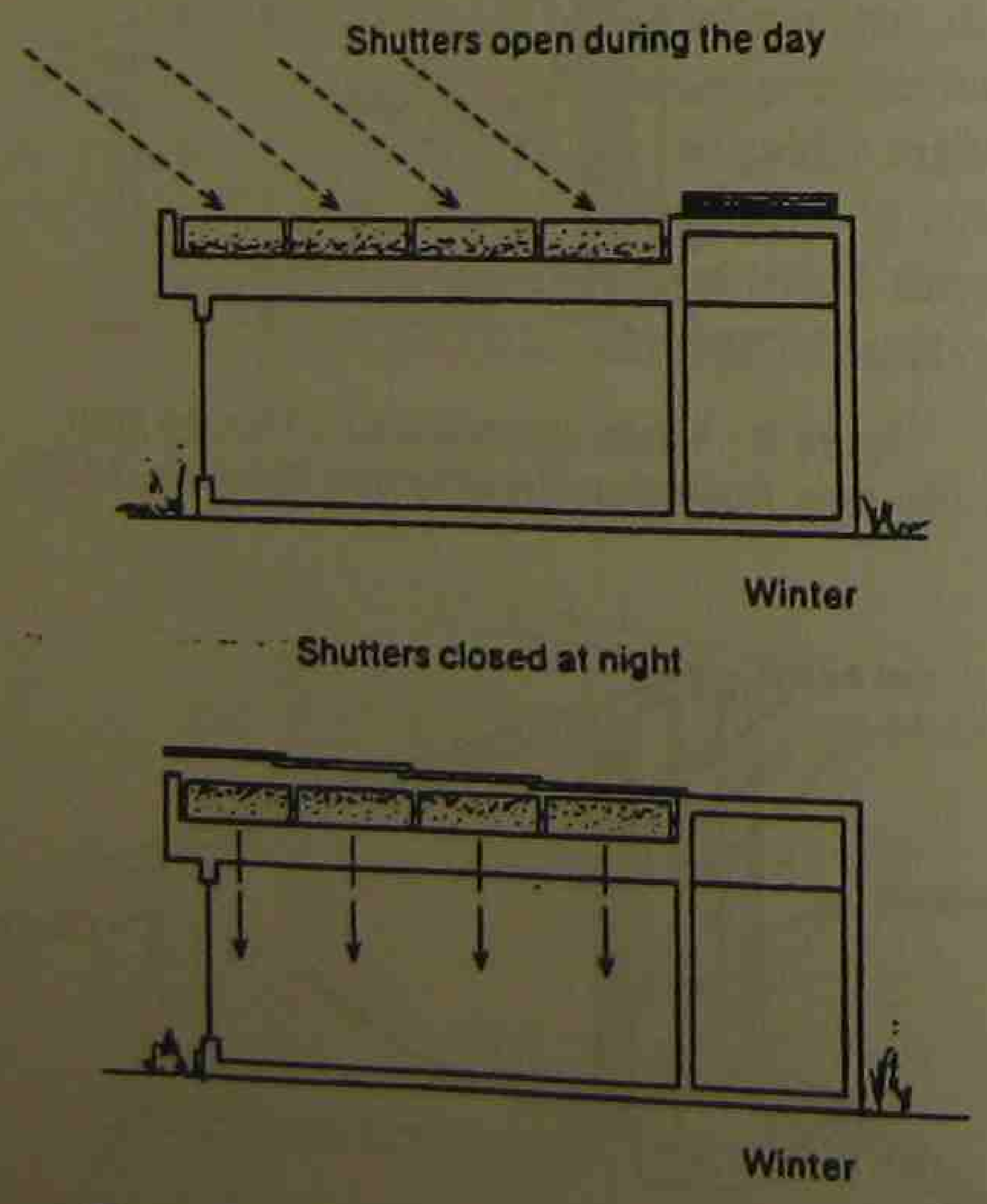


Figure 10 - Operation of a water roof for heating.
(Source: Australian Construction Services, 1983).

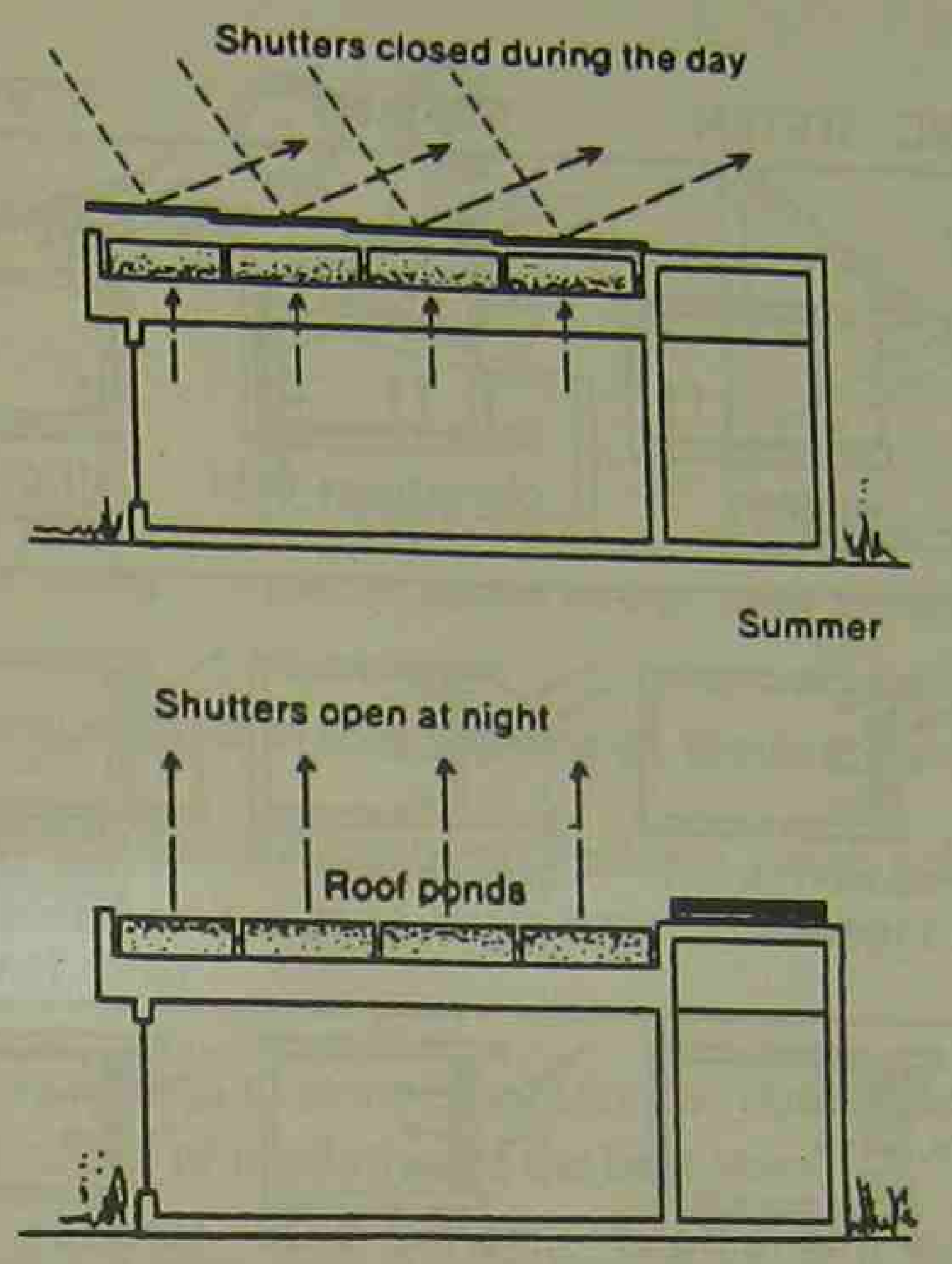


Figure 11 - Operation of a water roof for cooling.
(Source: Australian Construction Services, 1983).

Harold Hay's experimental building in Atascadero, California provides the earliest example of the roof pond system. PVC bags containing water cover the roof. They are supported by steel decking which is also the ceiling. Structural walls needed to support the water mass also serve as secondary thermal mass. Operation of this water roof is as described in Figures 10 and 11. Bags act as solar collectors and storage mass for heating and heat dissipators for cooling. The insulation panels are moved with an electric motor. A 1979 report stated that the Hays' house has been 100% solar heated and naturally cooled since it was occupied in 1973.

4.3 Classification of Passive Solar Systems

A generally accepted classification of passive solar systems, reflecting previous discussion, has been presented by Szokolay, as shown in Figure 12. The direct gain system and three basic types of indirect gain systems are illustrated in the left-hand column of Figure 12. The middle column illustrates some variations to basic designs. The right-hand column illustrates hybrid systems which involve both passive and active elements.

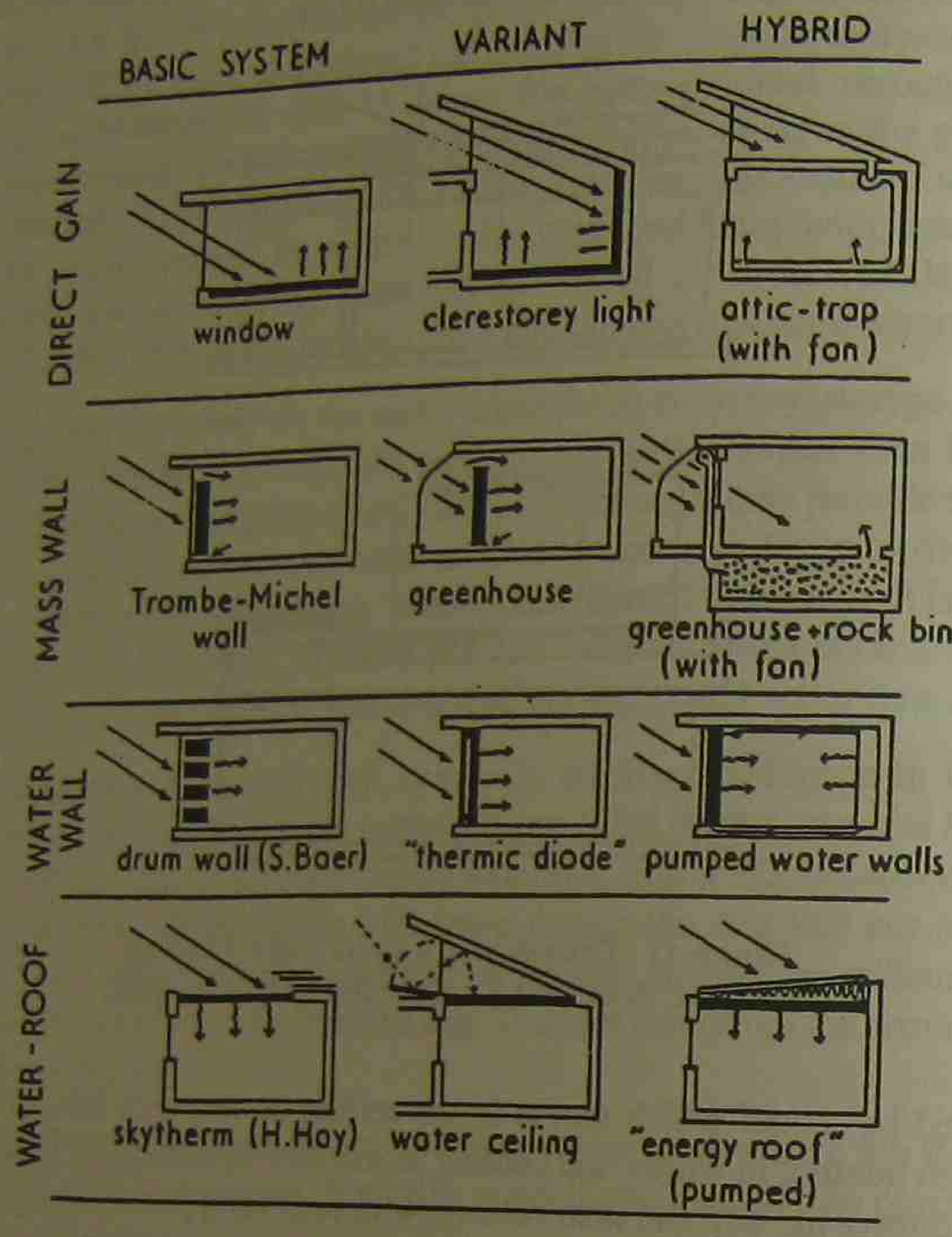


Figure 12 - Classification of passive solar systems.
(Source: Adapted from Szokolay, 1991).

5 ACTIVE SOLAR SYSTEMS FOR SPACE HEATING AND COOLING

Active solar systems for space heating and cooling use purpose-built collecting panels, storage tanks or bins, an energy transfer mechanism and an energy distribution system. They use one or more working fluids which collect, store and distribute the collected solar energy. Active solar systems are sometimes defined as being those which use fans or pumps to move heat around. However for the purposes of this manual, an active system need not have a pump or a fan, while a passive system may use fans.

5.1 Basic Principles

There are two basic types of active systems for space heating and cooling - air-based and water-based - where air and water respectively are the means of heat transfer. Solar collectors for both air-based and water-based systems may be fabricated in many ways and are most often mounted on the northern side of the roof. The tilt depends on the proposed usage of the system over the course of the seasons.

Space heating systems are used only in winter, whereas solar air-conditioning systems can be used either for cooling in summer or heating in winter. Figure 13 illustrates the different tilts appropriate for different applications. Solar collectors used for space heating systems are usually tilted at an angle equal to the appropriate angle of latitude plus 10 degrees.

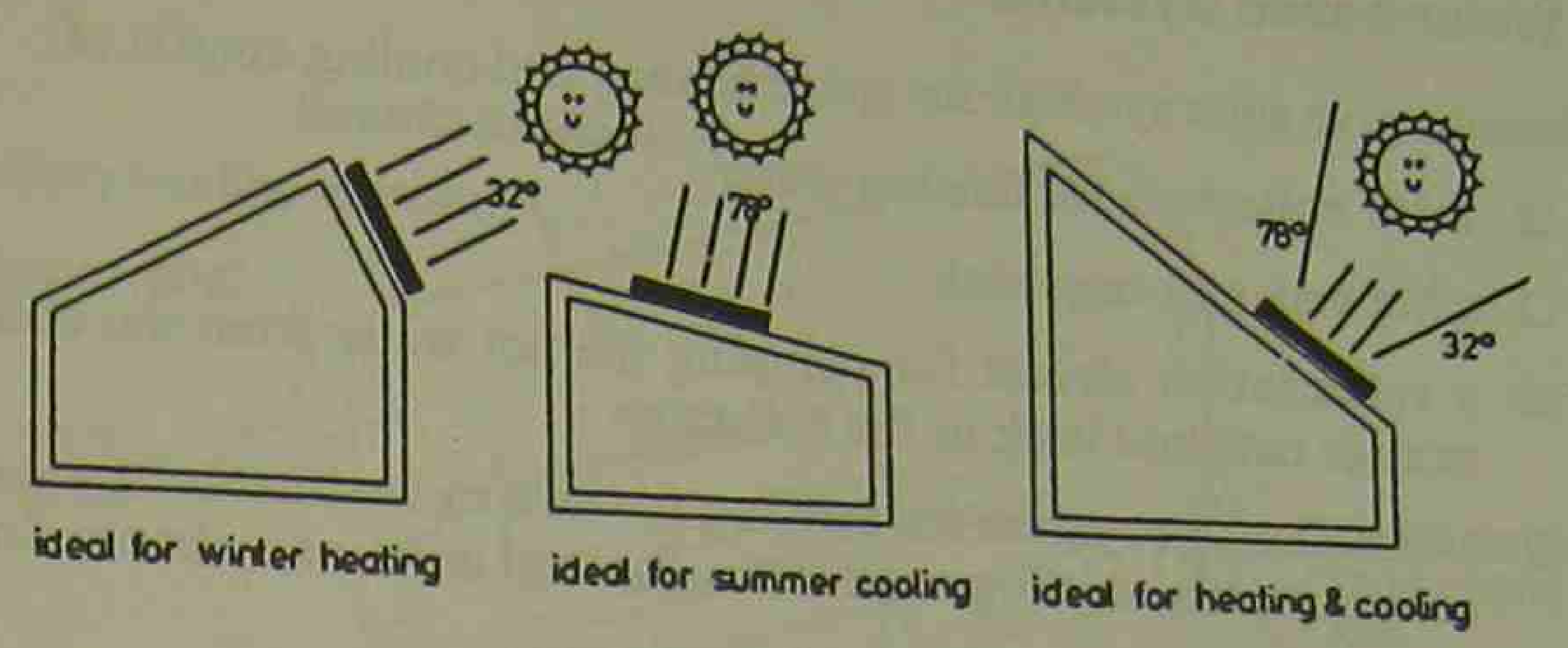


Figure 13 - Seasonal changes in solar collector tilt. (Source: Parnell and Cole, 1983).

The ability of an active system to store energy for use during cloudy days is determined by the size, type and extent of insulation of the heat store.

In an active solar heating system, heat is reticulated from the solar collectors to the storage medium and back to the collectors. Pipes or ducts for transferring energy must be kept short and well-insulated. The distribution system transfers the heat from the heat store to various points of end-use in the building.

5.2 Air-based Systems

There are many different approaches to air-based active solar systems. Most commonly they use specially designed, flat-plate solar air collectors to heat air which is then forced by a fan via ducting to the heat store or directly into the space to be heated. The heat store usually contains graded rock pebbles. Another fan forces air from the interior of the house through the heat store, as required. The heated air returns to the interior of the house via a series of ducts. The process is shown schematically in Figure 14.

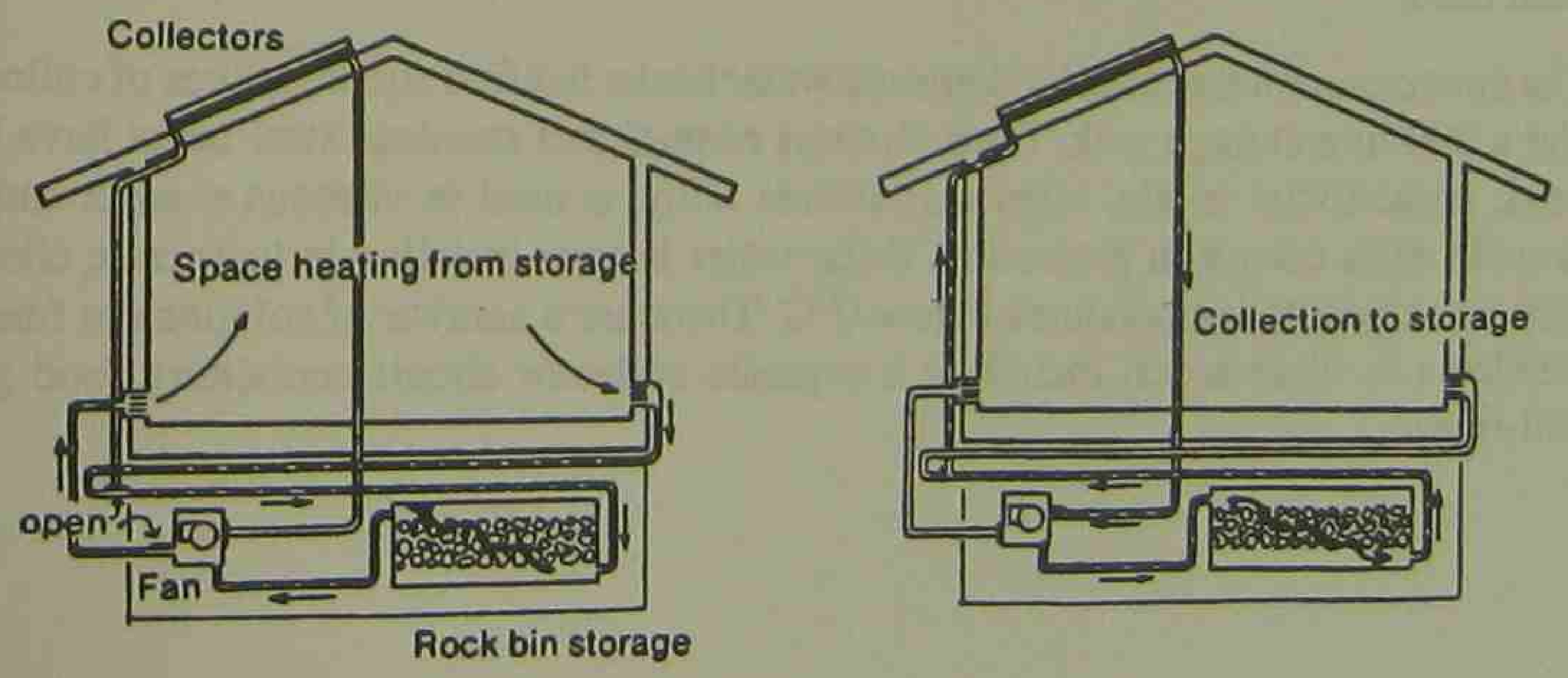


Figure 14 - Schematic diagram of an air-based solar system.
(Source: Department of Housing and Construction, 1985).

5.3 Water-based Systems

Water-based active solar systems for space heating and cooling consist of:

- **solar collectors** for heating water
- a **hot water storage** tank
- a **reticulation circuit** for pumping the hot water from the collectors to a storage tank and back to the collectors
- a **distribution system** for sending the heat to the interior space (usually by radiant panels, skirting conductors, fan-coil units, or hydronic floor heating)

Figure 15 illustrates these features in a schematic way.

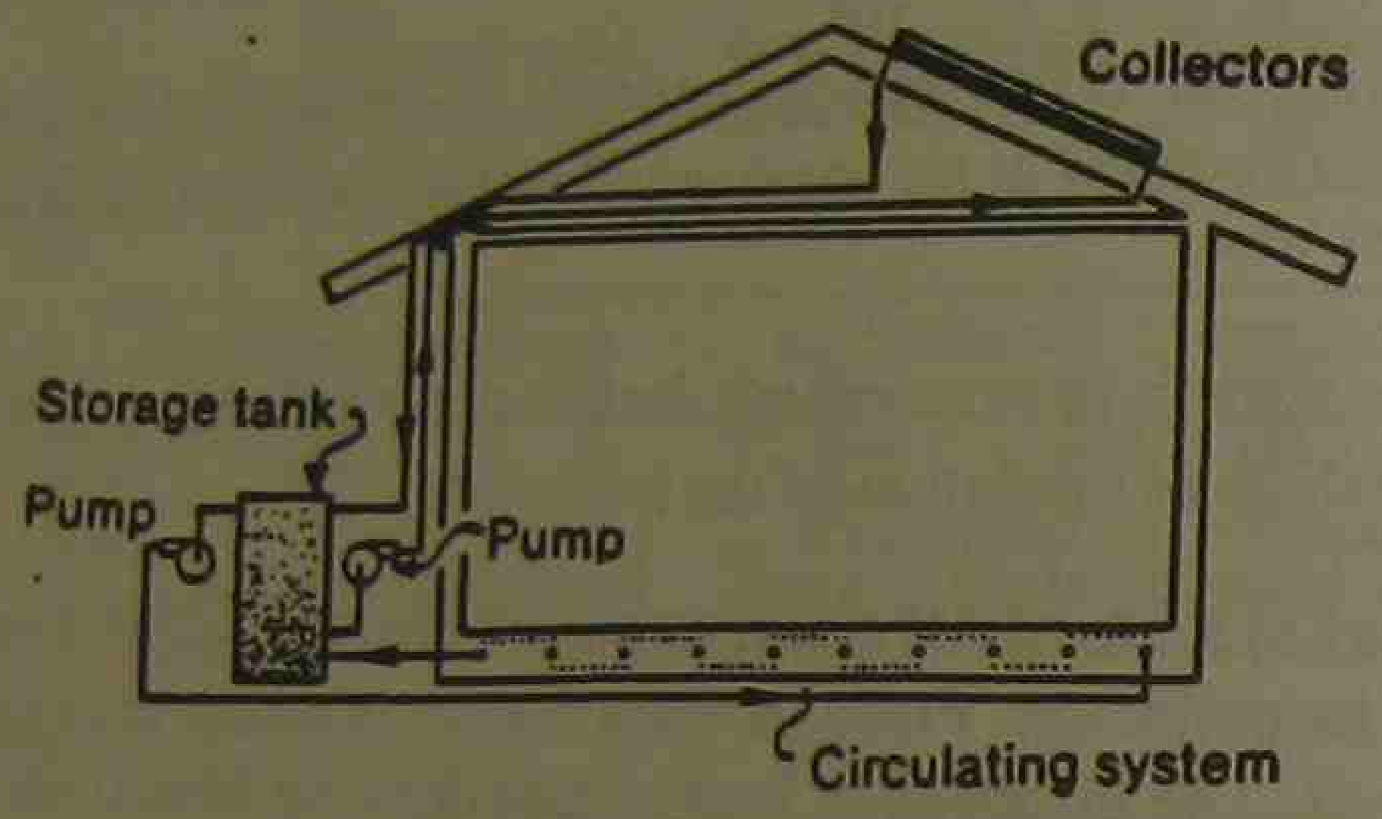


Figure 15 - Schematic diagram of a water-based system.
(Source: Department of Housing and Construction, 1985).

6 SOLAR DOMESTIC WATER HEATING

Solar domestic water heaters are the most commonly used solar devices, installed in some 5% of Australian homes. Solar water heating is seen to be an integral part of a truly solar efficient house. The most popular system has been the roof-mounted, close-coupled, mains-pressure thermosyphon type with electric booster, as shown in Figure 16. Remote tank systems both of the pumped and thermosyphon type have also been used.

The most common size of solar domestic water heater has four square metres of collectors and a 300 litre storage tank. Both vitreous enamel and stainless steel tanks have been used. A sacrificial anode, often magnesium alloy, is used in vitreous enamel tanks to provide extra corrosion protection. Solar water heaters installed in temperate climates may be subject to temperatures below 0°C. There are a number of solutions to freezing problems in these areas, including a separate collector circuit containing food grade anti-freeze.

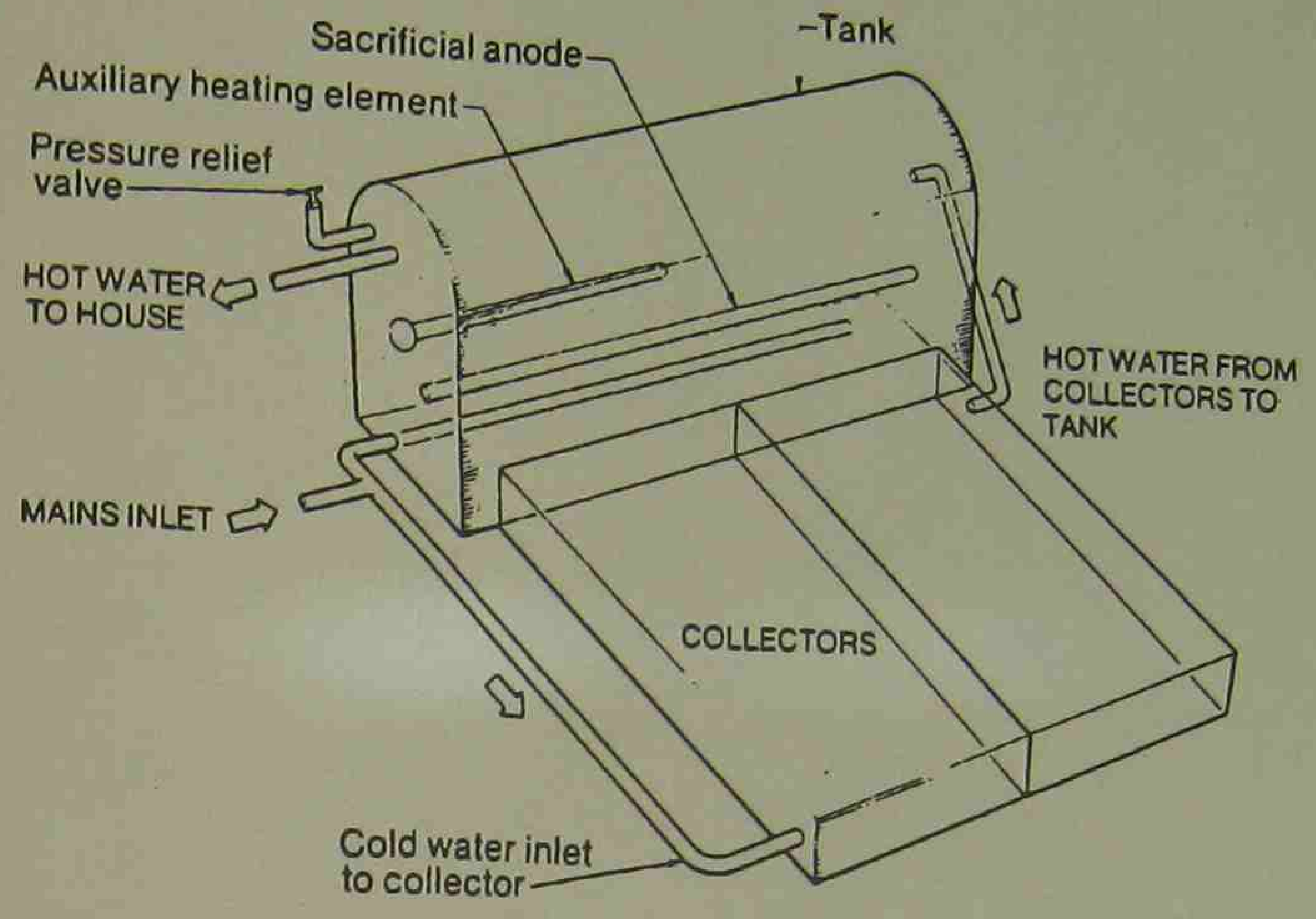


Figure 16 - The close-coupled thermosyphon hot-water system.
(Source: Department of Employment and Industrial Relations, 1983).

Unit 2

Climate and Human Comfort

1 INTRODUCTION

The extent to which a house will need to protect the occupants and provide comfortable conditions can be determined from the differences between the prevailing weather conditions and the desired comfort conditions. In order to achieve this an understanding of the region where the building is located is required.

These notes include a discussion of climate, climatic data and human comfort.

2 CLIMATE

2.1 Difference Between Weather and Climate

Weather is the set of atmospheric conditions prevailing at a given place and time. **Climate** is a description of weather conditions over a period of time for a particular geographical location.

2.2 Solar Radiation

The radiation emitted by our sun is equivalent to that emitted by a body at about 5,600°C. After travelling 150 million kilometres to just outside the earth's atmosphere, the energy density is 1367 W/m^2, varying +/-3.4% over the year with the change in the sun-earth distance.

The total annual solar radiation received by the earth is about 5.6×10^{24}J. This is about 13000 times the 1990 annual energy consumption of 4.3×10^{20} J. Of this energy 30% is reflected by clouds, vapour, and particles in the atmosphere as well as from the earth's surface. 50% of this light is absorbed, changed to heat and re-radiated back into space. 20% is used to drive the water cycle, the wind and photosynthesis (Figure 1).

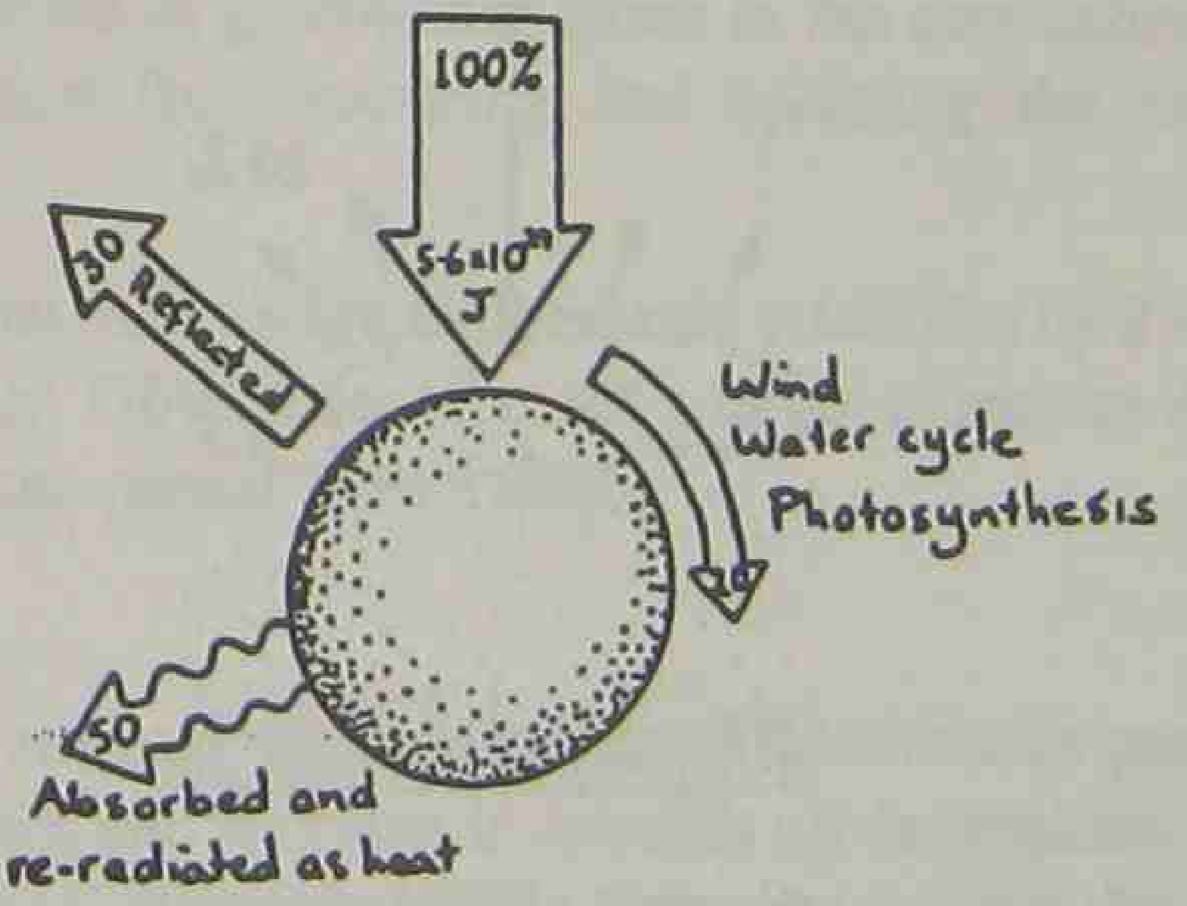


Figure 1 - Annual solar radiation received by the earth.

The maximum radiation received at the earth's surface is about 1000 W/m^2 when the sun is directly overhead on a clear day. This is referred to as air mass 1 (AM1) since the sunlight has to travel directly through one atmosphere. If the radiation has to travel obliquely through the atmosphere the intensity is further reduced. Through the equivalent of two atmospheres (AM2) the clear sky intensity is 740 W/m^2 (Figure 2).

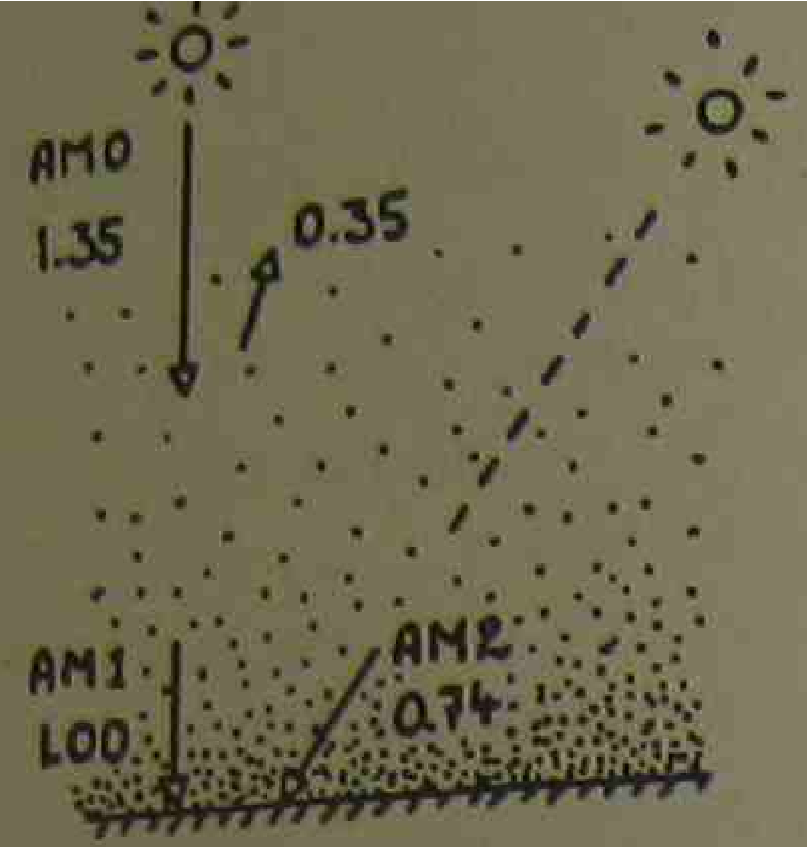


Figure 2 - Reflection and absorption by the atmosphere.

The atmosphere has a scattering effect which gives a clear sky diffuse component of about 20% (Figure 3).

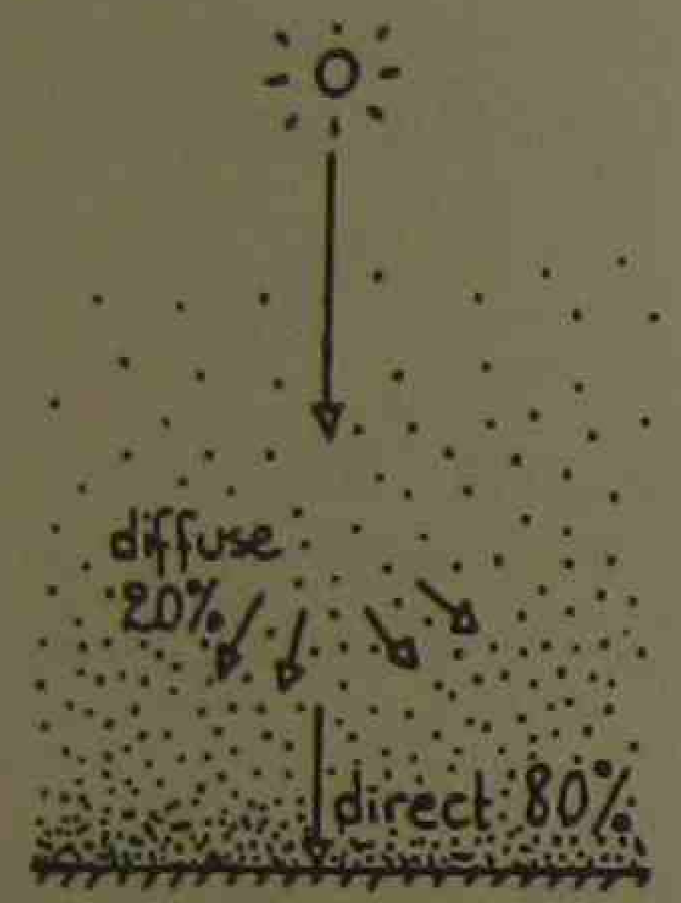


Figure 3 - Scattering by the atmosphere.

Cloud covers about half of the planet at any time. Up to 80% of the radiation may be reflected back into space (Figure 4).

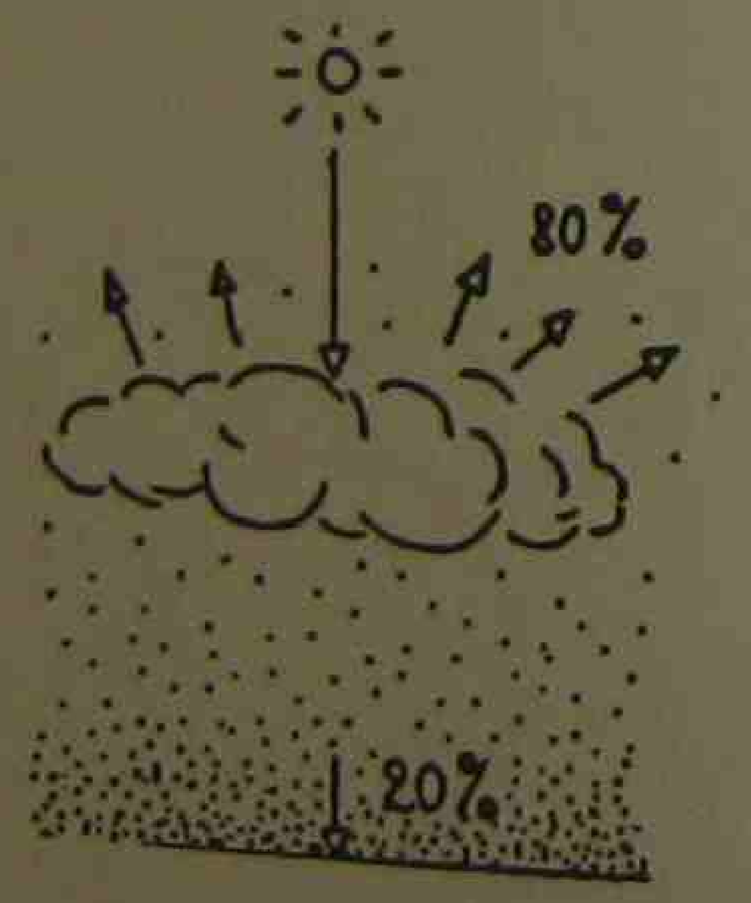


Figure 4 - Effect of clouds.

However, the amount of radiation reaching a particular point on the earth's surface is influenced by the earth/sun geometry.

The earth rotates once around its axis, every 24 hours. The axis of rotation is tilted at an angle of 23.5° from the perpendicular to the plane of the earth's orbit around the sun (Figure 5). The direction of this axis changes slowly over eons. At present the axis is pointing towards the polar star in the northern hemisphere.

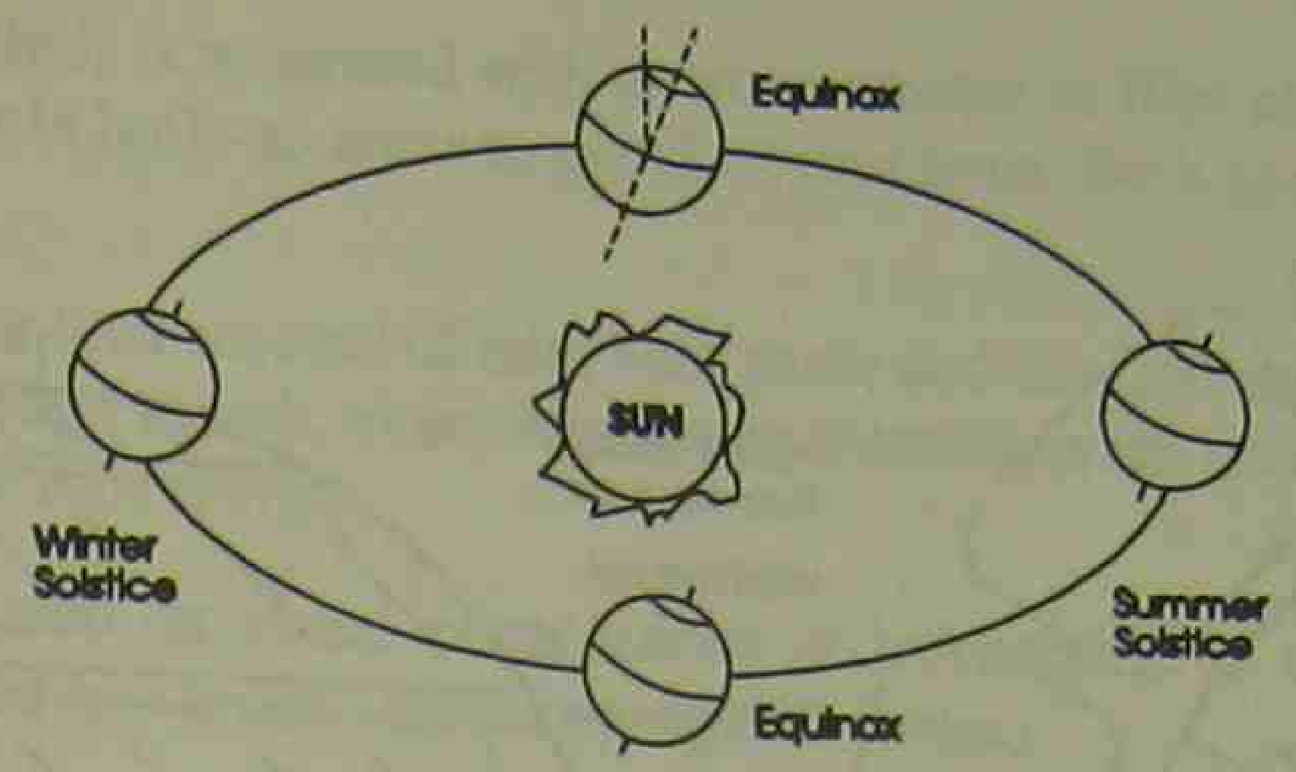


Figure 5 - Earth's orbit around the sun.

As the earth moves in its yearly orbit around the sun, locations at different latitudes receive varying amounts of solar radiation. When the earth's axis is tilted towards the sun for a particular hemisphere, the hours of sunlight exceed the hours of darkness. Also the path of the sun in the sky is higher. Together this has the effect of increasing the total amount of radiation received compared with the situation when the axis is tilted away from the sun. This produces the seasons experienced in higher latitudes.

Radiation is absorbed in the atmosphere by ozone, water vapour, dust particles etc. The lower the sun in the sky, the longer will be the path through the atmosphere and the greater this absorption will be.

On average, the tropical regions receive more radiation than the mid-latitudes, which in turn receive more radiation than the polar regions.

2.3 Global Thermal Balance

The total amount of heat absorbed by the earth is balanced by a corresponding heat loss. Heat is lost by, long wave radiation to outer space, evaporation and convection to the atmosphere. Without these balancing losses, the earth's temperature would rise dramatically. The increase in greenhouse gases in the atmosphere is stopping some of the long wave radiation from escaping and upsetting the balance, producing the Greenhouse Effect.

It has been predicted that the average temperature could rise by 2 to 4 degrees in the next 50 years. The Australian Government has set a target to reduce Australia's greenhouse emissions by 20% for the period 1991 - 2005.

2.4 Winds

Winds are convection currents which equalize differences in pressure, temperature or humidity. Heated air rises and is drawn in towards cooler regions, while air from cooler regions is drawn in to replace the heated air. Taken on its own this effect would produce northerly winds in the northern hemisphere and southerly winds in the southern hemisphere. However, the spin of the earth produces the Coriolis Effect which deflects this air movement to the right in the northern hemisphere and to the left in the southern hemisphere (Figure 6).

Surface roughness, proximity to water masses, topography and obstructions can produce local variations to wind direction and speed. Winds effect cloud formation which in turn affects solar radiation.

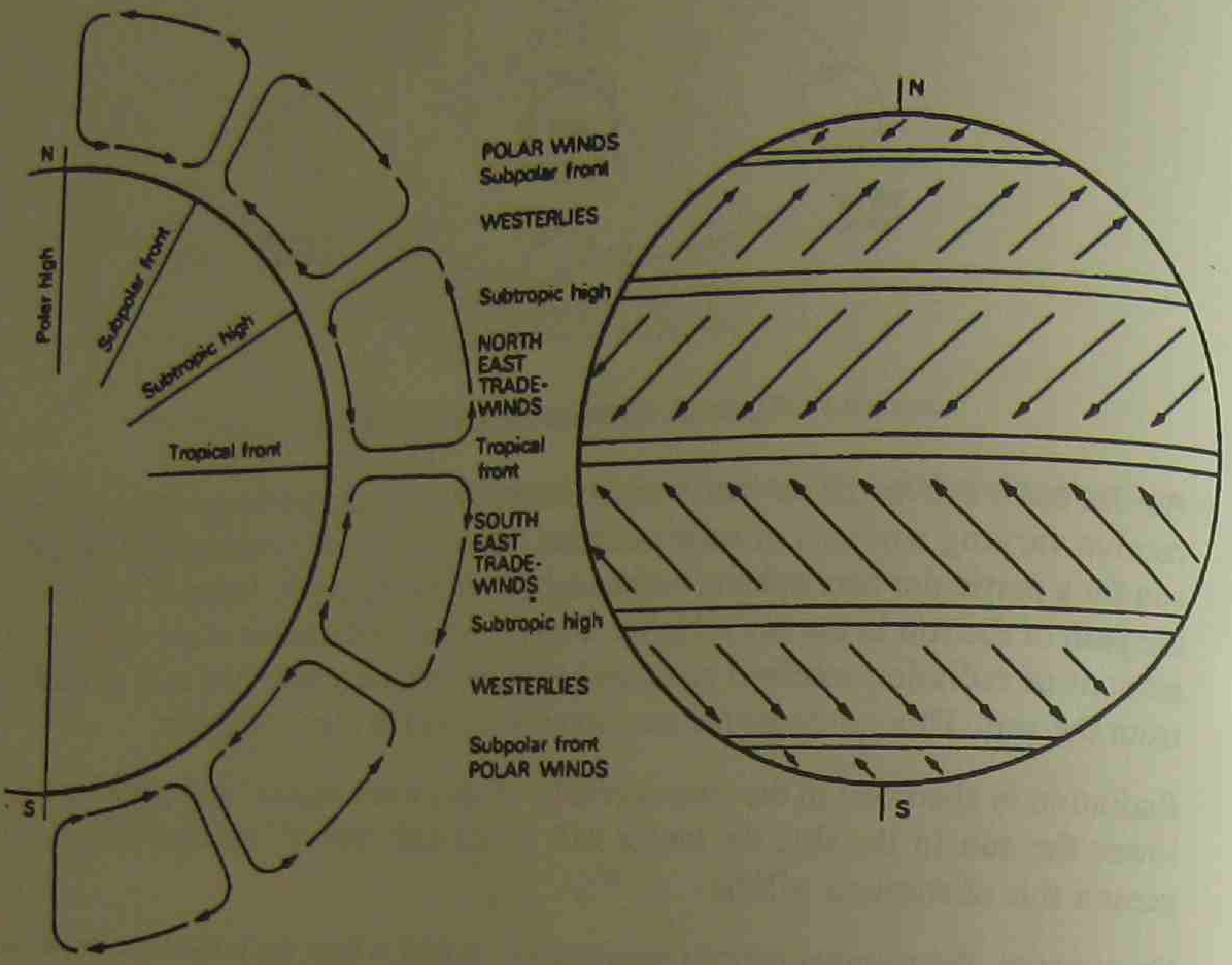


Figure 6 - Global wind pattern. (Source: Szokolay, 1980).

2.5 Climatic Quantities

The main climatic elements that are regularly measured by meteorological stations and published in summary form are:

Temperature (dry bulb temperature - DBT), is a measure of the thermal state of the air, measured in the shade, usually in a ventilated box called a Stevenson Screen.

Humidity can be expressed as absolute humidity (AH) or relative humidity (RH). Humidity can be calculated from wet bulb temperature (WBT).

- absolute humidity (AH) is the vapour content of air, measured in grams of water vapour per kilogram of air (g/kg)
- saturation humidity (SH) gives the maximum amount of water vapour that the air can support for a particular temperature (g/kg)
- relative humidity (RH) is the vapour content of a given atmosphere expressed as a percentage of the saturation humidity at the same temperature

  $RH = AH/SH \times 100\%$
- wet bulb temperature (WBT) is measured by a hygrometer (or psychrometer) which consists of two thermometers, one measuring DBT and the other enclosed in a wick. Air contact with the wick (by whirling for example) causes evaporation and a resultant lower temperature - WBT.

Air movement (wind) is measured with an anemometer at 10m above ground in open country, but higher in built-up areas to avoid obstructions. Both speed and direction are indicated.

Precipitation is the total amount of rain, hail, snow and dew measured in rain gauges in mm per unit time (day, month, year). Maximum intensities are useful for the prediction of flooding and for roof design.

Cloud cover is based on visual observations and expressed as a fraction of the sky hemisphere covered by clouds - tenths or eighths (octas).

Sunshine duration is the period of clear sunshine (when a sharp shadow is cast), measured by a sunshine recorder which burns a trace on a paper strip. Expressed as hours per day or month.

Solar radiation is measured with a pyranometer (solarimeter) on an unobstructed horizontal surface. Can be measured continuously as irradiance (W/m^2) or through an electronic integrator as irradiation (Wh/m^2 or MJ/m^2) over the hour or day.

2.6 Classification of Climates

Many different systems of climate classifications are in use for different purposes. As far as building design for Australia is concerned three major climatic zones are considered necessary (Drysdale '81). These are:

Hot-humid zone

Summer:	High day-time dry-bulb temperatures (30° to 35°C). High dry-bulb temperatures at night (25° to 30°C). High relative humidities day and night (70 to 80%).
Winter:	Warm to hot days (25° to 30°C). Mild nights (15° to 20°C).
General:	Heavy summer rainfall; dry winter. Small diurnal temperature range, particularly during summer (5° to 20°C) The overheating is not as great as in hot-arid areas, but conditions can be comfortable due to high humidities decreasing the evaporative cooling effect on the body, (sweating).

Hot-arid zone

Summer:	Very high day-time temperatures (35° to 40°C). Hot nights (20° to 25°C). Low relative humidity day and night (20 to 35%). Prolonged heat waves; hot, dry winds.
Winter:	Warm to hot days (18° to 25°C). Cool to cold nights (5° to 13°C).
General:	Irregular rainfall, occurring principally in summer. Large diurnal and seasonal variations in temperature (10° to 20°C). Here the main problem is overheating, but low humidity enables evaporative cooling to be effective.

Temperate zone

Summer: High day-time dry-bulb temperatures (30° to 35°C).
Moderate dry-bulb temperatures at night (13° to 18°C).
Moderate humidity (30% to 40%).

Winter: Cool to cold days (10° to 15°C).
Cold nights (2° to 7°C).

General: Rainfall throughout the year, with winter maximum except in northern N.S.W. Considerable diurnal temperature range (11° to 16°C) and a seasonal range of about 16°C.
Both underheating and overheating can be a problem depending on the season but neither is severe.

The movement of air masses across the continent cause some areas to experience climatic conditions peculiar to two or more climatic zones. Such areas can be designated as sub-zones of the climate whose characteristics predominate. The geographical extent of the climatic zones is shown on the map of Figure 7.

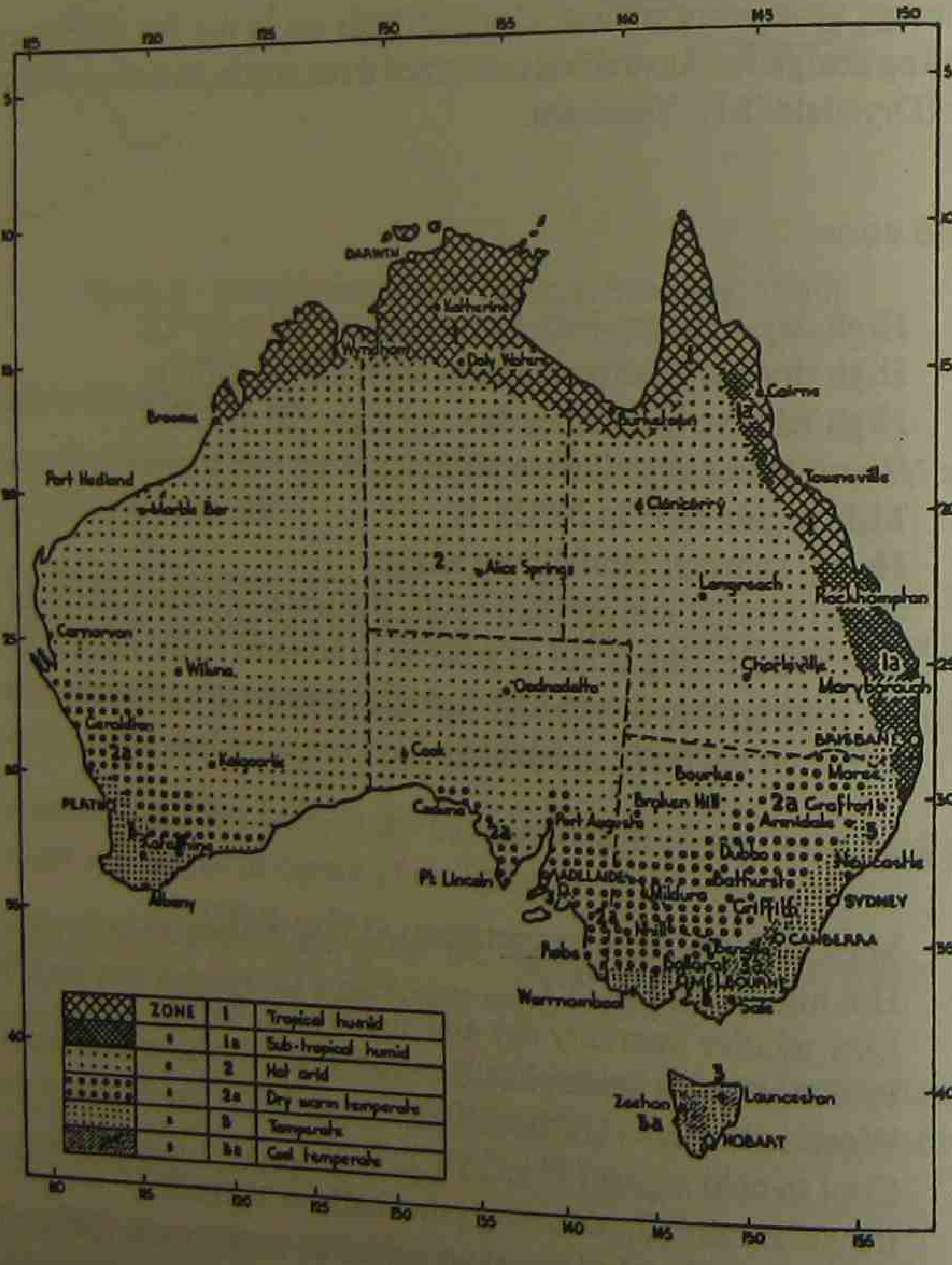


Figure 7 - Geographical extent of the climatic zones.
(Source: Drysdale, 1975).

2.7 Microclimate

Microclimate is the effect on climate due to local factors such as elevation, proximity to water and local winds. The climatic zones mentioned previously are only broad generalisations and major differences in climate can occur over relatively short distances. One important climatic quantity that can be used as an indication of climate in a particular area is heating degree days.

	Base Temp. °C		
	12	15	18
Queensland			
Ayr	0	2	30
Birdsville	41	167	428
Brisbane	2	41	238
Bundaberg	5	51	236
Burketown	0	0	8
Coolangatta	8	84	347
Gympie	32	141	402
Kingaroy	144	402	834
Longreach	12	75	256
Maryborough	14	88	309
Nambour	38	171	485
Roma	85	261	578
Toowoomba	176	483	977
Western Australia			
Albany Airport	141	559	1,256
Broome	0	0	8
Bunbury	57	327	888
Derby P.O.	0	0	2
Eucla	90	353	859
Fremantle	23	202	675
Kalgoorlie	155	451	914
Laverton	95	303	665
Marble Bar	0	4	35
Northam	136	457	961
Perth Regional Off.	22	198	645
Perth (Kings Park)	36	245	734
Rottnest Island	3	105	525
Victoria			
Aberfeldy	1,549	2,414	3,403
Bairnsdale	320	820	1,549
Ballarat(Wendouree)	735	1,416	2,268
Benalla	465	972	1,636
Bendigo	468	1,002	1,701
Colac	615	1,290	2,150
Dandenong	339	871	1,627
Euroa	462	971	1,637
Geelong	378	935	1,725
Hamilton	454	1,052	1,850
Kerang	314	751	1,361
Melbourne	234	693	1,378
Mildura	222	596	1,146
Seymour	504	1,040	1,748
Warragul P.O.	458	1,026	1,800
Wodonga	422	891	1,512
Yallourn S.E.C.	446	1,039	1,842
South Australia			
Adelaide (W. Terr.)	106	437	1,000
Berri	146	477	1,000
Bordertown	380	912	1,625
Coober Pedy	58	263	635
Coonawarra	445	1,027	1,801
Kapunda	291	726	1,357
Lameroo P.O.	294	752	1,401
Moomba	53	182	446
Mt Gambier Area	443	1,066	1,895
Murray Bridge P.O.	207	615	1,236
Naracoorte P.O.	371	909	1,653
Port Pirie	93	373	860
Whyalla	76	332	804
New South Wales			
Albury	502	1,004	1,657
Bathurst (Gaol)	719	1,288	2,023
Broken Hill	243	603	1,112
Campbelltown	181	528	1,073
Canberra Airport	819	1,421	2,186
Casino P.O.	18	120	401
Cessnock	124	387	838
Corowa	393	855	1,468
Dubbo P.O.	283	652	1,164
Goulburn	646	1,208	1,945
Hay P.O.	250	629	1,168
Jenolan Caves	912	1,574	2,413
Liverpool	137	452	970
Moree	140	382	773
Moss Vale	662	1,260	2,049
Narooma	143	528	1,170
Sydney	29	215	642
Thredbo Village	1,967	2,900	3,942
Wagga Airport	493	980	1,608
Tasmania			
Burnie A.P.P.M.	457	1,124	2,041
Cradle Valley	2,073	3,076	4,149
Hobart Airport	555	1,231	2,133
Launceston Airport	761	1,488	2,416
Mt Wellington	2,892	3,952	5,040
Wynyard Airport	646	1,414	2,395
Northern Territory			
Alice Springs	109	298	618
Ayers Rock	85	256	543
Darwin R.O.	0	0	0
Katherine R.O.	0	0	7

Table 1 - Heating degree days. (Source: AIRAH Handbook, 1988).

2.8 Heating Degree Days

Heating Degree Days indicates the amount of heating that is required in a given location. Heating degree days are taken to a particular base temperature which is the external temperature at which it is predicted that heating will begin to be required to keep the internal temperature at comfortable levels. The heating degree days to various base temperatures as published in the AIRAH handbook are shown in Table 1.

Heating degree days can be calculated for a particular month using the formula:

$$DD = N \times (T_b - T_a)$$

where DD = degree days per month
N = number of days in month
T_b = base temperature
T_a = mean daily temperature for month

To find the heating degree days for the year all the monthly values need to be totalled.

2.9 Use of Climatic Data

Climatic data for such quantities as temperature, humidity and irradiance is required by thermal designers for a number of reasons, some of the main ones being outlined below:

- ☐ monthly values of temperature and humidity are used to define comfort zones.
- ☐ 86th and 14th percentile values of daily minimum and maximum temperatures along with mean minima and maxima for each month can be used to calculate temperature distributions. This enables hourly temperatures to be calculated.
- ☐ monthly average daily solar irradiation on a horizontal surface is often used to calculate direct and diffuse irradiation on inclined surfaces (usually vertical), this is required in order that solar gains for a building can be determined.
- ☐ windspeed and direction gives a general indication of prevailing winds in summer and winter, however site specific information is essential if the designer is to take advantage of cooling breezes in summer and exclude cold winds in winter.

2.10 Sources of Climatic Data

The main source of raw climatic data is the Bureau of Meteorology, this is usually hourly data available on tape or disk. Most of the data sources listed below use the Bureau of Meteorology as their primary source. Other sources of data are the C.S.I.R.O. and various tertiary institutions.

"Climatic Averages, Australia" and "Climate of Australia" - Bureau of Meteorology

The former is a detailed reference while the latter is designed for more general reading with much of the information presented in the form shown in Figure 8.

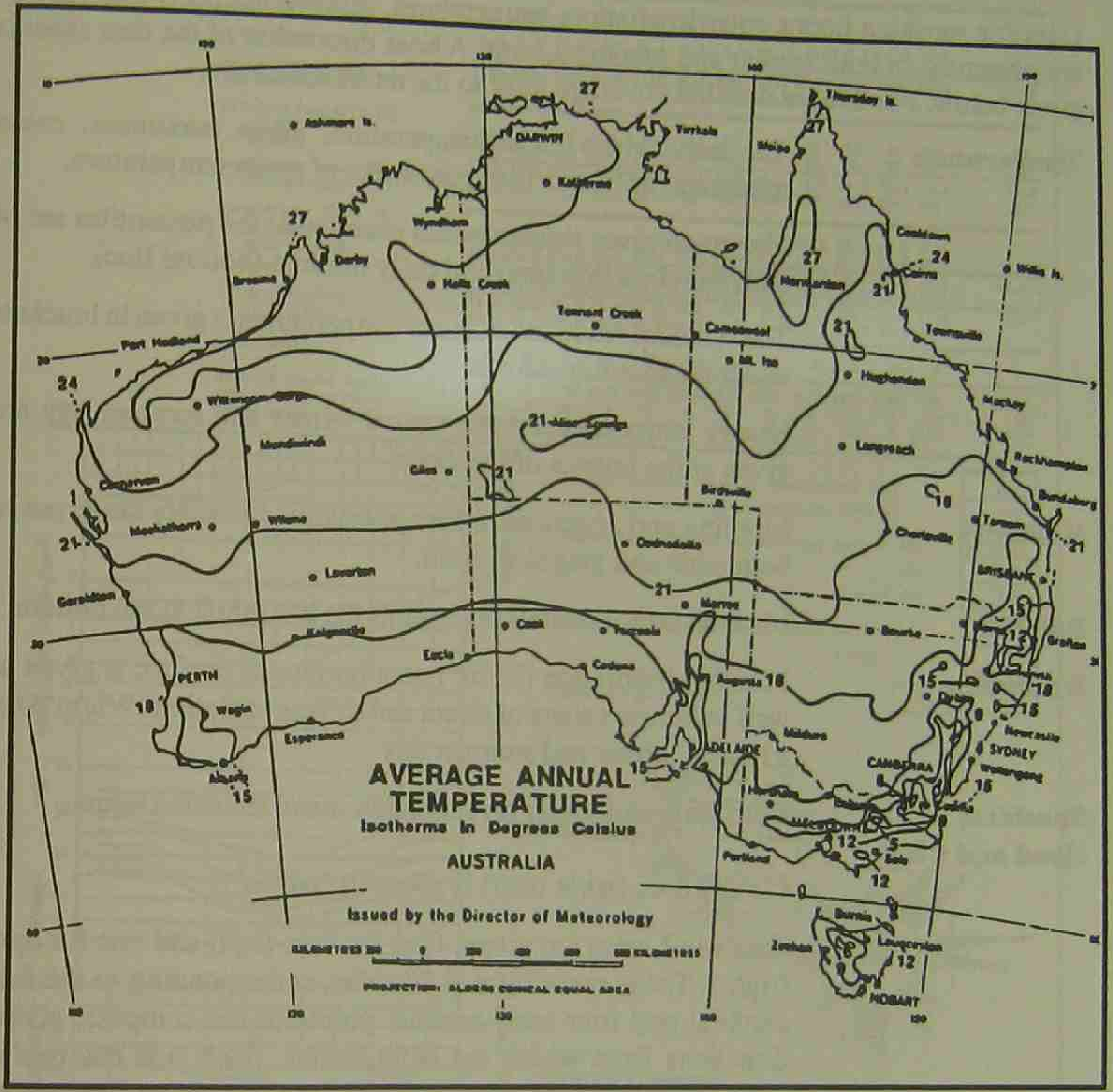


Figure 8 - Average annual temperature. (Source: Bureau of Meteorology, 1978).

"Data Handbook For Australian Energy Designers" - Roy and Miller

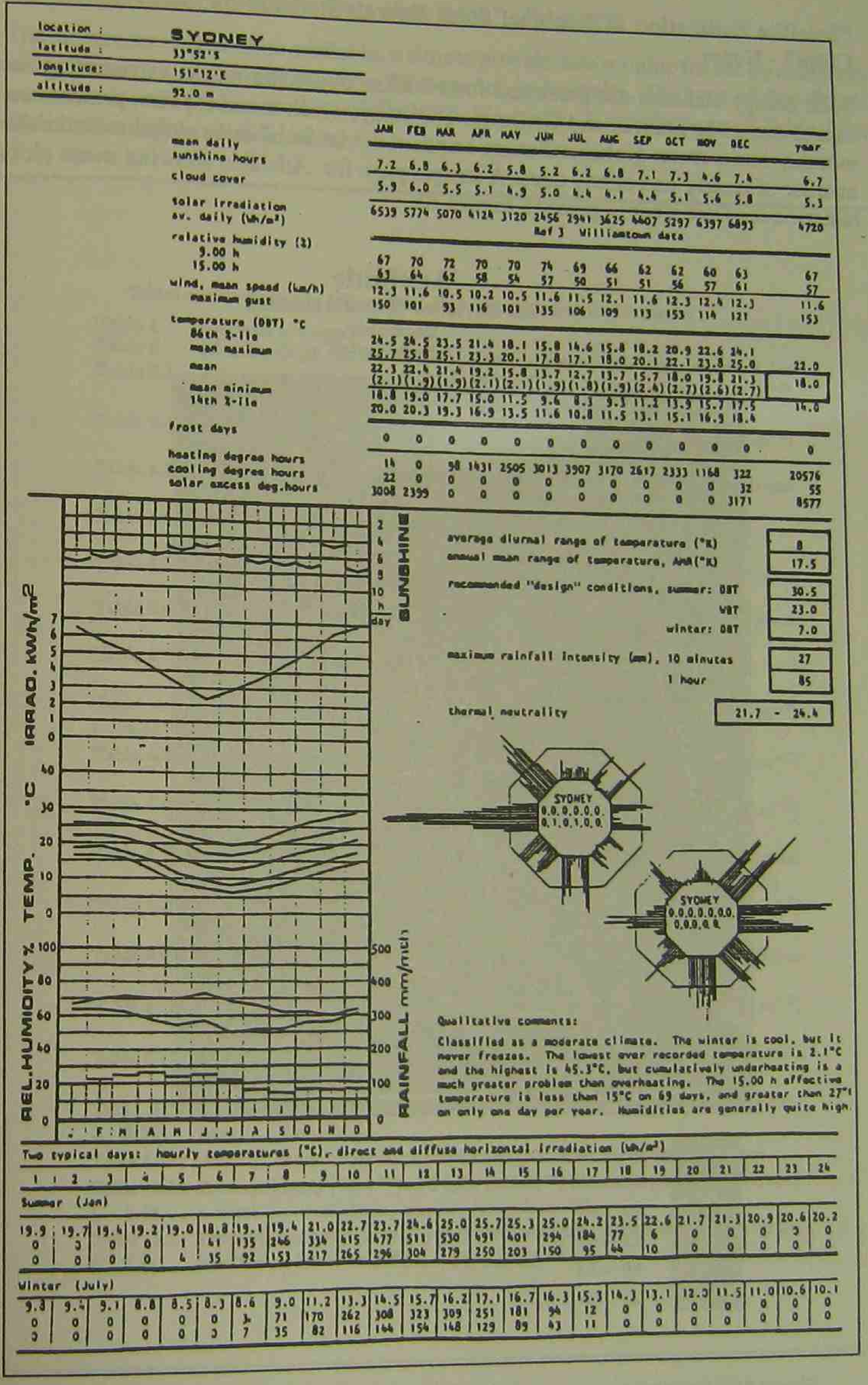
This handbook gives general climatic data for sixteen Australian sites and includes: temperature (wet and dry bulb), wind speed, cloud cover and various irradiation information. The results were derived from climatic data tapes as prepared by the C.S.I.R.O. which in turn were derived from Bureau of Meteorology data. The data is presented as hourly averages for each month of the year.

"Climatic Data and its use in Design" - *Szokolay*

This text presents climatic data in a convenient format and shows the ways this data can be used. The data is presented for fifty locations around Australia with one page for each location. The climatic data for Sydney is shown in Figure 9.

Data for sunshine hours, solar irradiation, temperatures, relative humidity and rainfall are presented in both tabular and graphical form. A brief discussion of the data sheet is given below. For a more detailed coverage refer to the reference above.

Temperature	The table gives mean temperature, mean maximum, mean minimum, 86th and 14th percentile, of mean temperature.
	The graph gives similar values except that the percentiles are of daily maxima (top line) and daily minima (bottom line).
	The standard deviation of mean temperatures is given in brackets under the monthly values.
	Hourly temperatures for a typical winter and summer day are given at the bottom of the sheet.
Humidity	Morning and afternoon values of relative humidity are given in both table and graphical form.
Rainfall	Mean monthly rainfall is given in the bar graph at the bottom.
Irradiation	Monthly irradiation (W/m^2) on a horizontal surface is given as well as hourly values of direct and diffuse radiation (Wh/m^2) for a typical winter and summer day.
Sunshine, cloud and wind	Both table and graph give monthly mean sunshine hours.
	Cloud cover (table only) is given in "tenths".
	Two wind roses are given. One for 9am (left) and one for 3pm (right). These roses have eight sides, corresponding to the four cardinal and four semi-cardinal points of the compass, giving directions from which the wind comes. Each side has twelve lines, corresponding to the twelve months, from January to December in a clockwise direction. The outer octagon defines the scale: 12.5%, ie., if the wind were evenly distributed, coming from all eight directions with the same frequency, all lines would be this length. The twelve numbers inside the octagon indicate the percentages of calm for the twelve months in sequence. A small dash on the inside of the inner octagon would indicate that there is no wind from that direction in that month.
Thermal neutrality	This is the theoretical mean temperature at which the average person would feel neither hot nor cold. The values given are two discrete values. The first is for the three winter months and the second for the three summer months. The "comfort zone" can then be taken as +/- 2^{o}C of each value.



location :	SYDNEY
latitude :	33°52'S
longitude:	151°12'E
altitude :	92.0 m

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	year
mean daily sunshine hours	7.2	6.8	6.3	6.2	5.8	5.2	6.2	6.8	7.1	7.3	4.6	7.4	6.7
cloud cover	5.9	6.0	5.5	5.1	4.9	5.0	4.4	4.1	4.4	5.1	5.6	5.8	5.3
solar irradiation av. daily (Wh/m²)	6539	5774	5070	4124	3120	2456	2941	3625	4407	5297	6397	6893	4720
						Ref 3	Williamtown data						
relative humidity (%) 9.00 h	67	70	72	70	70	74	69	66	62	62	60	63	67
15.00 h	63	64	62	58	54	57	50	51	51	56	57	61	57
wind, mean speed (km/h)	12.3	11.6	10.5	10.2	10.5	11.6	11.5	12.1	11.6	12.3	12.4	12.3	11.6
maximum gust	150	101	93	116	101	135	106	109	113	153	114	121	153
temperature (DBT) °C 86th %-ile	24.5	24.5	23.5	21.4	18.1	15.8	14.6	15.8	18.2	20.9	22.6	24.1	
mean maximum	25.7	25.8	25.1	23.3	20.1	17.8	17.1	18.0	20.1	22.1	23.8	25.0	22.0
mean	22.3	22.4	21.4	19.2	15.8	13.7	12.7	13.7	15.7	18.0	19.8	21.3	18.0
	(2.1)	(1.9)	(1.9)	(2.1)	(2.1)	(1.9)	(1.8)	(1.9)	(2.4)	(2.7)	(2.6)	(2.7)	
mean minimum	18.8	19.0	17.7	15.0	11.5	9.6	8.3	9.3	11.2	13.9	15.7	17.5	14.0
14th %-ile	20.0	20.3	19.3	16.9	13.5	11.6	10.8	11.5	13.1	15.1	16.9	18.4	
frost days	0	0	0	0	0	0	0	0	0	0	0	0	0
heating degree hours	14	0	98	1431	2505	3013	3907	3170	2617	2333	1168	322	20576
cooling degree hours	22	0	0	0	0	0	0	0	0	0	0	32	55
solar excess deg.hours	3008	2399	0	0	0	0	0	0	0	0	0	3171	8577

average diurnal range of temperature (°K)	8
annual mean range of temperature, AMR(°K)	17.5
recommended "design" conditions, summer: DBT	30.5
WBT	23.0
winter: DBT	7.0
maximum rainfall intensity (mm), 10 minutes	27
1 hour	85
thermal neutrality	21.7 - 24.4

Qualitative comments:

Classified as a moderate climate. The winter is cool, but it never freezes. The lowest ever recorded temperature is 2.1°C and the highest is 45.3°C, but cumulatively underheating is a much greater problem than overheating. The 15.00 h effective temperature is less than 15°C on 69 days, and greater than 27°C on only one day per year. Humidities are generally quite high.

Two typical days: hourly temperatures (°C), direct and diffuse horizontal irradiation (Wh/m²)

Summer (Jan)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
19.9 0 0	19.7 0 0	19.4 0 0	19.2 0 0	19.0 1 4	18.8 41 35	19.1 135 92	19.4 246 153	21.0 334 217	22.7 415 265	23.7 477 296	24.6 511 304	25.0 530 279	25.7 491 250	25.3 401 203	25.0 294 150	24.2 184 95	23.5 77 44	22.6 6 10	21.7 0 0	21.3 0 0	20.9 0 0	20.6 0 0	20.2 0 0

Winter (July)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
9.3 0 0	9.4 0 0	9.1 0 0	8.8 0 0	8.5 0 0	8.3 0 0	8.6 3 7	9.0 71 35	11.2 170 82	13.3 262 116	14.5 308 144	15.7 323 154	16.2 309 148	17.1 251 129	16.7 181 89	16.3 94 43	15.3 12 11	14.3 0 0	13.1 0 0	12.0 0 0	11.5 0 0	11.0 0 0	10.6 0 0	10.1 0 0

Figure 9 - Climatic data sheet for Sydney. (Source: Szokolay, 1988).

"Satellite Estimation of Regional Solar Energy Statistics for Australian Capital Cities" - Nunez

Solar energy statistics are presented for a 200km by 200km region surrounding each capital including Darwin and Canberra. The study, which lasted 3 years, presents on a monthly basis: mean global radiation, standard deviation of daily global radiation and number of cloudy and sunny days. A sample page for Adelaide showing mean global radiation for December is given in Figure 10.

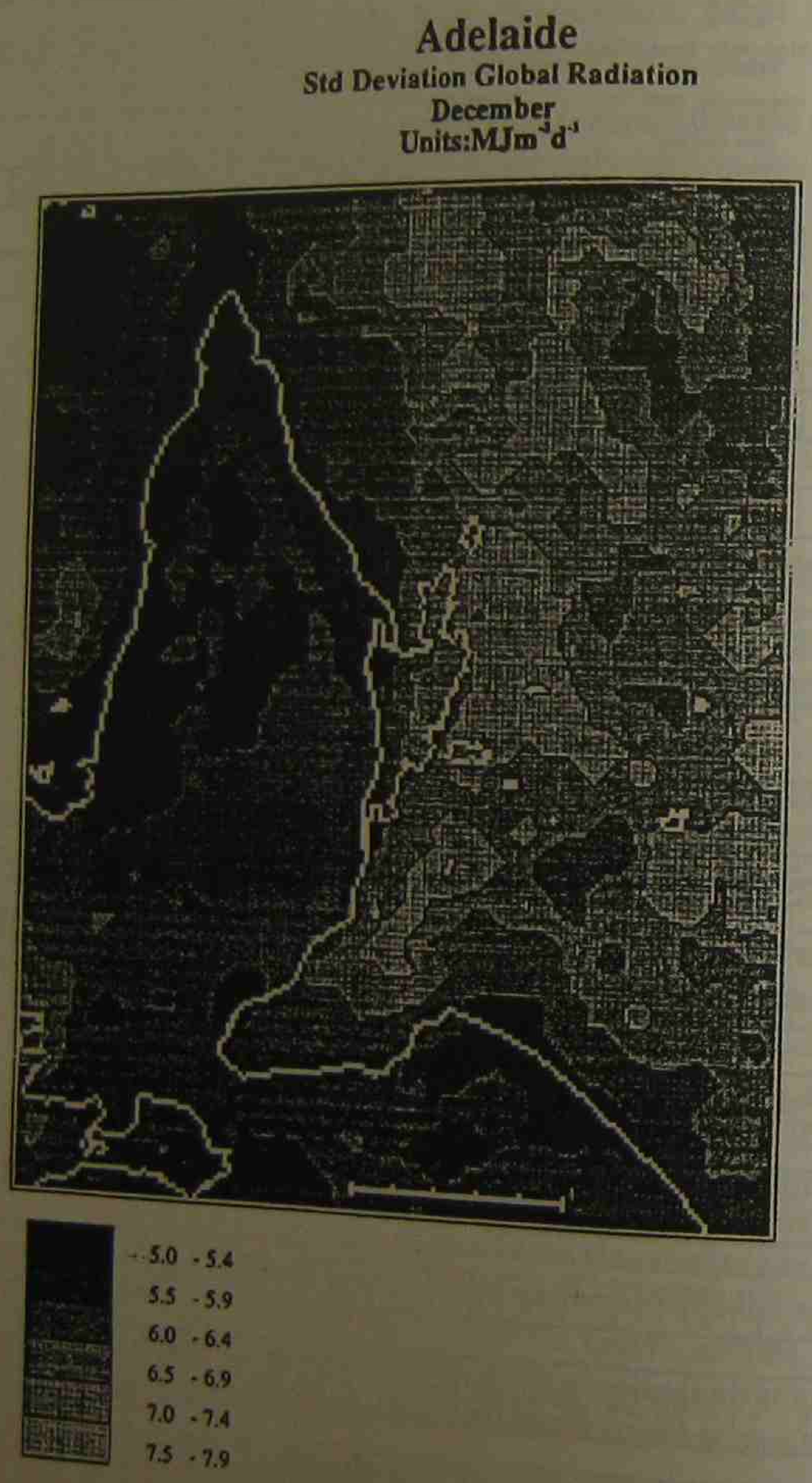
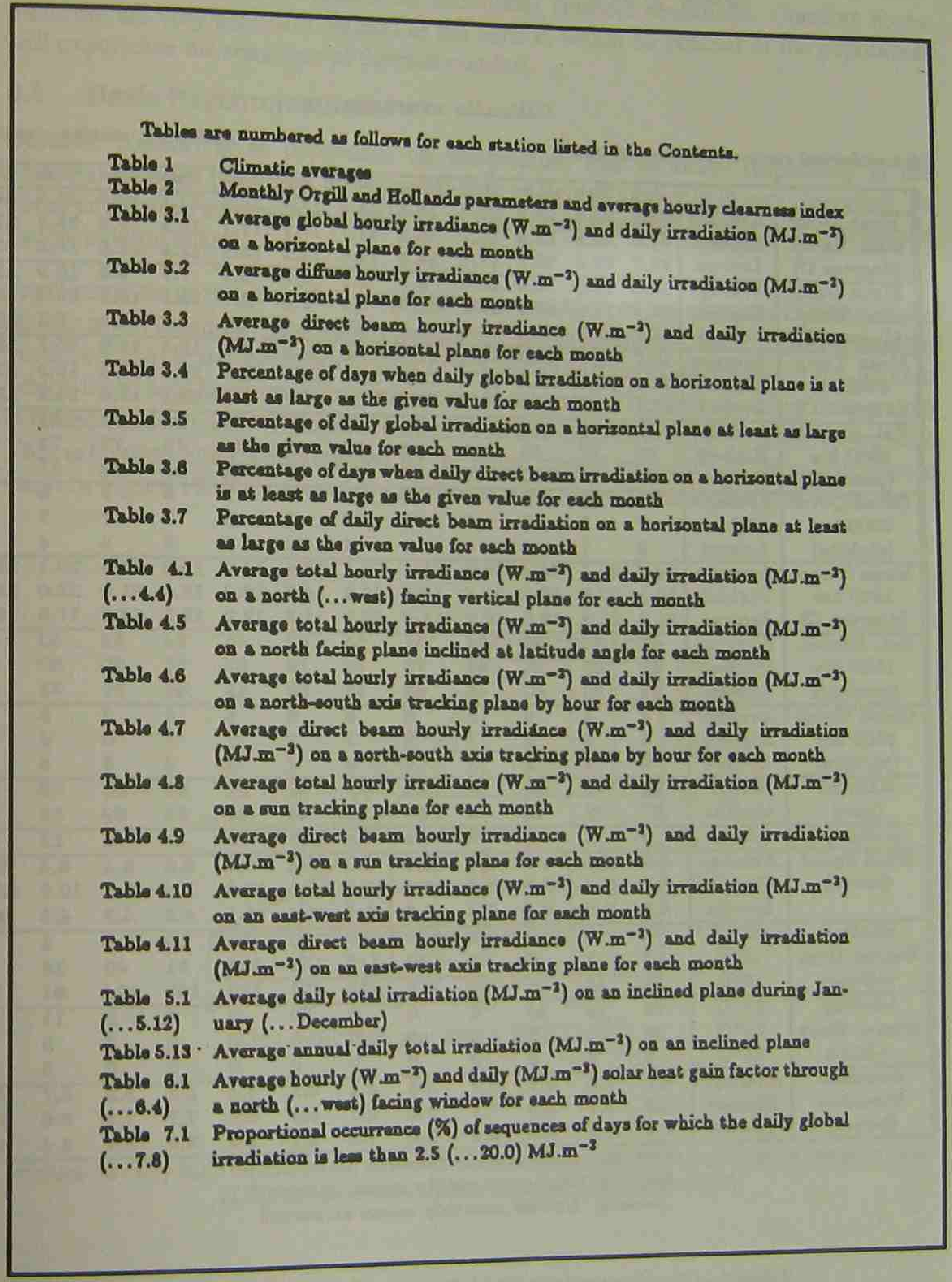


Figure 10 - December mean global radiation for Adelaide. (Source: Nunez, 1990).

"Australian Solar Radiation Data Handbook" - Frick et al

The most recent publication available, it aims to provide data suitable for use by designers of various types of solar systems for 24 locations in Australia. The type of data that is available is indicated in the List of Tables in Figure 11. A sample page of *Table 1* for Melbourne is given in Table 2.



Tables are numbered as follows for each station listed in the Contents.

Table 1	Climatic averages
Table 2	Monthly Orgill and Hollands parameters and average hourly clearness index
Table 3.1	Average global hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a horizontal plane for each month
Table 3.2	Average diffuse hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a horizontal plane for each month
Table 3.3	Average direct beam hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a horizontal plane for each month
Table 3.4	Percentage of days when daily global irradiation on a horizontal plane is at least as large as the given value for each month
Table 3.5	Percentage of daily global irradiation on a horizontal plane at least as large as the given value for each month
Table 3.6	Percentage of days when daily direct beam irradiation on a horizontal plane is at least as large as the given value for each month
Table 3.7	Percentage of daily direct beam irradiation on a horizontal plane at least as large as the given value for each month
Table 4.1 (...4.4)	Average total hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a north (...west) facing vertical plane for each month
Table 4.5	Average total hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a north facing plane inclined at latitude angle for each month
Table 4.6	Average total hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a north-south axis tracking plane by hour for each month
Table 4.7	Average direct beam hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a north-south axis tracking plane by hour for each month
Table 4.8	Average total hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a sun tracking plane for each month
Table 4.9	Average direct beam hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on a sun tracking plane for each month
Table 4.10	Average total hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on an east-west axis tracking plane for each month
Table 4.11	Average direct beam hourly irradiance ($W.m^{-2}$) and daily irradiation ($MJ.m^{-2}$) on an east-west axis tracking plane for each month
Table 5.1 (...5.12)	Average daily total irradiation ($MJ.m^{-2}$) on an inclined plane during January (...December)
Table 5.13	Average annual daily total irradiation ($MJ.m^{-2}$) on an inclined plane
Table 6.1 (...6.4)	Average hourly ($W.m^{-2}$) and daily ($MJ.m^{-2}$) solar heat gain factor through a north (...west) facing window for each month
Table 7.1 (...7.8)	Proportional occurrence (%) of sequences of days for which the daily global irradiation is less than 2.5 (...20.0) $MJ.m^{-2}$

Figure 11 - List of tables from "Australian Solar Radiation Data Handbook". (Source: Frick et al, 1987).

MELBOURNE (150 LONSDALE ST.)

Latitude: 37°50' S Longitude: 144°58' E Elevation: 123.1m

Climatic averages

Metereological station number 086338

Radiation station number

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Daily Max. Temp. (degrees C)	Average	25.8	25.7	23.8	20.2	16.5	13.9	13.3	14.8	17.1	19.5	21.8	24.1
	Highest	31.0	30.2	28.9	22.9	19.6	17.7	15.7	17.7	19.5	23.3	25.5	27.3
	Lowest	22.7	22.4	20.1	17.1	14.6	11.6	11.2	13.1	13.5	15.5	18.9	20.9
Mean Daily Min. Temp. (degrees C)	Average	14.0	14.3	13.0	10.6	8.4	6.7	5.7	6.5	7.7	9.3	10.9	12.7
	Highest	17.7	17.7	16.8	13.8	10.9	9.4	8.4	8.7	10.3	12.2	13.3	15.4
	Lowest	11.7	11.3	10.1	8.5	6.3	3.3	3.8	4.0	5.6	7.5	8.1	10.2
Mean Temp. 0900 hrs (degrees C)	Average	19.7	19.7	18.0	14.5	11.4	9.0	8.3	9.9	12.4	14.9	16.7	18.5
	Highest	25.2	22.3	21.2	16.6	13.2	11.7	10.1	11.6	14.7	17.8	19.3	21.2
	Lowest	16.3	16.9	15.9	12.3	9.8	5.4	6.7	7.5	10.1	12.9	14.2	15.9
Rel. Humid. 0900 hrs (percent)	Average	59	63	65	72	78	82	81	75	68	62	61	59
	Highest	68	77	80	82	87	92	86	82	76	72	71	70
	Lowest	49	48	50	65	68	73	72	62	56	52	51	48
Cloud Cover 0900 hrs (eighths)	Average	5	5	5	.5	5	6	5	5	5	5	6	5
	Highest	7	6	7	7	7	7	7	6	7	7	7	7
	Lowest	3	3	4	4	3	4	4	4	3	4	4	4
Mean Temp. 1500 hrs (degrees C)	Average	24.0	24.1	22.4	19.0	15.8	13.1	12.6	13.9	16.0	18.1	20.1	22.3
	Highest	29.1	27.8	26.4	21.4	18.8	16.9	14.7	16.9	18.4	21.9	23.0	25.4
	Lowest	21.3	21.4	19.6	16.2	14.0	10.9	11.2	12.2	13.0	15.6	17.6	19.3
Rel. Humid. 1500 hrs (percent)	Average	46	48	50	54	61	65	63	58	54	52	50	47
	Highest	58	63	63	66	73	74	73	67	63	60	60	62
	Lowest	38	36	40	44	49	58	53	43	44	39	33	35
Cloud Cover 1500 hrs (eighths)	Average	4	4	4	5	6	6	6	6	5	5	5	4
	Highest	5	6	6	7	7	7	7	7	7	6	6	6
	Lowest	2	2	2	2	4	4	4	4	4	3	3	3
Rainfall (mm)	Mean	48	48	53	58	58	49	48	51	59	68	59	58
	Median	37	32	41	52	56	43	44	49	54	69	52	48
Raindays	Mean	8	7	9	12	14	14	15	16	15	14	12	11
Wind Speed (knots)	Average	6.0	5.6	4.9	5.1	5.5	5.7	6.4	6.5	6.6	6.4	6.4	6.4
	Highest	8.9	8.1	7.9	8.8	9.0	10.6	11.4	12.2	9.4	10.3	10.5	10.4
	Lowest	3.8	3.6	3.1	2.4	3.1	2.5	3.4	4.1	4.3	4.2	4.8	4.5
Heating Degree Days —Base:	12°C	0	0	0	3	20	60	80	51	20	5	1	0
	15°C	3	2	6	26	82	142	171	135	81	40	14	4
	18°C	18	14	34	84	172	232	264	228	168	114	61	29
Cooling Degree Days —Base:	18°C	76	70	44	5	0	0	0	0	0	2	11	41
	21°C	27	24	9	0	0	0	0	0	0	0	0	7
	24°C	5	4	0	0	0	0	0	0	0	0	0	0
Sunshine Duration (hours)	Average	8.1	7.5	6.2	4.9	3.8	3.1	3.5	4.4	5.2	5.9	6.7	7.4
	Highest	10.8	9.7	8.9	7.1	6.0	4.7	5.3	6.1	7.7	7.8	9.0	9.9
	Lowest	6.2	5.5	4.0	2.2	1.6	1.2	2.1	2.3	3.6	3.9	4.4	4.9

Average: Overall daily mean
Highest: Highest monthly mean on record
Lowest: Lowest monthly mean on record

Table 2 - Climate averages for Melbourne. (Source: Frick et al, 1987).

3 THERMAL COMFORT

Comfort within buildings is primarily controlled by four major factors: air temperature, radiant heat, humidity and airflow. Each can have a dominating effect. Other factors which affect comfort include clothing, activity level and acclimatization. Some psychological triggers, such as certain colours, also seem to affect comfort, and "state of mind" can have major effects on individual comfort sensations. Comfort zones therefore are very generally defined as the zone in which 80 percent of the population will experience the sensation of thermal comfort.

3.1 Basic Psychrometrics

Because comfort is so dependent on temperature and humidity (especially at the overheated end of the scale), an understanding of their relationship is very important. To better understand temperature, humidity and the "comfort zone", it is necessary to discuss psychrometric charts.

Psychrometric charts provide a graphical representation of the state or condition of the air at a given location. They relate temperature on the horizontal scale to moisture on the vertical scale. If the temperature of a given volume of air is decreased to the point at which it can hold no more moisture it becomes saturated. The corresponding temperature is called the dewpoint. When air is cooled to its dew point it is at 100% relative humidity. This saturation point is represented by the outer, curved boundary of the psychrometric chart in Figure 12. If air is cooled to below its dew point, condensation takes place.

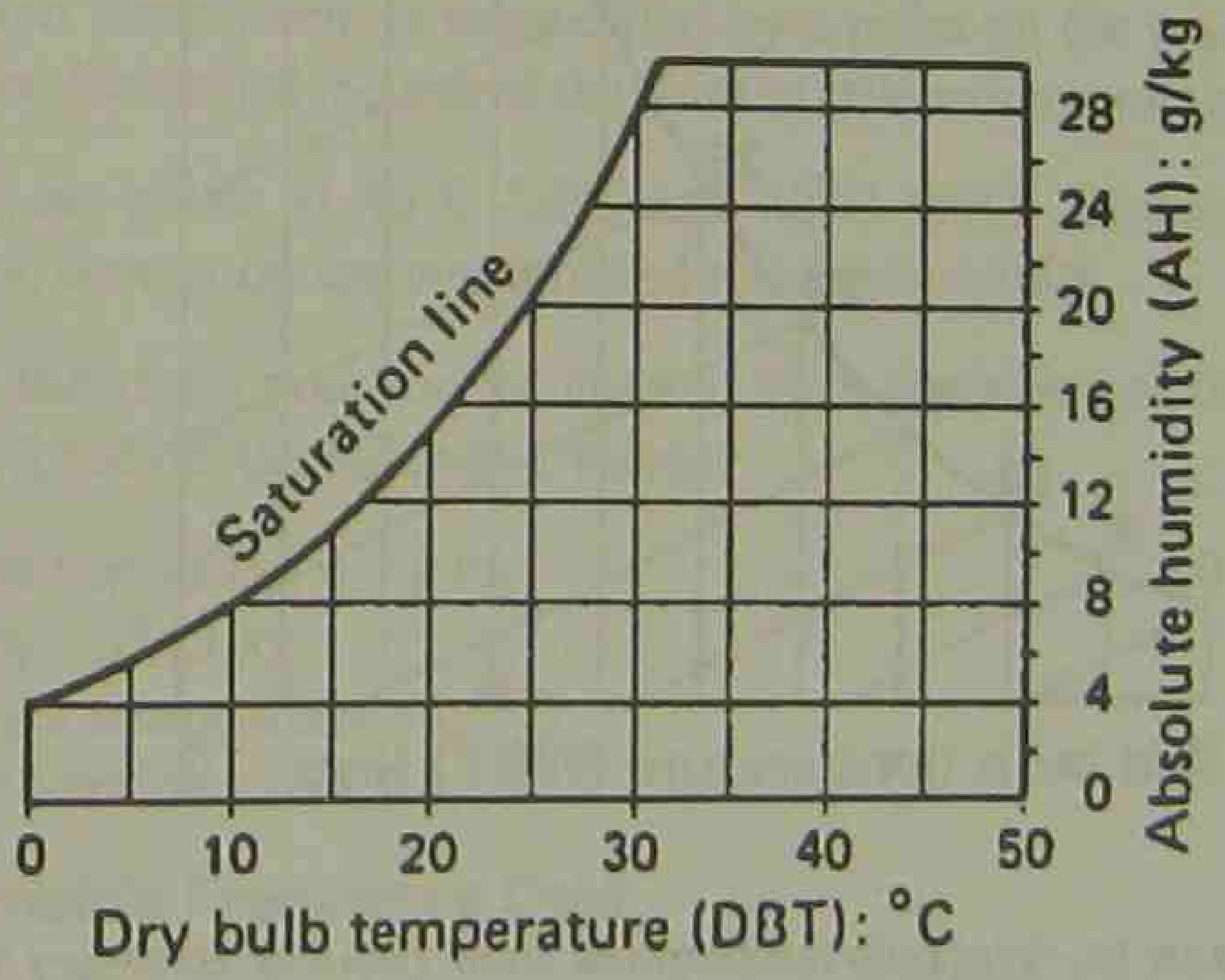


Figure 12 - Dry bulb temperature, absolute humidity and saturation points form the boundary of the psychrometric chart. (Source: Szokolay, 1987).

The air temperature represented by the horizontal axis of the psychrometric chart is known as the dry bulb temperature (^{o}C). The vertical axis is known by a number of names, one often used is absolute humidity or moisture content (g/kg).

Relative humidity lines can be included on the chart and are shown in Figure 13.

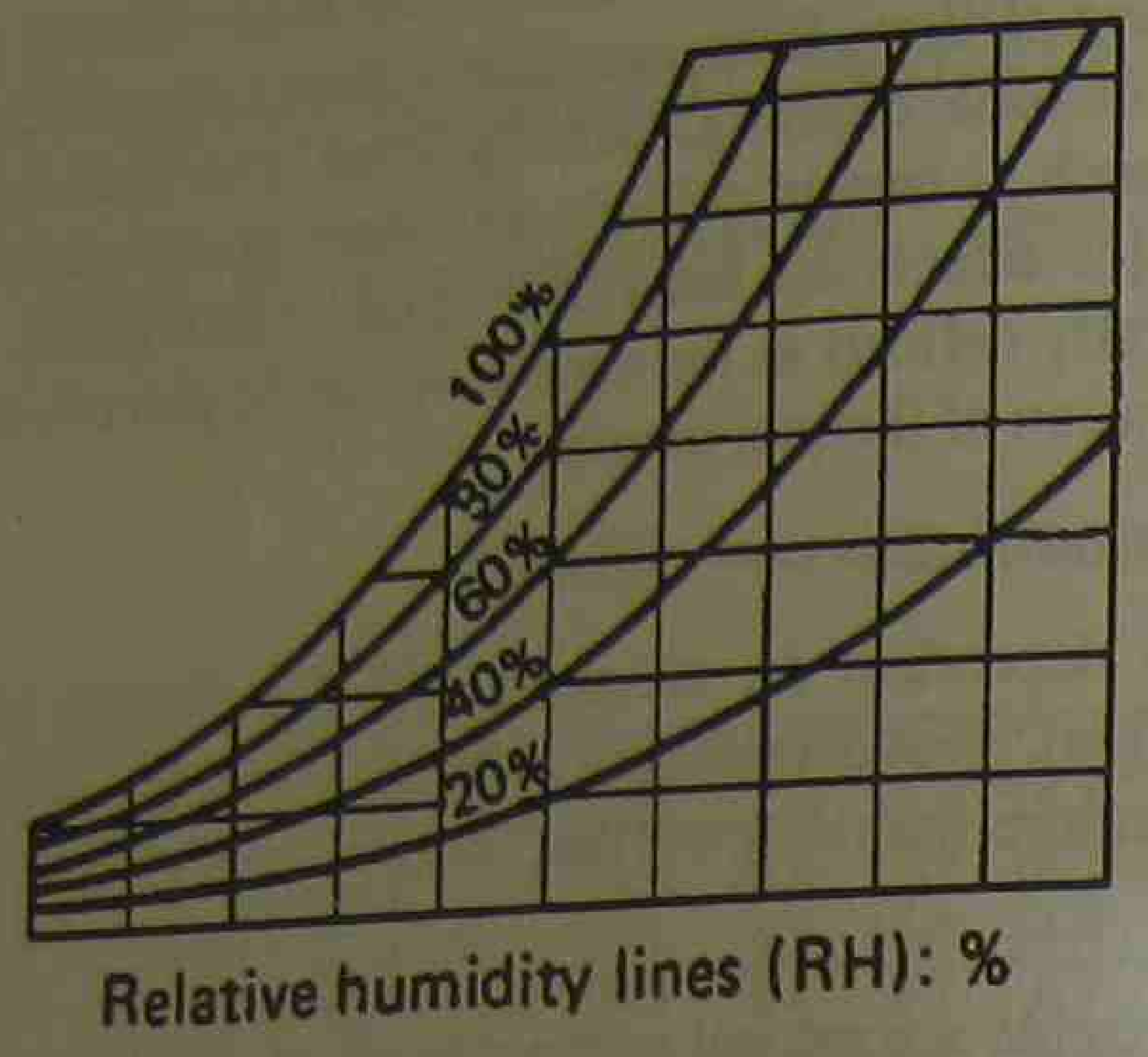


Figure 13 - Relative humidity lines. (Source: Szokolay, 1987).

Wet bulb temperature lines can also be included on the chart. This enables a point representing the condition of the air to be plotted if the dry bulb and wet bulb temperatures are known (Figure 14).

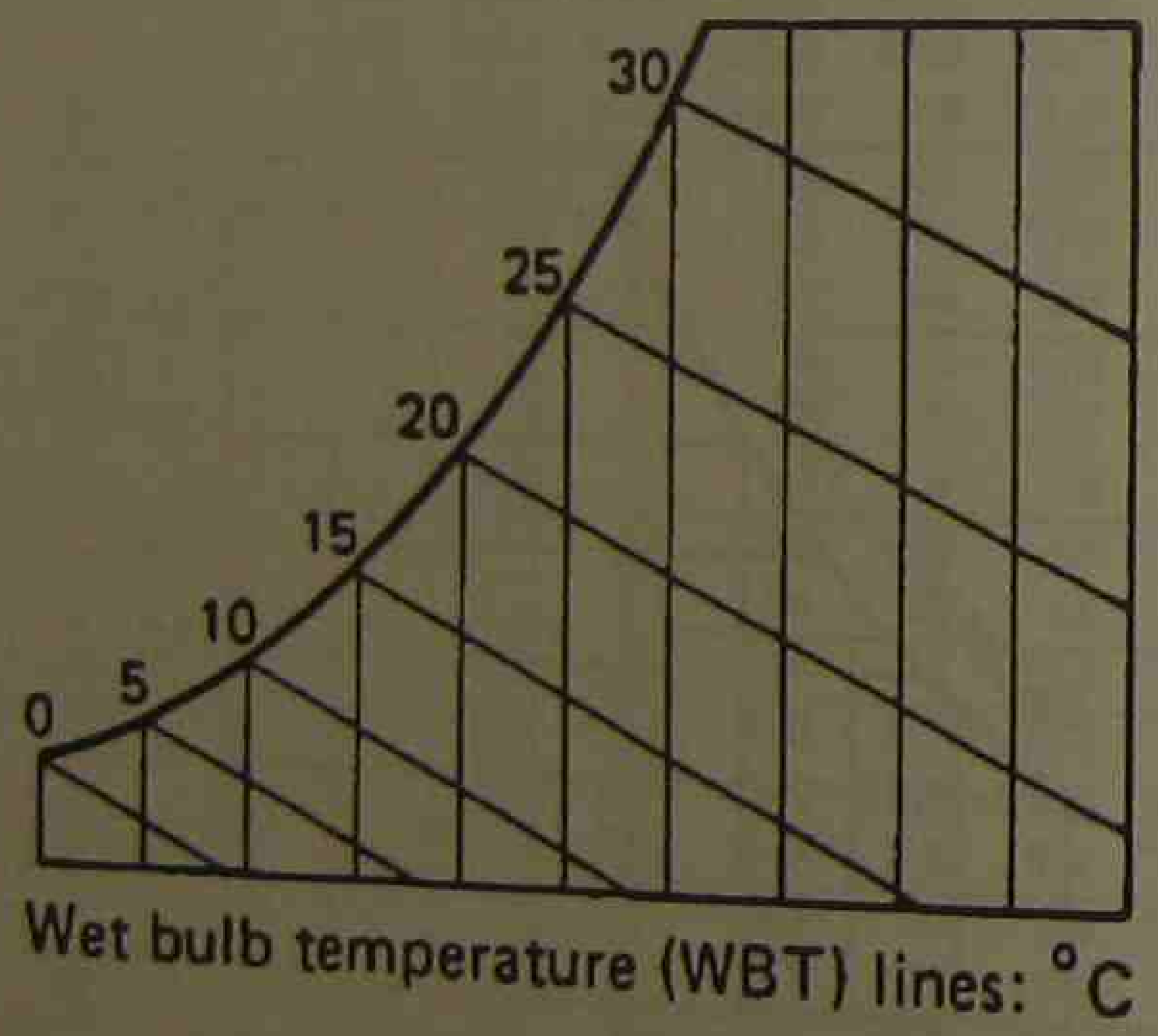


Figure 14 -Wet bulb temperature lines. (Source: Szokolay,1987).

One further and important quantity, the energy content of the air, is expressed by the chart. This total air energy is the sum of both the temperature content of the air (sensible heat) and the vaporized moisture content of the air (latent heat). The sum of the sensible and latent heat of a particular atmosphere relative to that of 0°C dry air is known as enthalpy (kJ/kg). Enthalpy lines can be included on the chart as shown in Figure 15. For air condition P the enthalpy is read at point A. The sensible heat component can be read at point B, corresponding to the enthalpy of dry air at the same temperature. The remainder, that is A-B, is the latent heat content.

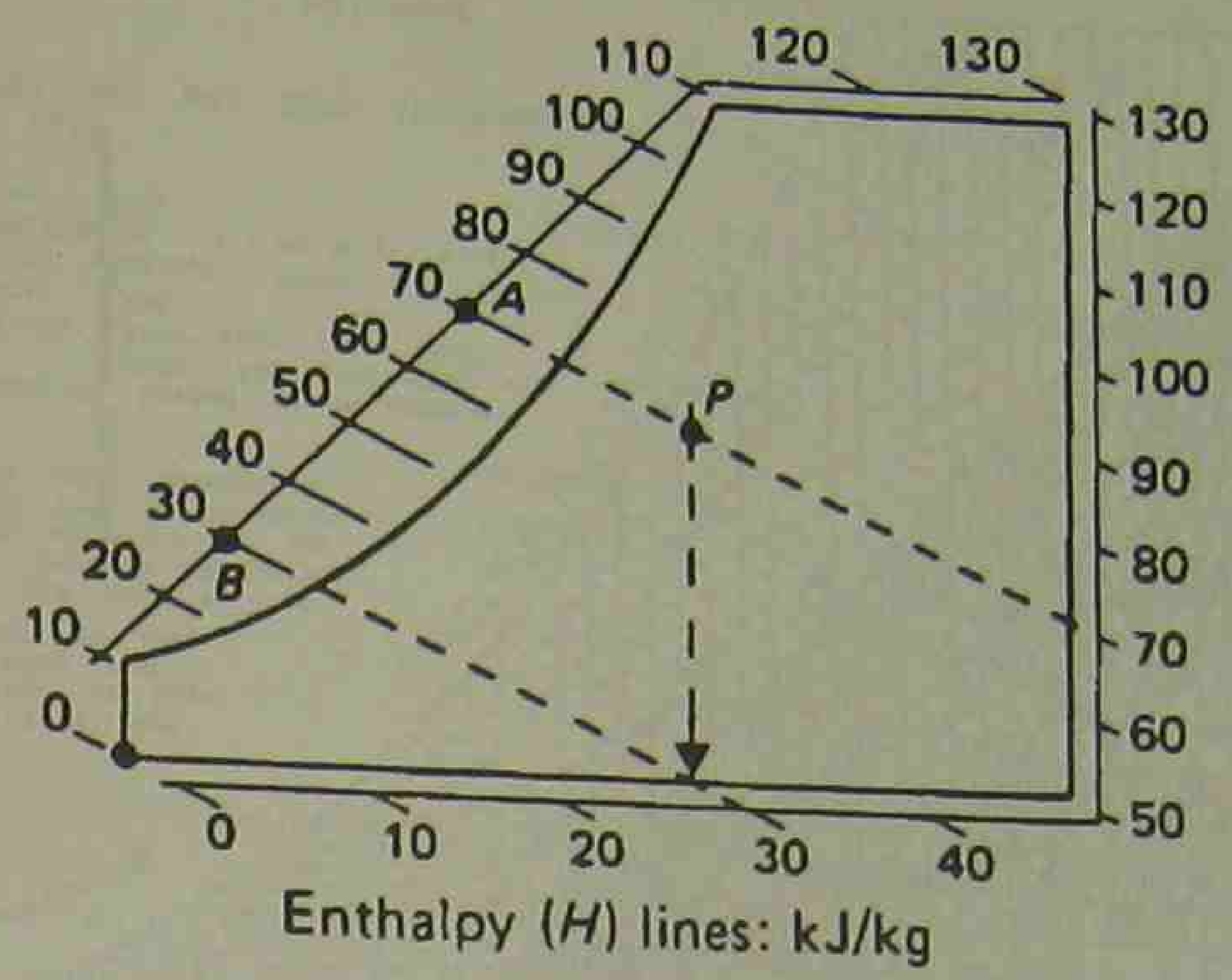


Figure 15 - Enthalpy lines. (Source: Szokolay, 1987).

The enthalpy lines almost coincide with the WBT lines. To avoid confusion the enthalpy scale is given at the sides of the chart and can be read by using a straight edge.

A complete psychrometric chart is shown in Figure 16.

3.2 Moist Air Characteristics: Example

The state of a given atmosphere is represented by a point on the psychrometric chart. The example below illustrates the use of the chart to determine moist air characteristics:

Example - Moist air exists at 40°C DBT and 20°C WBT. Determine the absolute humidity, enthalpy, dew point temperature and relative humidity.

Solution - Locate the status point on the chart at the intersection of the 40°C DBT and 20°C WBT lines. Read off the following values:

- ☐ absolute humidity - 6.4 g/kg
- ☐ enthalpy - 57 kJ/kg
- ☐ dew point temperature - 7.5°C
- ☐ relative humidity - 14%

3.3 Psychrometric Frequency Data

These air condition charts have been prepared by the CSIRO Division of Mechanical Engineering from original material supplied by the Australian Bureau of Meteorology. The charts for ten Australian cities can be found in the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) Handbook. The air condition chart for Brisbane is shown in Figure 17. The chart shows hours per year spent in one of a matrix of air condition states. Thus it can be seen that in Brisbane, for example, 114 hours per year are spent in the region defined by the dry bulb temperature between 23 and 24°C with simultaneous wet bulb temperatures between 20 and 21°C.

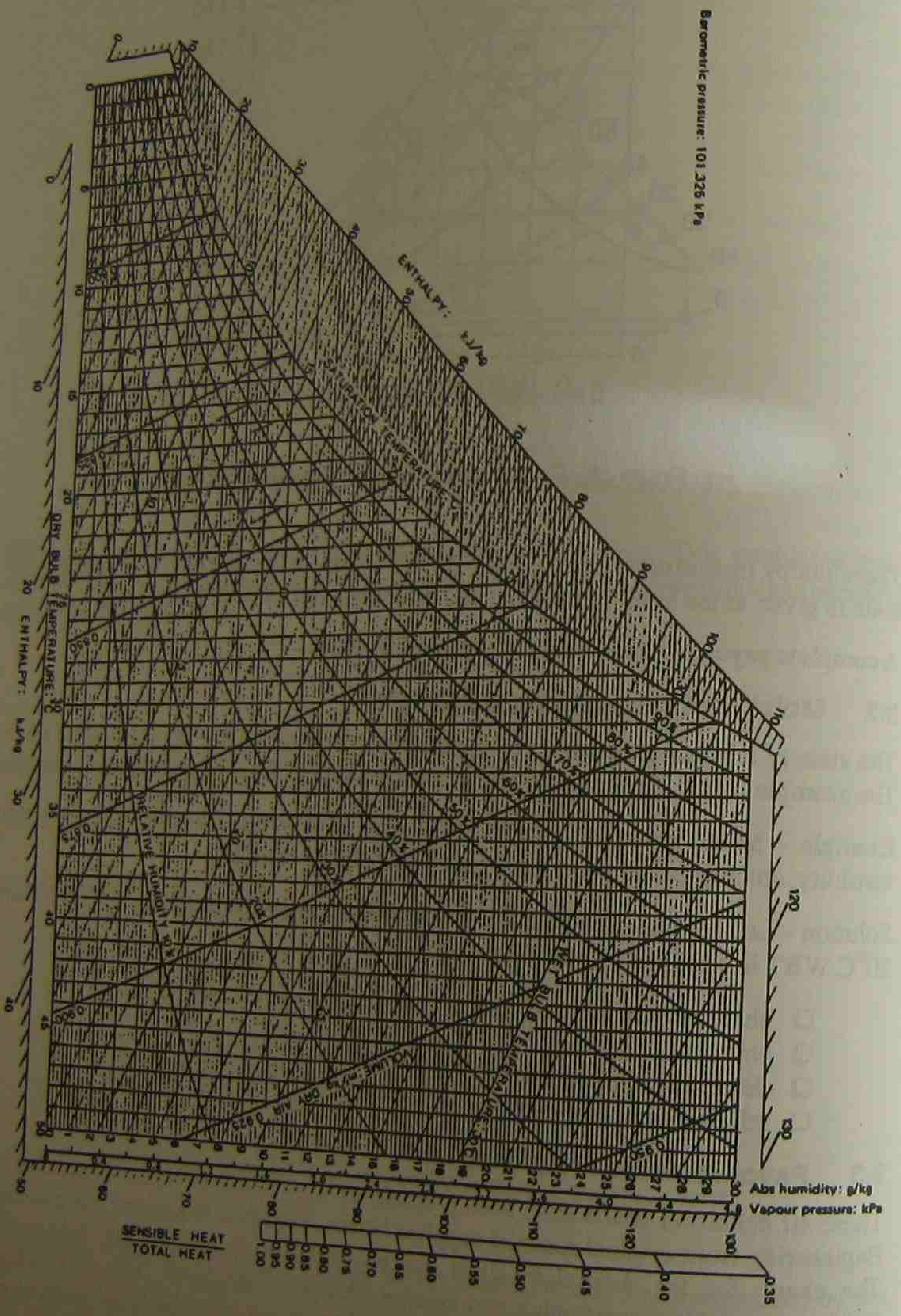
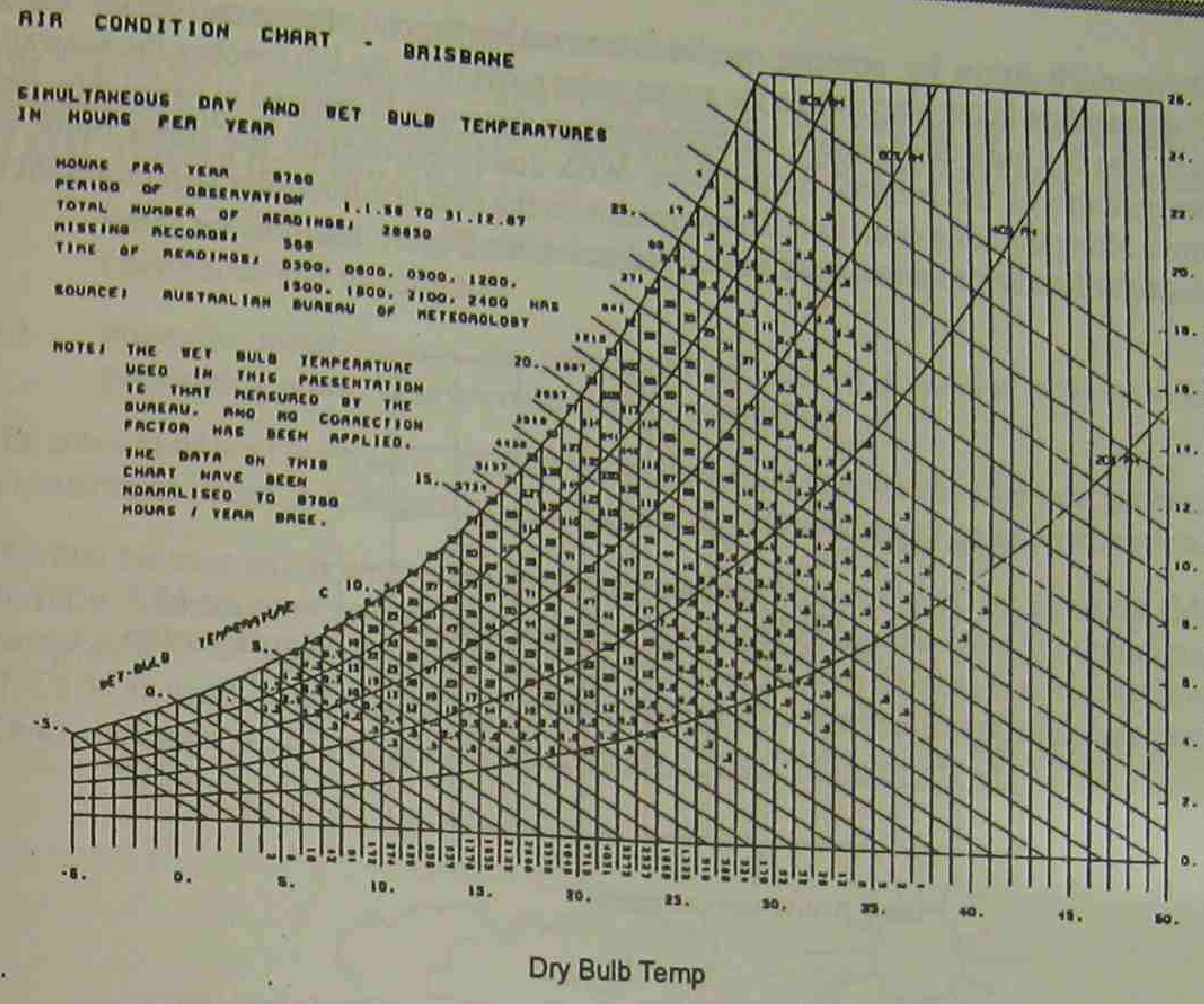


Figure 16 - The complete psychrometric chart. (Source: AIRAH).


AIR CONDITION CHART - BRISBANE

SIMULTANEOUS DRY AND WET BULB TEMPERATURES IN HOURS PER YEAR

HOURS PER YEAR 8760
PERIOD OF OBSERVATION 1.1.58 TO 31.12.87
TOTAL NUMBER OF READINGS: 20830
MISSING RECORDS: 508
TIME OF READINGS: 0300, 0600, 0900, 1200, 1500, 1800, 2100, 2400 HRS
SOURCE: AUSTRALIAN BUREAU OF METEOROLOGY

NOTE: THE WET BULB TEMPERATURE USED IN THIS PRESENTATION IS THAT MEASURED BY THE BUREAU, AND NO CORRECTION FACTOR HAS BEEN APPLIED.

THE DATA ON THIS CHART HAVE BEEN NORMALISED TO 8760 HOURS / YEAR BASE.

Figure 17 - Air condition chart for Brisbane. (Source: AIRAH handbook, 1988).

3.4 Psychrometric Processes

Changes in the condition of the atmosphere can be represented by the movement of the status point. These processes are often studied by engineers so that, for example, air conditioning systems can be sized. Some of the simpler processes are outlined below:

Heating or cooling refers to the addition or removal of heat, without any change in absolute humidity. Only the dry bulb temperature will change. Figure 18 shows that the status point will move horizontally to the left (cooling) or to the right (heating).

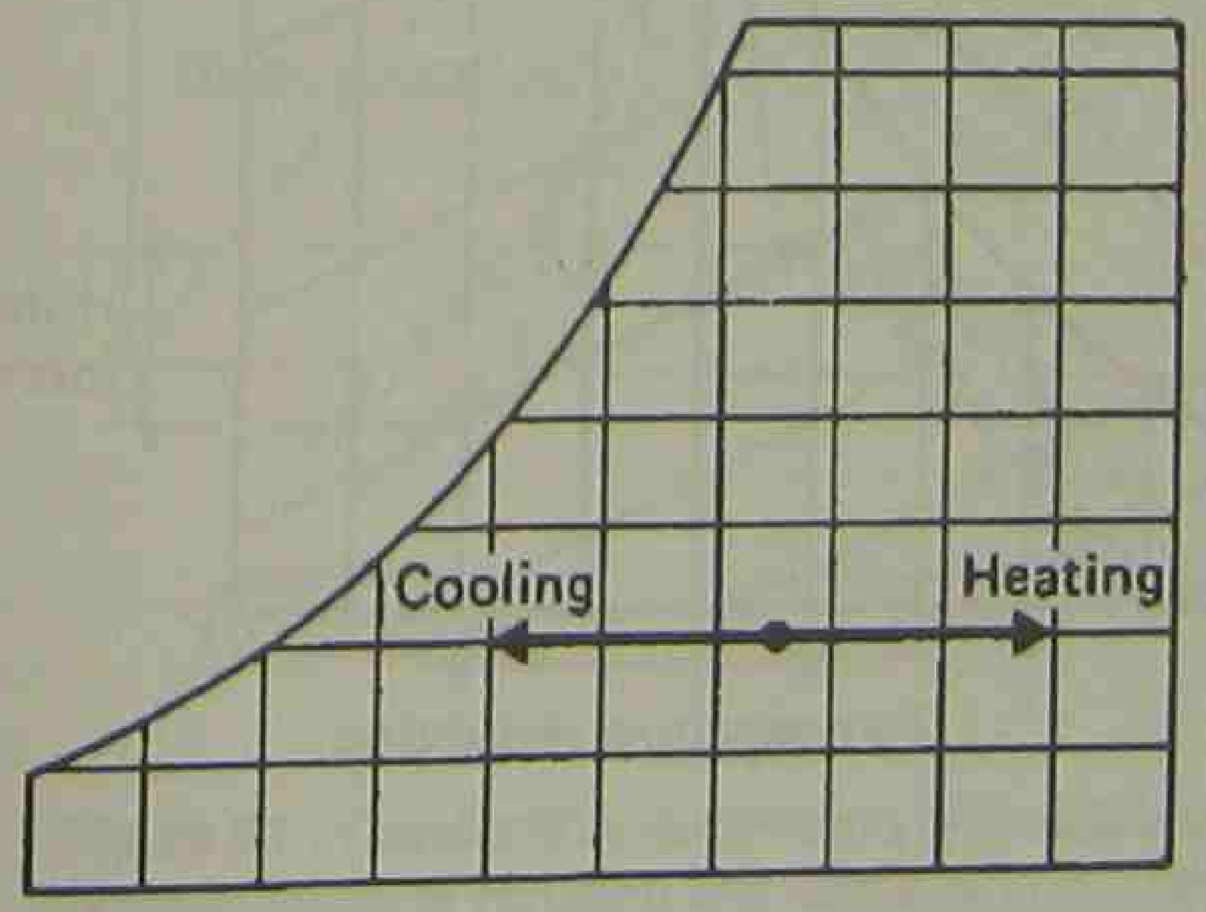


Figure 18 - Heating and Cooling. (Source:Szokolay, 1987).

Dehumidification by cooling occurs when water vapour condenses out of the air. Condensation takes place when the status point moving to the left reaches the saturation line. The dry bulb temperature corresponding to this point is referred to as the dew point temperature of the original atmosphere. With continued cooling the status point will move along the saturation line. The reduction in the absolute humidity will represent the amount of moisture that would have condensed out (Figure 19).

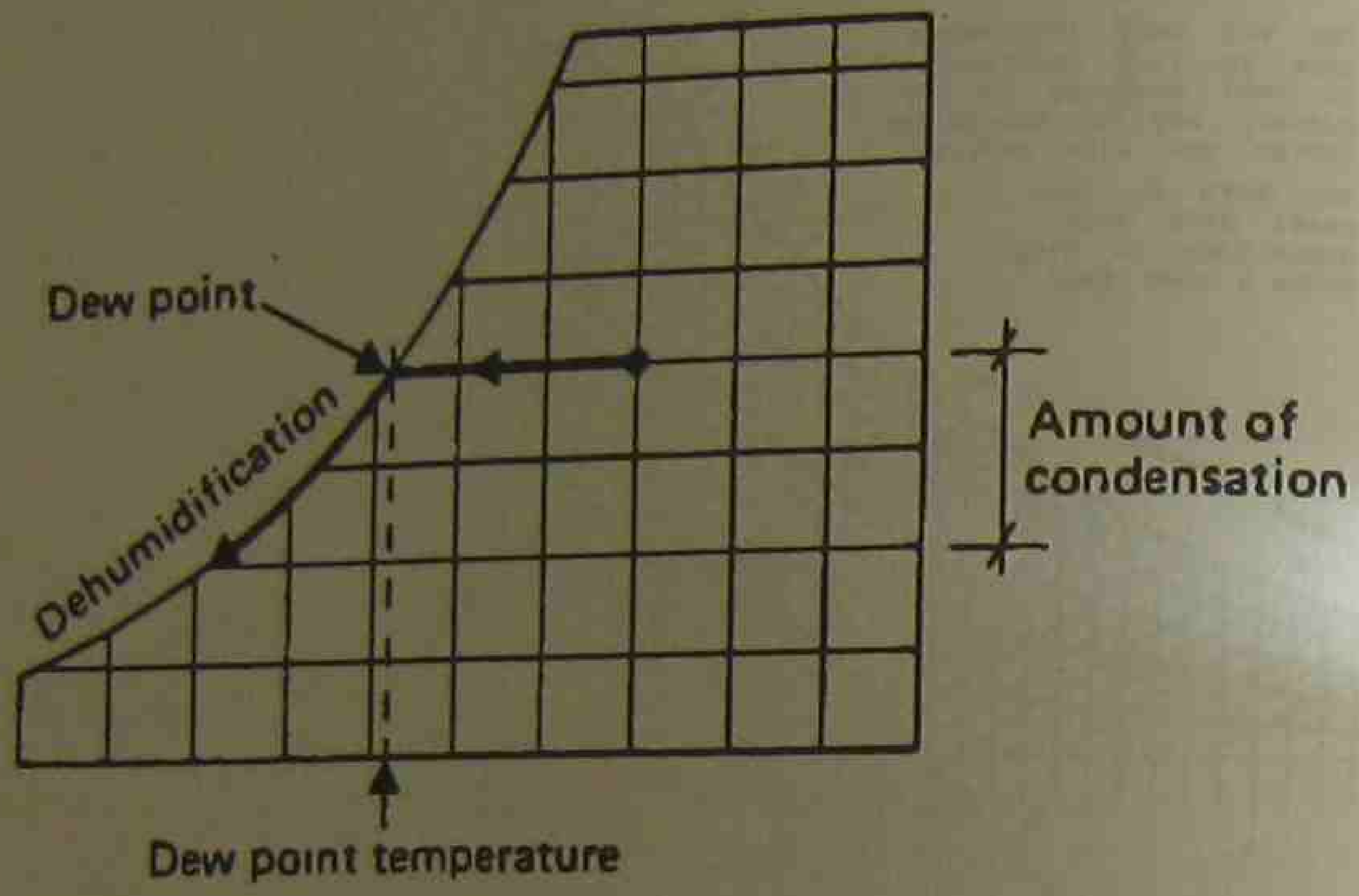


Figure 19 - Dehumidification by cooling. (Source: Szokolay, 1987).

Adiabatic humidification takes place if moisture is evaporated into the air without any heat input or removal. This is the process in evaporative cooling. The latent heat of evaporation is taken from the air. The sensible heat content is reduced and as a result the dry bulb temperature decreases. The status point will move upwards towards the left along a wet bulb temperature line as shown in Figure 20.

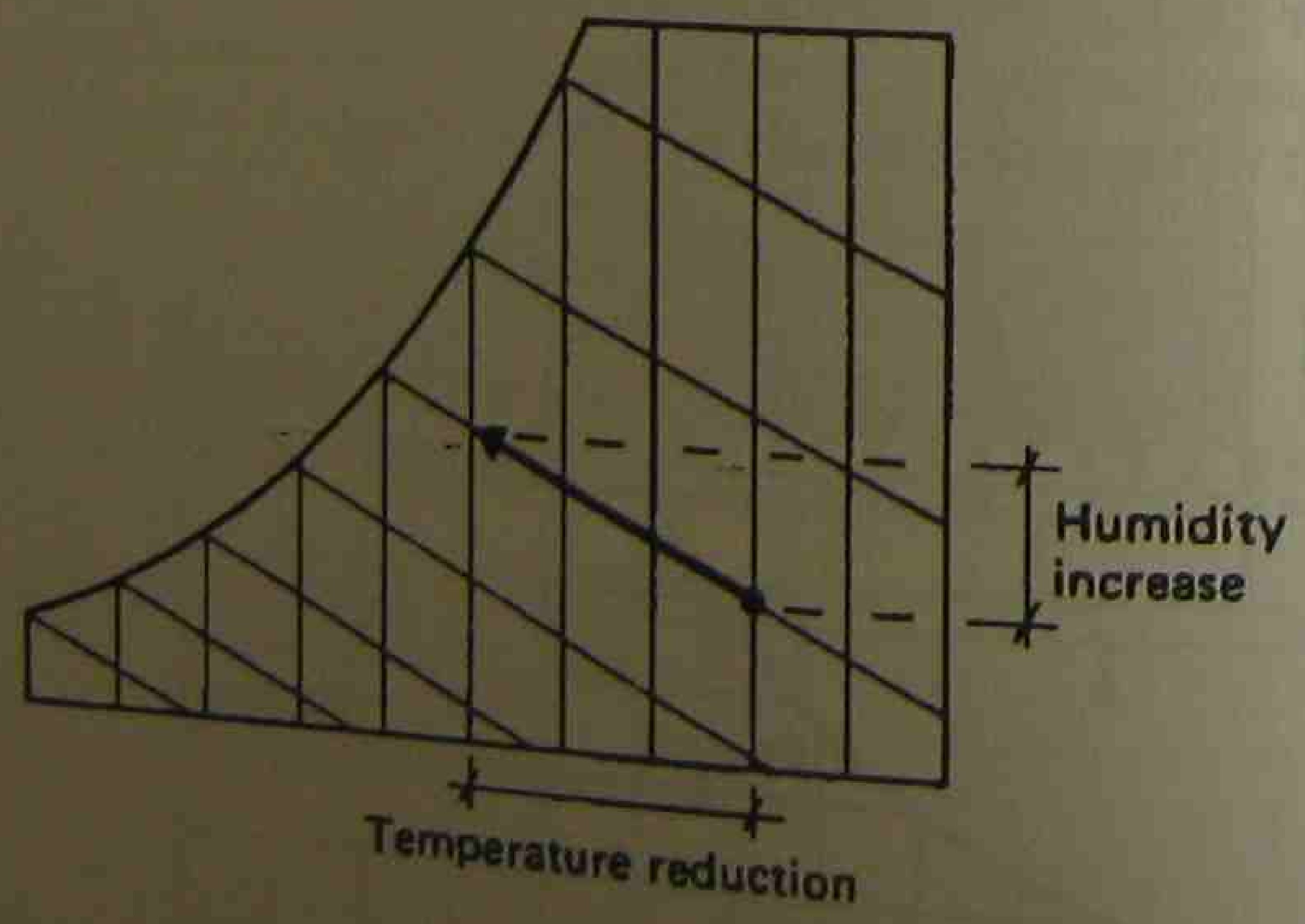


Figure 20 - Adiabatic humidification (evaporative cooling). (Source: Szokolay, 1987).

3.5 Heat Generation by the Human Body

The human body constantly generates excess heat, but at a varying rate. Metabolism is the term describing the biological processes within the body that lead to the production of heat. This can be of two kinds:

(i) basal metabolism - the production of heat by vegetative processes which are continuous and unconscious.

(ii) muscular metabolism - the production of heat by muscular activity whilst performing work. This is consciously controllable.

The amount of heat generation depends on activity level and whether the heat generated is sensible or latent. A heat gain of 100 W/person is often taken as an approximation.

Thermal balance exists when external heat gains and heat produced by the body (Met) are fully dissipated to the environment. The heat produced in the body is continuously transported to the skin surface. If the body temperature is to be kept constant (at about 37°C) heat must be dissipated to the environment by conduction (Cnd), convection (Cnv), radiation (Rad) or evaporation (Evp) as shown in Figure 21.

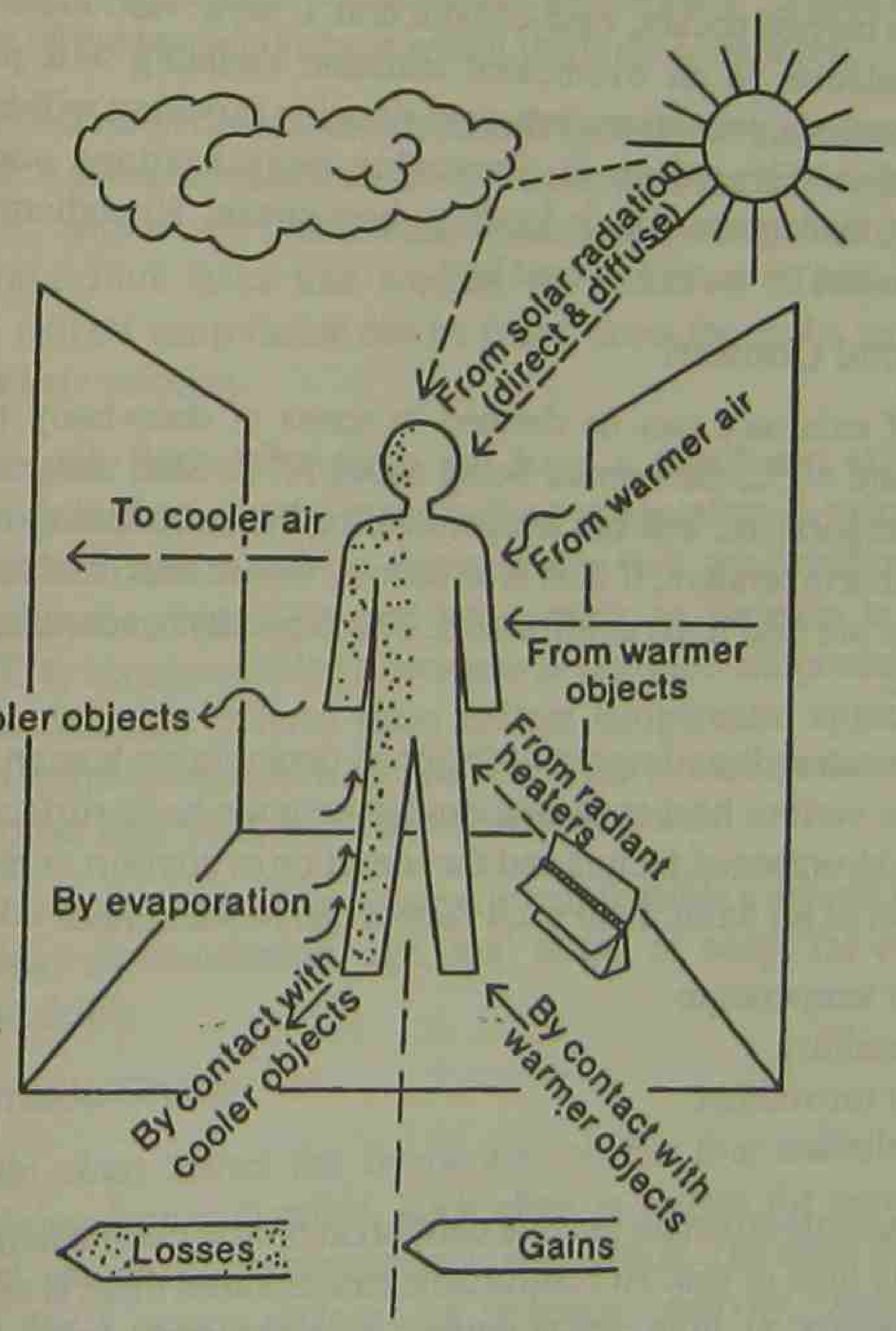


Figure 21 - Conduction, convection and radiation. (Source: Dept. of Housing and Construction, 1985).

The condition of equilibrium is:

$$\mathrm{Met} - \mathrm{Cnd} - \mathrm{Cnv} - \mathrm{Rad} - \mathrm{Evp} = 0$$

A positive value of Cnd, Cnv or Rad represents a heat loss and a negative value represents a heat gain. If the sum is more than zero, this extra heat is stored in the body and the body temperature will rise.

If a person is engaged in sedentary activity in still air of about 18°C, and if there is no contact with colder objects (thus no conductive heat loss) the total heat loss is distributed as:

- ☐ radiation - 45%
- ☐ convection - 30%
- ☐ evaporation - 25%

The skin temperature is normally between 31 and 34°C and it is subject to automatic adjustments in the body's physiological mechanisms. When the balance tends to be positive (too hot), vaso-dilation increases the blood flow to the skin surface, elevates the skin temperature and thus increases the heat dissipation. When the balance is negative (too cold), the reverse occurs, vaso-constriction. If these vaso-motor adjustments cannot restore the balance, in an overheated situation sweating will provide an increased evaporative cooling, or in an underheated situation shivering will increase the muscular heat production. Hyperthermia (inevitable body heating) occurs when the heat dissipation is inadequate and it leads to heat-stroke. Hypothermia (inevitable body cooling) is caused by excessive heat loss.

3.6 Thermal Comfort

The limits of existence can be defined in terms of deep-body temperature as lying between 35 and 40°C, the normal being about 37°C. Skin temperature must be below deep body temperature, and the temperature of the surrounding environment must be below the skin temperature, if heat is to be lost. Where heat dissipation is not excessive, the conditions are said to be comfortable. These circumstances can be referred to as the comfort zone.

The air temperature is an important factor in determining human comfort, but not the only one. The various heat exchange processes at the body surface are influenced by a number of environmental factors and the sensation of comfort or discomfort depends on the joint effect of all these. Four such factors can be identified:

- ☐ air temperature
- ☐ humidity
- ☐ air movement
- ☐ radiation

Humidity has little effect on thermal comfort at or near comfortable temperatures unless it is extremely high or low. At comfortable temperatures there is no need for evaporative cooling, however at high temperatures it is the most important heat dissipation mechanism. The cooling is due to moisture on the skin absorbing heat when it changes state to water vapour. This heat is referred to as the latent heat of vaporisation. The rate of evaporation of perspiration depends on the absolute humidity. High humidities (above 12g/kg) restrict the evaporation and thus the cooling effect. Low humidities (below

4g/kg) can be unpleasant due to drying out of the mucous membranes. An increase in relative humidity reduces the cooling effect with 100% relative humidity theoretically allowing no evaporative cooling effect at all.

Air movement across the skin accomplishes cooling by convective heat transfer (removing warm air close to the skin) and by helping evaporative cooling. The skin is surrounded by a thin, still air layer which is close to skin temperature and insulates the body from its surroundings. Air movement decreases the thickness of this insulating layer and thus provides a cooling affect provided that the dry bulb temperature is lower than the skin temperature. The rate of evaporation of perspiration depends on the absolute humidity and increased air movement has the affect of reducing moisture laden air close to the skin thus helping the evaporative affect.

Thermal radiation will travel from high temperature surfaces (source) to low temperature surfaces (sink). The source will loose heat and the sink will gain heat, with corresponding changes in temperatures occurring. As a result a body can loose or gain heat from its surroundings due to radiation. If the temperature of surrounding objects is lower than skin temperature then the body will loose heat. With higher temperature surroundings the body will gain heat. Both of these effects will be increased with lighter (e.g. summer) clothing. The quantity "mean radiant temperature" is used to describe the average temperature of the surroundings to which the body is exposed.

One method used to find mean radiant temperature is to measure globe temperature with a globe thermometer. A globe thermometer is a hollow sphere made of copper and coated with matt black paint, with a bulb thermometer placed at the centre of the sphere. The measured globe temperature takes into account the radiation effect of surrounding surfaces. The mean radiant temperature can be found from the globe temperature, dry bulb temperature and air velocity.

Radiation exchange with the surroundings can have a significant effect on human comfort. For lightly clothed people the mean radiant temperature is twice as important as dry bulb temperature and in cooler climates the two temperatures are equally important. The bioclimatic chart discussed below uses an increase in mean radiant temperature of 0.8°C to compensate for a decrease in dry bulb temperature of 1°C. For human comfort it is desirable to have mean radiant temperature approximately 2°C higher than dry bulb temperatures. As a general rule if the two temperatures are not kept within 5°C of each other then discomfort will be experienced.

Other factors which can determine how thermally comfortable a person feels in a given situation are: clothing, acclimatisation, age, sex, shape of body, fat content, health, activity and food and drink.

3.7 The Bioclimatic Chart

Olgyay's bioclimatic chart shows the interaction of the four basic environmental variables in determining human comfort. Each chart is shown for certain conditions namely, activity level, amount of clothing and acclimatisation. The chart shown in Figure 22, for example is for a person engaged in sedentary activity, wearing a normal lightweight suit and acclimatised to Sydney conditions.

The comfort zone is defined according to dry bulb temperature and relative humidity, assuming still air and no radiation gain or loss. The comfort zone can be used to show whether a particular environmental condition is comfortable and what changes are required if it is not. If temperature can be controlled then it is possible to read off the required change to achieve comfort. Otherwise the upper comfort limit can be increased by various velocities of air movement and the lower comfort limit can be decreased by the presence of radiation.

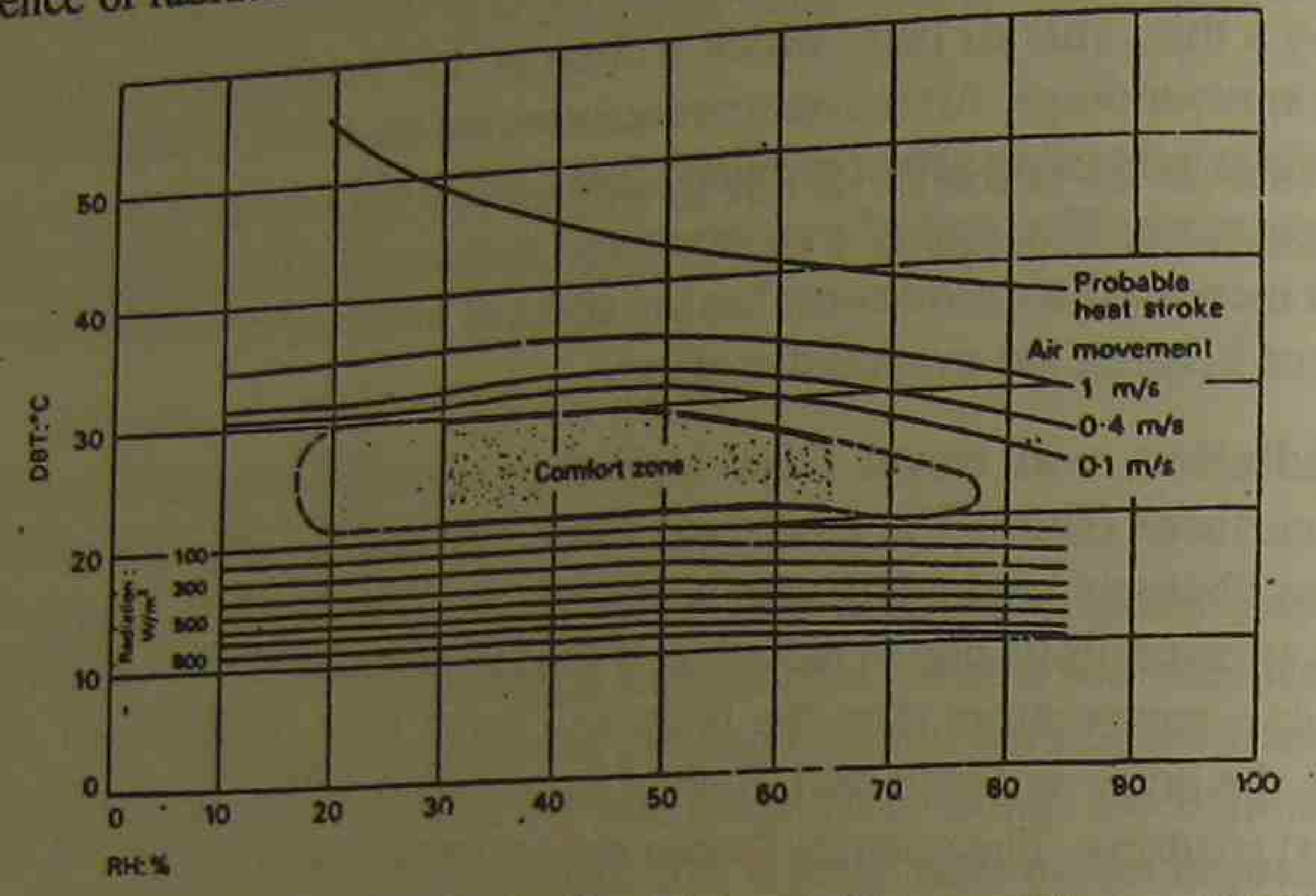


Figure 22 - Bioclimatic chart for Brisbane. (Source: Olgyay, 1963).

Example:

1. What change is required to make the following condition comfortable?

dry bulb temperature 30°C
relative humidity - 60%

Solution: 0.1 m/s air movement

2. What change is required to make the following condition comfortable?

dry bulb temperature 14°C
relative humidity 60%

Solution: 500 W/m² radiation

3.8 Comfort Indices

There have been numerous attempts to try to develop a measurement of human comfort.

Effective Temperature takes into account humidity as well as dry bulb temperature and air movement but does not allow for radiant heat. This measurement was devised in 1923 and has been the best known and most widely used comfort index. The effective temperature can be found by using the chart shown in Figure 23, which is for people in normal light clothing.

Corrected Effective Temperature - this is similar except that the globe temperature (mentioned earlier) is used instead of the dry bulb temperature so radiation effects can be taken into account. The chart in Figure 23 shows how a corrected effective temperature of 26.7°C is arrived at from a globe temperature of 32.2°C, a wet bulb temperature of 24.4°C and an air speed of 1 m/s.

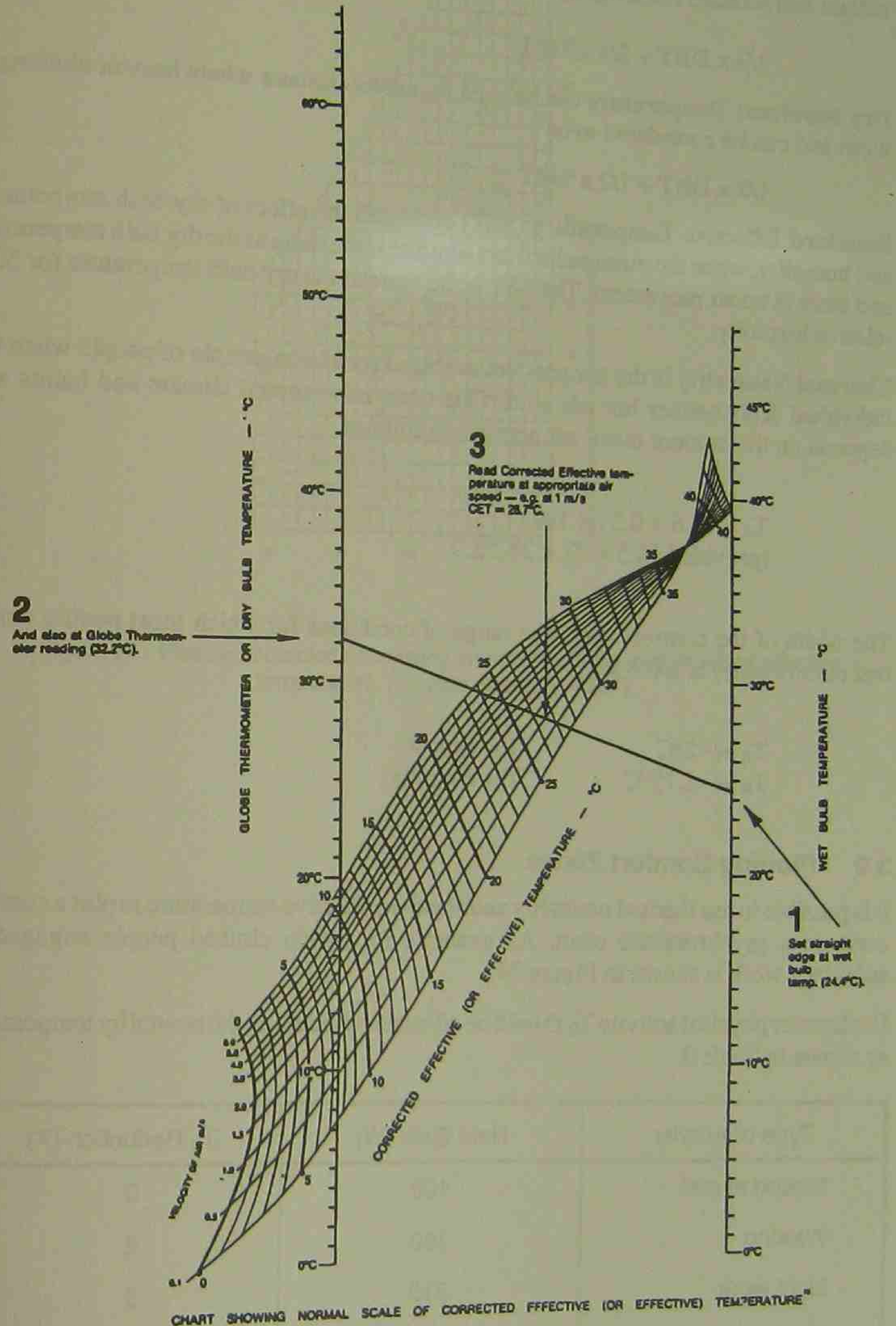


Figure 23 - Chart showing normal scale of corrected effective (or effective) temperature. (Source: Hassell, 1977).

Environmental Temperature takes into account dry bulb temperature as well as mean radiant temperature For a lightly clothed person this can be considered to be:

$$1/3 \times DBT + 2/3 \times MRT$$

Dry Resultant Temperature can be used for cooler climates where heavier clothing is worn and can be considered to be :

$$1/2 \times DBT + 1/2 \times MRT$$

Standard Effective Temperature (SET) combines the effect of dry bulb temperature and humidity, when the mean radiant temperature is the same as the dry bulb temperature and there is no air movement. The SET is the same as the dry bulb temperature for 50% relative humidity.

Thermal Neutrality is the temperature averaged for a large sample of people when the individual feels neither hot nor cold. This takes into account climate and habits and depends on the outdoor mean temperature as follows:

$$T_n = 17.6 + 0.31 \times T_{av}$$
$$(\text{provided } 18.5 < T_n < 28.5^\circ C)$$

The width of the comfort zone (the range of conditions for which most people would feel comfortable) is taken as:

T_n +/- 2°C T_{av} annual
T_n +/- 1.75°C T_{av} monthly

3.9 Plotting Comfort Zones

It is possible to use thermal neutrality and standard effective temperature to plot a comfort zone on a psychrometric chart. An example for lightly clothed people engaged in sedentary work is shown in Figure 24.

For heavier physical activity T_n should be adjusted by reducing the neutrality temperature as shown in Table 3.

Type of Activity	Heat Gain (W)	T_n Reduction (K)
Seated at rest	100	0
Walking	150	2
Light work	210	2
Medium work	300	4.5
Heavy work	400	7

Table 3 - Heat gain from people engaged in different activities.

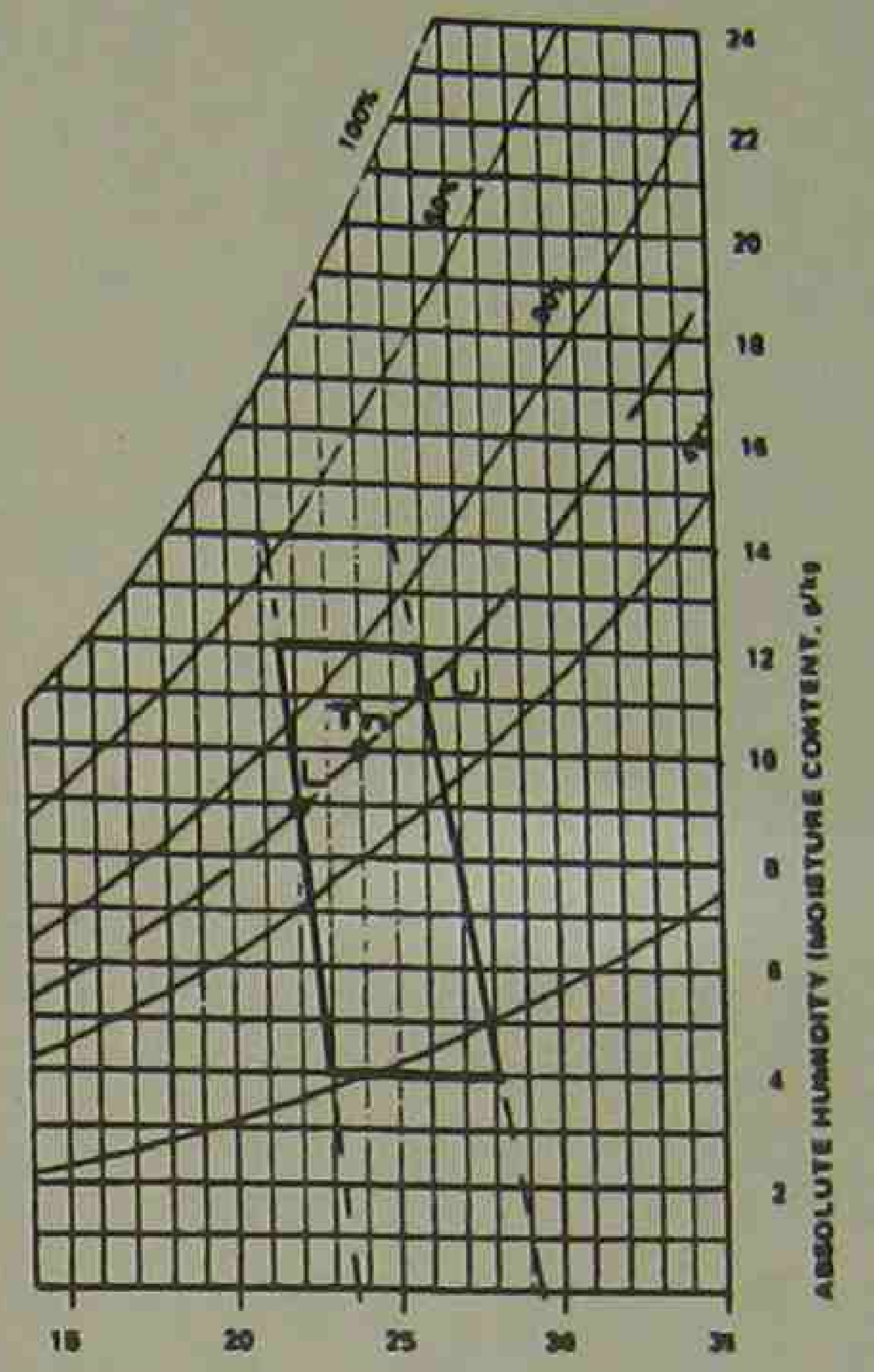


Figure 24 - Plotting of comfort zone using thermal neutrality and standard effective temperature. (Source: Szokolay, 1987).

Unit 3

Solar Geometry and Radiation

1 INTRODUCTION

To design a house according to solar efficient principles it is necessary to be able to predict the position of the sun, and the radiation on building surfaces of different orientations, for different times of the day and year.

This unit defines the relevant geometry and radiation quantities and demonstrates various methods that can be used to calculate them. Students are not meant to calculate the lengthier mathematical relationships manually, these are included simply to outline the method required to obtain certain quantities. The use of tables and charts for obtaining these quantities is discussed. Computer programs may also be used.

2 SOLAR GEOMETRY

2.1 Apparent Motion of the Sun

The earth's axis of rotation is inclined at an angle of 23.5^{o} to the plane of the earth's orbit about the sun. When one hemisphere of the earth is tilted towards the sun a maximum of 23.5^{o}, it will experience the summer solstice while the other hemisphere experiences the winter solstice (Figure 1). Half way between the solstices both hemispheres will experience an equinox.

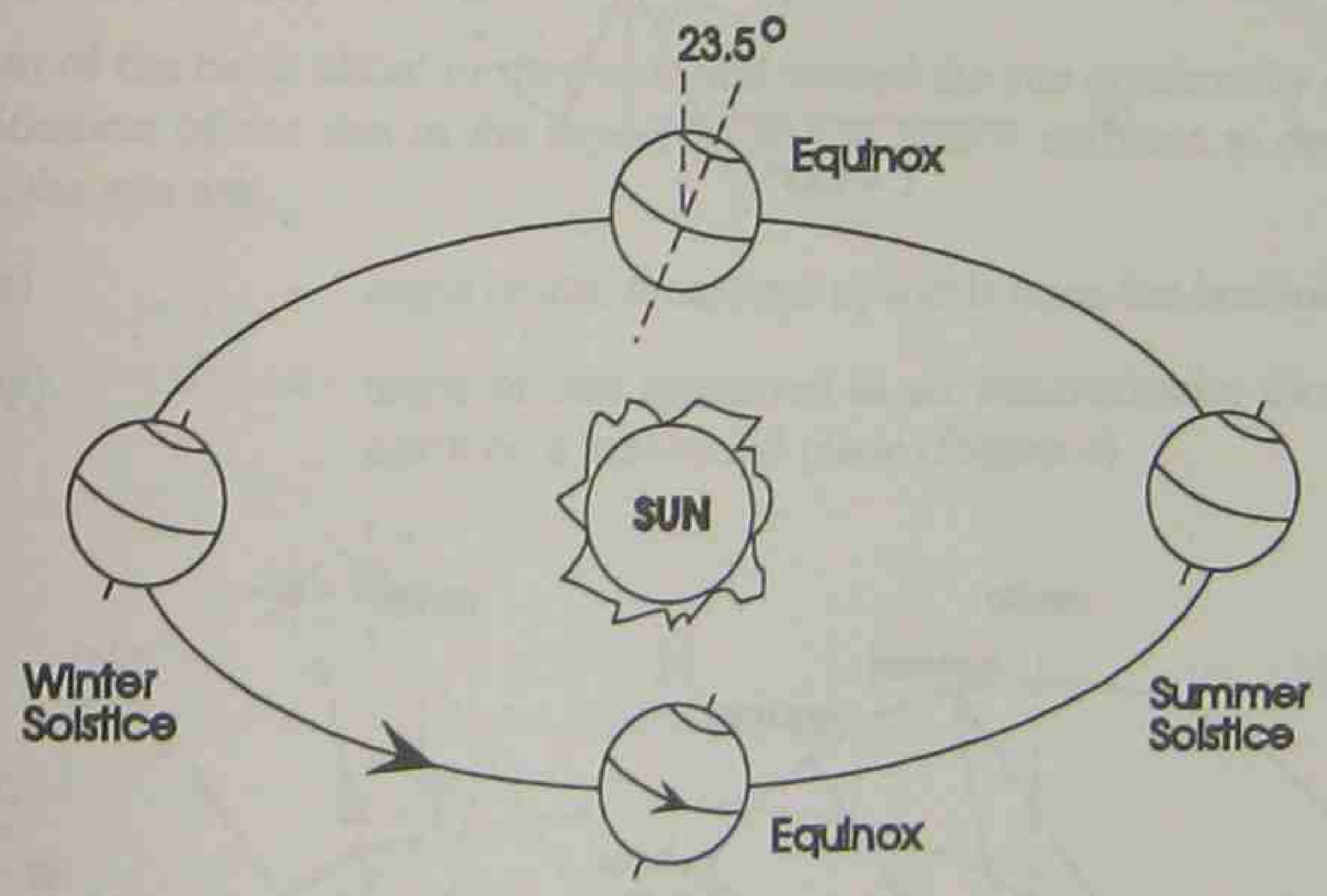


Figure 1 - Equinox and solstice position for the earth during its orbit around the sun.

During the equinox, the minimum angle the sun will make with the zenith (vertically up), will be equal to the angle of latitude. This occurs at solar noon. The periods of day time and night time will be equal, (12 hours each). The sun will rise due east and set due west (see Figures 2 and 3). On the day of the summer solstice the minimum angle the sun will make with the zenith will be the latitude angle minus 23.5^{o}. In summer, the sun will rise south of east and set south of west, (in the southern hemisphere).

During the winter solstice the angle at mid-day between the sun and the zenith will be the latitude angle plus 23.5°. In winter, the sun will rise north of east and set north of west, (in the southern hemisphere).

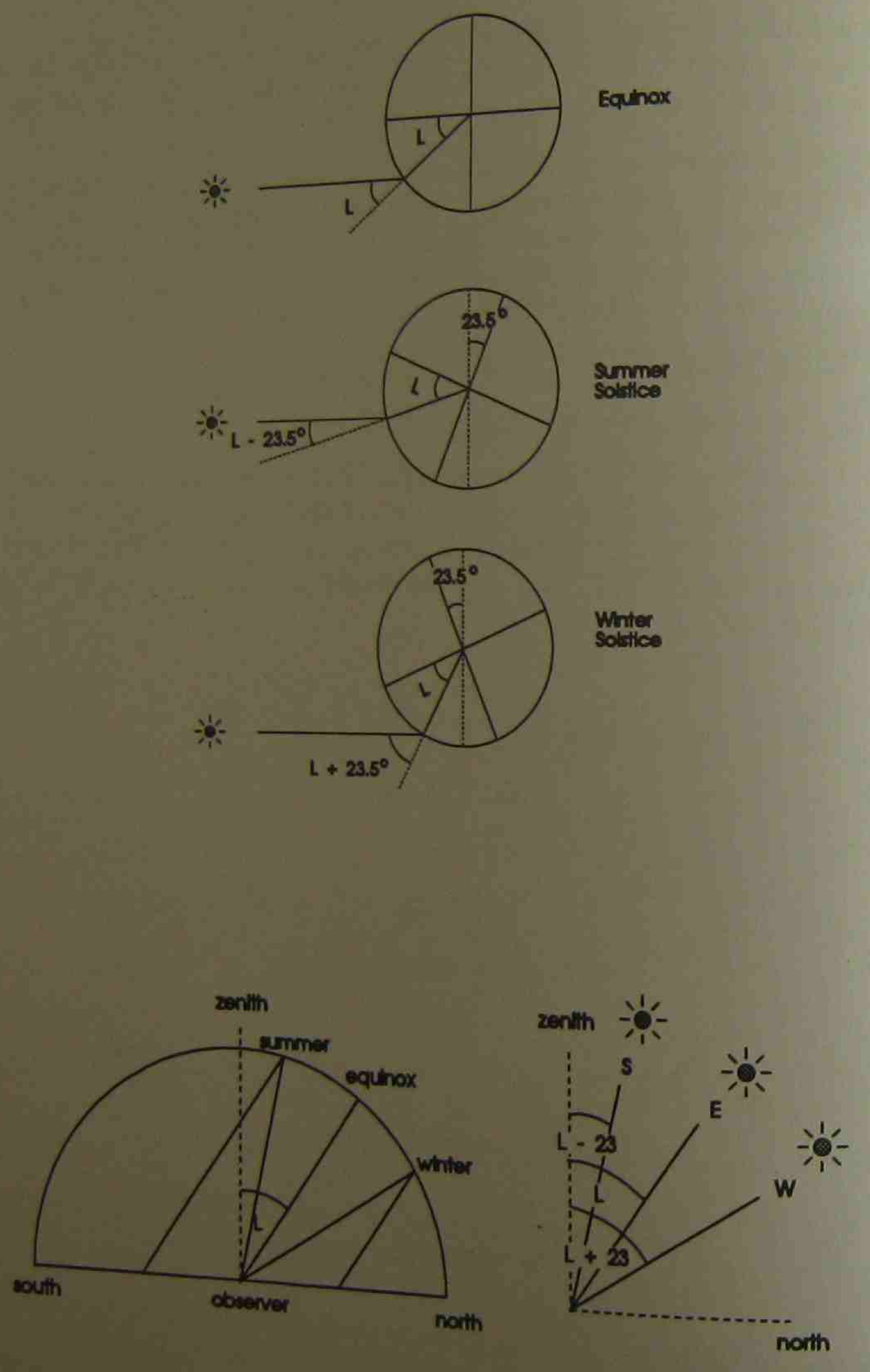


Figure 2 - At mid-day the angle between the sun and the zenith is equal to L for the equinoxes, L - 23.5° for the summer solstice and L + 23.5° for the winter solstice. (L is the latitude angle)

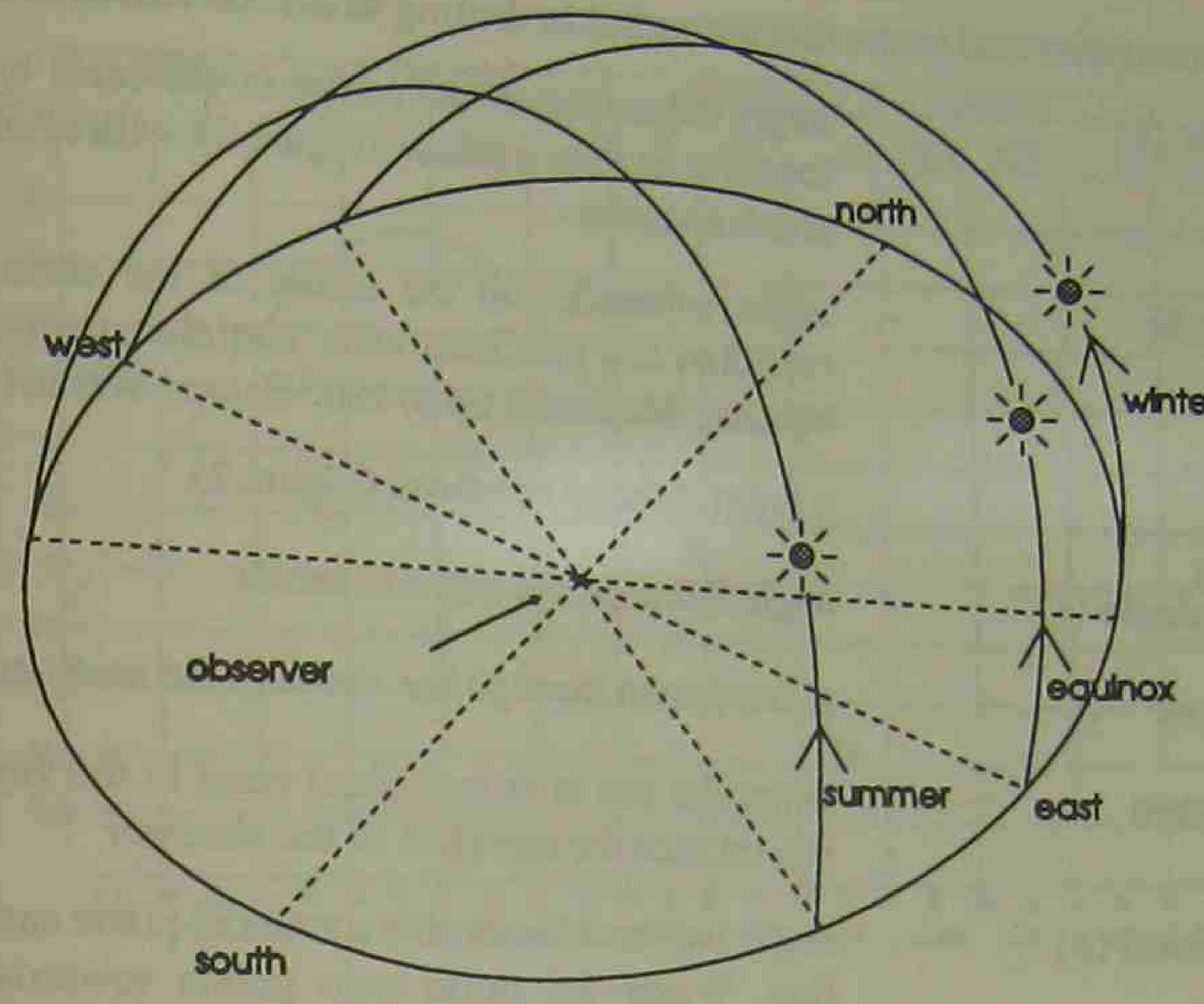


Figure 3 - The sun rises and sets at different orientations depending on the time of the year.

2.2 Solar Geometry Terms

The rotation of the earth about its own axis and around the sun continually changes the apparent position of the sun in the sky. Two angles which are used to determine the position of the sun are:

altitude (α)	- angle of sun measured upwards from the horizon (Figure 4)
azimuth (ψ)	- angle of sun measured in an anticlockwise direction from north on a horizontal plane (Figure 4)

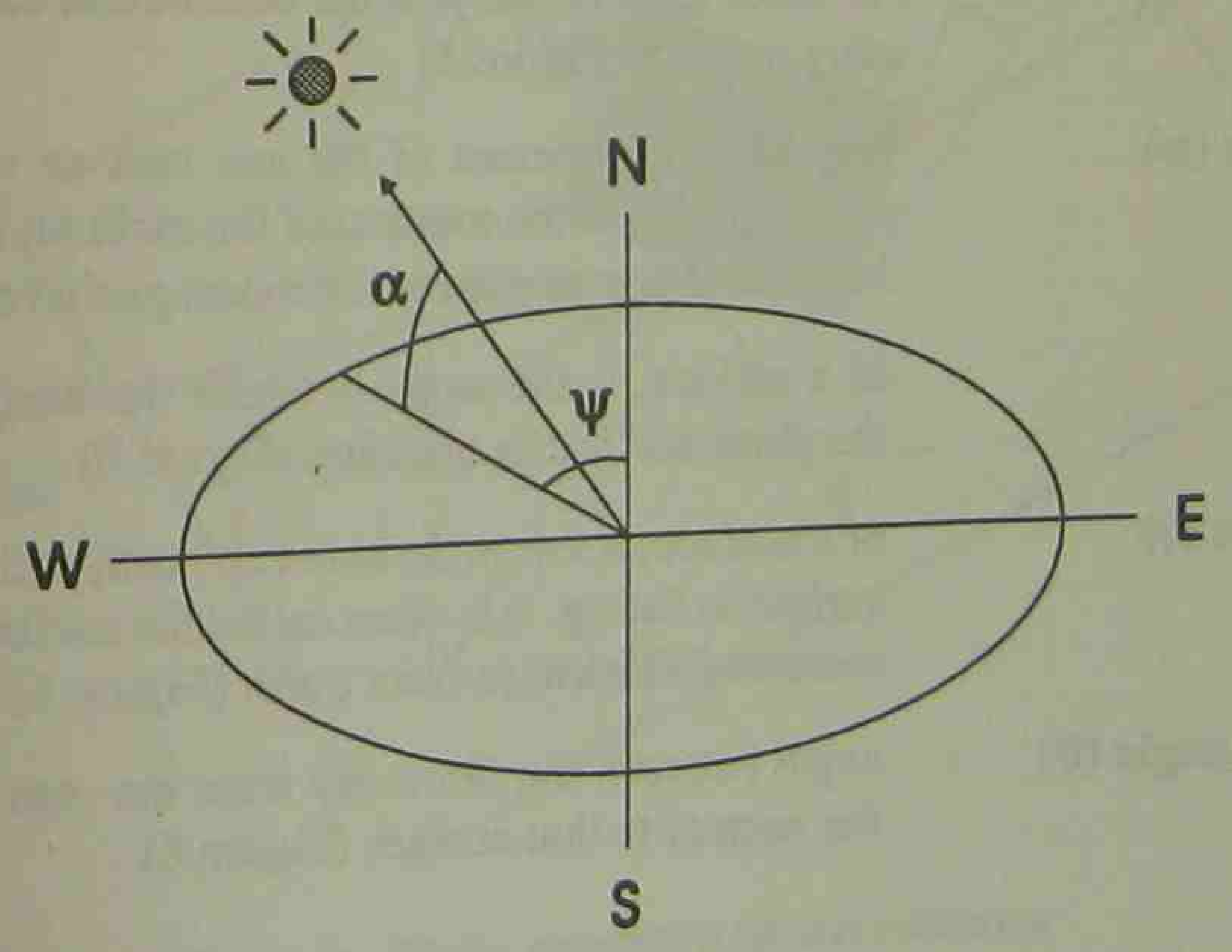


Figure 4 - Altitude and azimuth angles.

Other quantities and terms that are useful in dealing with solar radiation are:

latitude (ϕ) - angle subtended at the centre of the earth by the required location and the equator (Figure 2), with north positive and south negative

longitude - angle subtended at the centre of the earth by the local meridian and the Greenwich meridian, measured along the equator. Measured up to 180° East or West of Greenwich .

zenith - a point directly overhead (Figure 2)

zenith angle (z) - angle between the sun and zenith

meridian - a line drawn through the zenith in the north-south direction

solar noon - when the sun is at its highest point in the sky, or when the sun crosses the meridian of the observer

declination (δ) - angle between the earth's equatorial plane and the earth-sun line. When the north pole points towards the sun the declination is positive. Declinations for solstice and equinox dates (southern hemisphere) are:

March 21	autumn equinox,	$\delta = 0^{o}$
June 22	winter solstice,	$\delta = 23.5^{o}$
September 23	spring equinox,	$\delta = 0^{o}$
December 21	summer solstice,	$\delta = -23.5^{o}$

At solar noon the angle between the zenith and the sun is:

(L-S)	Southern hemisphere
(L-S)	Northern hemisphere

For other days of the year the declination can be found by using a graph (Figure 5)

hour angle (ω) - angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15° per hour (morning negative, afternoon positive)

tilt (β) - of a surface, is the angle between the horizontal plane and the plane surface in question (Figure 6)

orientation (γ) - of a surface, is the angle between north and the direction the surface is facing. It is often called the surface azimuth and is measured clockwise from north (Figure 6)

incidence angle (θ) - angle between the direct ray from the sun on a surface and the normal to that surface (Figure 6)

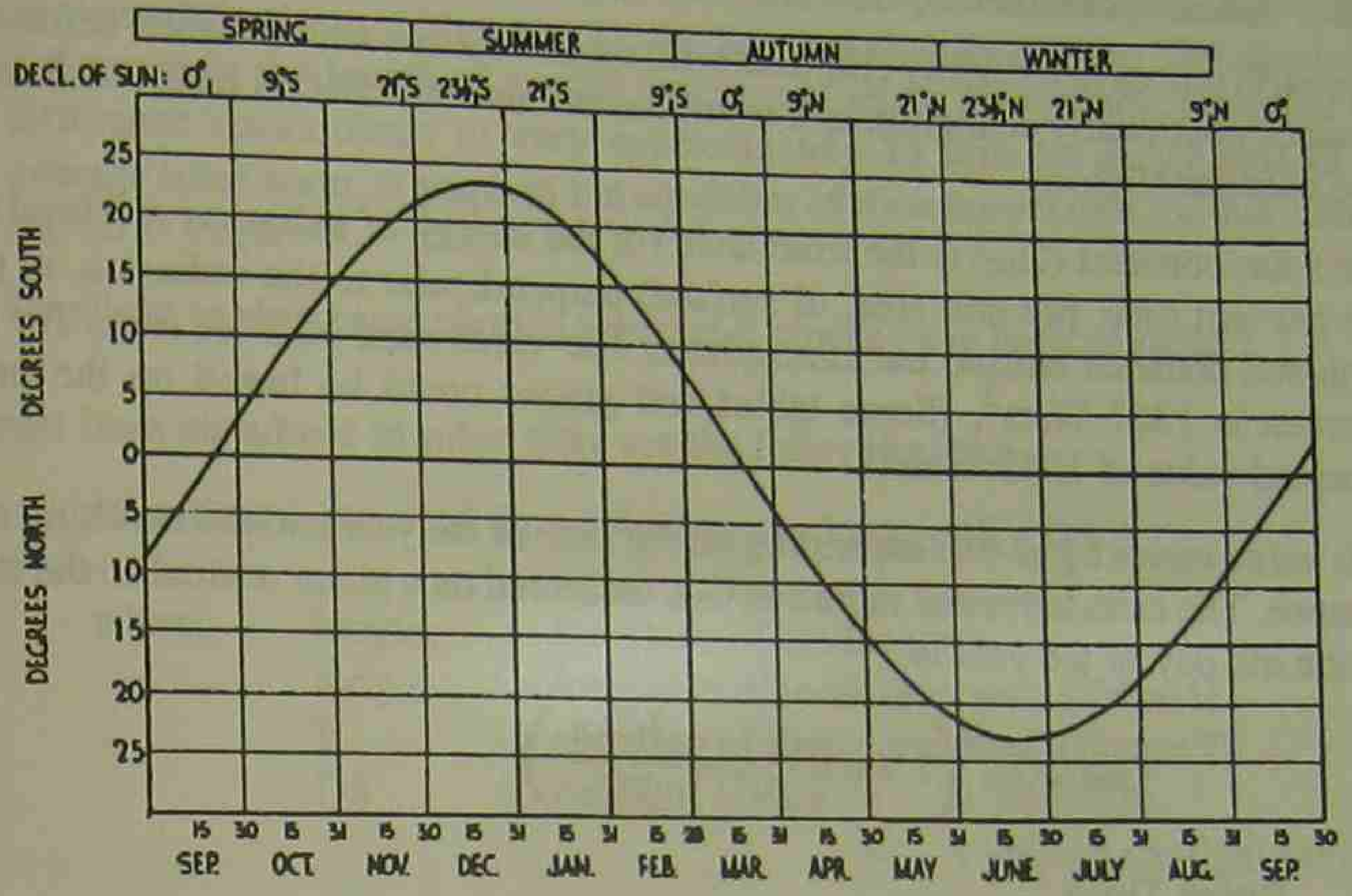


Figure 5 - Declination of the sun. (Source: Phillips, 1983).

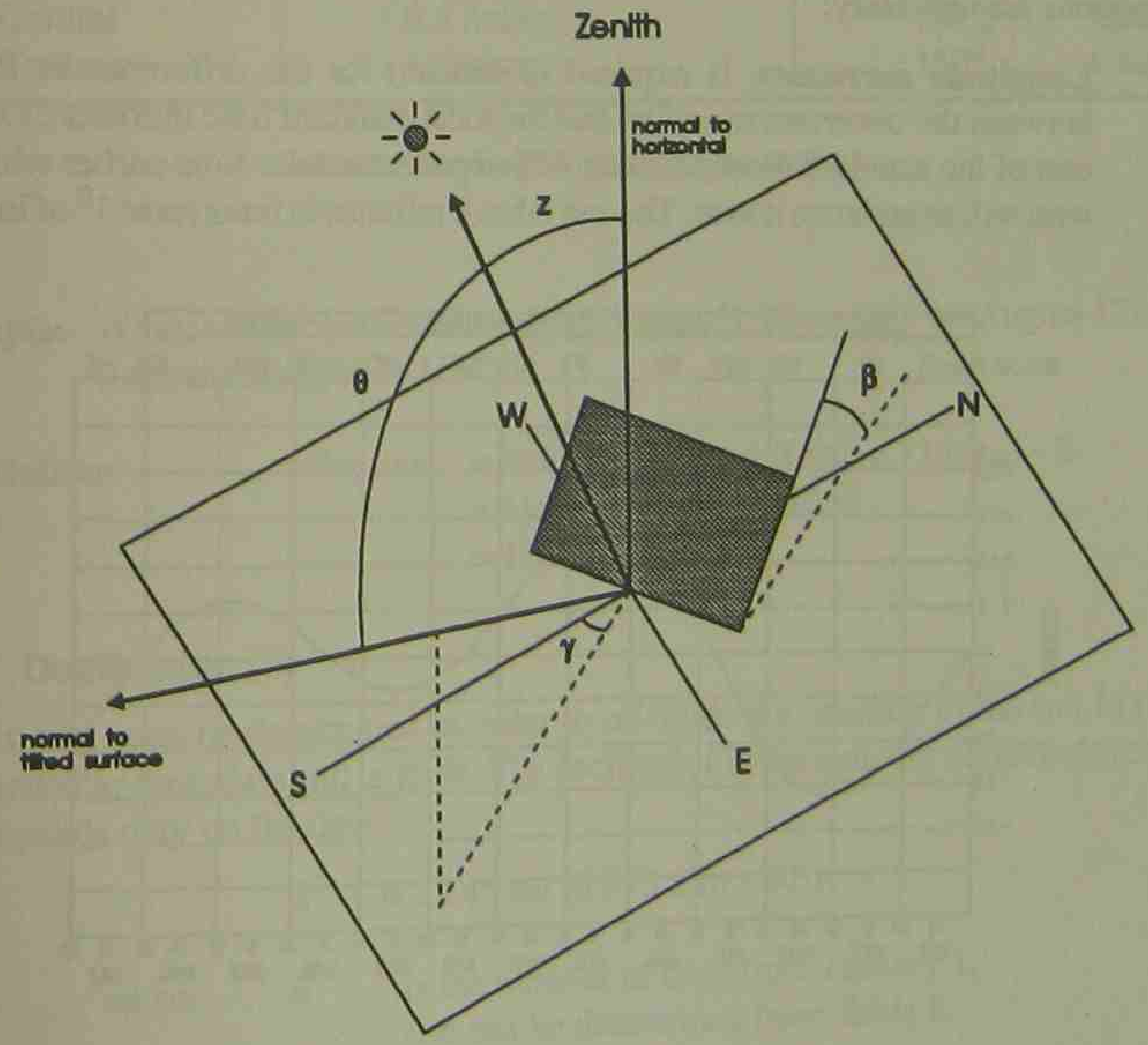


Figure 6 - Tilt (β), orientation (γ) and incidence angles (θ) for an inclined surface.

2.3 Solar Constant

The earth moves in a slightly elliptical orbit around the sun which results in the earth-sun distance continually changing, as a result the amount of radiation received from the sun also changes slightly.

The solar constant (G_{sc}) is the irradiance (or the energy of radiation received from the sun per unit time, per unit area. of surface) perpendicular to the radiation, at the mean earth-sun distance outside the atmosphere. The value used in these notes for the solar constant is 1367 W/m^2. (Some tables and graphs could be based on the previously excepted value of 1353 W/m^2).

This value varies by +/-3% depending on the time of the year and the resulting earth-sun distance. The extraterrestrial radiation G_{on} measured on a plane normal to the irradiance for the nth day of the year is:

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360.n}{365}\right)$$

2.4 Solar Time

Solar time is based on the apparent angular motion of the sun across the sky with solar noon occurring when the sun is at its highest point. Solar time is time used when specifying the position of the sun and when dealing with solar radiation data, and will be used in this unit unless otherwise specified. To convert standard time to solar time, 3 corrections are necessary:

1. **Longitude correction** is required to account for the difference in longitude between the observers meridian and the local standard time meridian. Observers east of the standard time meridian will experience solar time earlier while those west will experience it later. The sun takes 4 minutes to transverse 1^o of longitude.

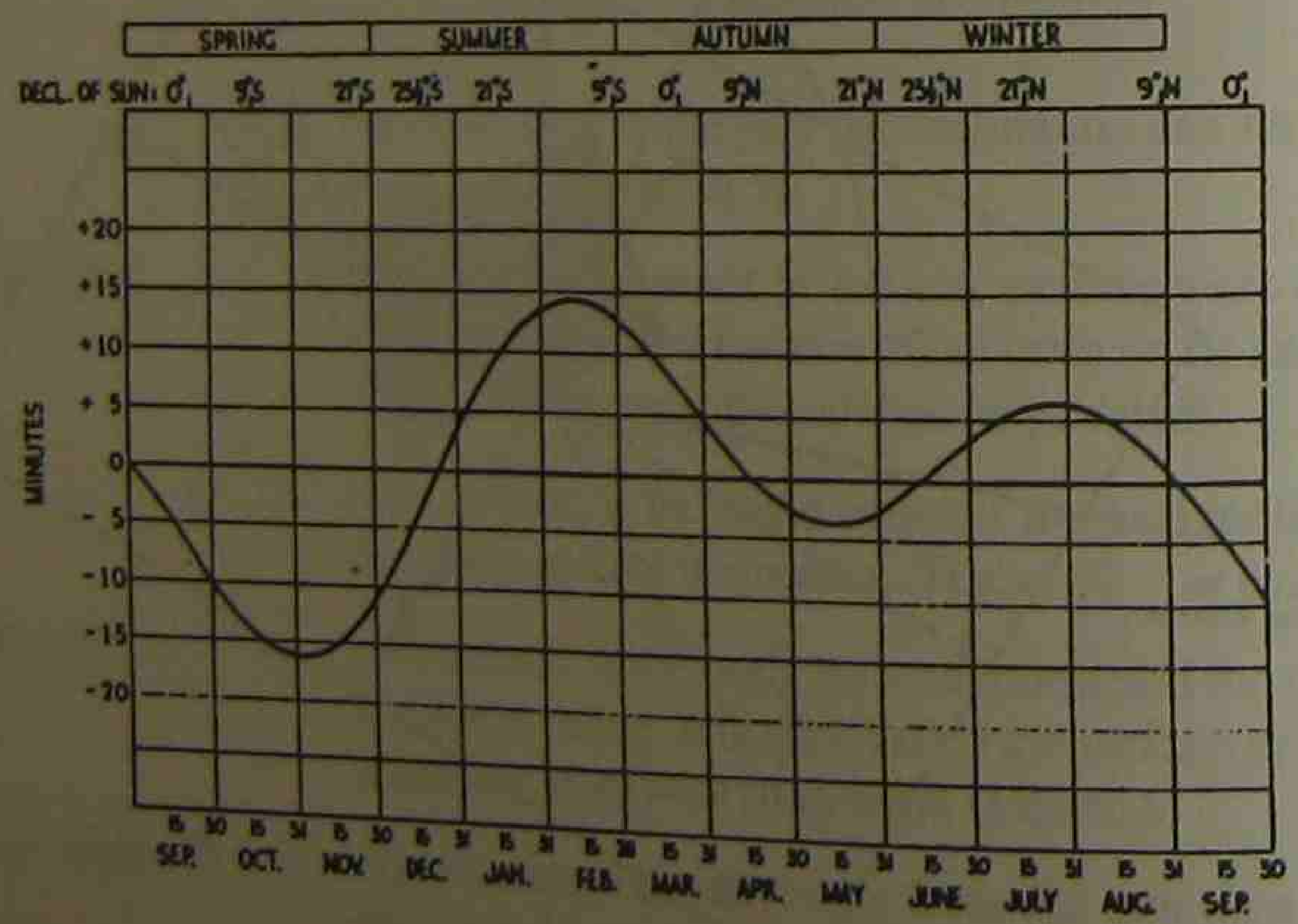


Figure 7 - Equation of time. (Source: Phillips, 1983).

2. Solar days vary in length because of the earth's elliptical orbit. The earth speeds up when it is closer to the sun, so the days are slightly shorter. The maximum difference in the length of a solar day is only about 50 seconds. However this difference accumulates to vary approximately 15 minutes either side of the average solar noon. A graph of the **equation of time correction** for this effect is shown in Figure 7.

3. **Daylight saving correction** is required if clocks have been advanced.

To convert from **standard to solar time** use the following rule:

$$\text{solar time} = \text{standard time} + 4\,(\text{long}_{loc} - \text{long}_{st}) - E - DS$$

where

long_{loc} - longitude of the location
long_{st} - longitude of local time zone (Table 1)
E - equation of time correction (Figure 7)
DS - daylight saving = 0 normally
= 1 during daylight saving

Zone	Relation to Greenwich	Longitude	
Western	+ 8 hours	120°	East
Central	+ 9.5 hours	142.5°	East
Eastern	+ 10 hours	150°	East

Table 1: Standard Time Zones for Australia.

Example: What is the solar time corresponding to 11:30am EST on August 12th for Brisbane (longitude 153°)?

Calculation:

$$\begin{aligned}\text{solar time} &= \text{standard time} + 4\,(\text{long}_{loc} - \text{long}_{st}) - E\\ &= 11{:}30 + 4\,(153 - 150) - 5\\ &= 11{:}37\text{am}\end{aligned}$$

2.5 Declination (δ)

Declination must be determined in order to calculate the position of the sun in the sky at a particular time, date and latitude. The declination is the same for all latitudes on earth and depends only on the date:

$$\delta = 23.45 \sin(0.973 \times (n - 80))$$

where n - is the number of days from January 1, and can be determined from Table 2.

Table 2 enables conversion of date to daynumber
daynumber for that month which best reflects the average for that month.

Month	n	nav
Jan	day	17
Feb	day + 31	47
Mar	day + 59	75
Apr	day + 90	105
May	day + 121	135
Jun	day + 152	162
Jul	day + 183	198
Aug	day + 213	228
Sep	day + 243	258
Oct	day + 273	288
Nov	day + 304	318
Dec	day + 334	334

Table 2 - Conversion of date to daynumber and average day number.

2.6 Hour Angle (ω)

Time of the day is usually measured as the hour angle where ω is the angle between the position of the sun at solar noon and its position at a particular time. Each hour represents 15° of hour angle. Angles before solar noon are negative and after solar noon are positive.

$$\omega = 15\ (\text{time} - 12) \quad \text{(in degrees)}$$

$$\omega = 2\pi \left(\frac{\text{time} - 12}{24} \right) \quad \text{(in radians)}$$

Sunrise and sunset hour angles (ω_{sr}, ω_{ss}) depend on declination (δ) and latitude (ϕ).

$$\omega_{sr} = -\arccos\ (-\tan\phi \tan\delta)$$

$$\omega_{ss} = -\omega_{sr}$$

The times of sunrise and sunset are:

$$t_{sr} = 12 + \frac{\omega_{sr}}{15}$$

$$t_{ss} = 12 - \frac{\omega_{sr}}{15}$$

2.7 Azimuth, Altitude and Incidence Angles

Azimuth and altitude only refer to the position of the sun in the sky. They depend on hour angle (time of day), declination and latitude.

$$\text{altitude} = \alpha = \arcsin\ (\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta)$$

$$\text{azimuth} = \psi = \arcsin \left(\frac{\cos\delta \sin\omega}{\cos\alpha} \right)$$

A plane surface is described by its tilt and orientation. The angle between the sun and the normal to the surface (angle of incidence) is:

$$\begin{aligned}\theta = \arccos\ (&\sin\delta \sin\phi \cos\beta + \sin\delta \cos\phi \sin\beta \cos\gamma \\ &+ \cos\delta \cos\phi \cos\beta \cos\omega - \cos\delta \sin\phi \sin\beta \cos\gamma \cos\omega \\ &- \cos\delta \sin\beta \sin\gamma \sin\omega)\end{aligned}$$

For a vertical surface, such as a wall or window of a building, $\beta = 90^\circ$ and the expression simplifies to:

$$\theta = \arccos\ (\sin\delta \cos\phi \cos\gamma - \cos\delta \sin\phi \cos\gamma \cos\omega - \cos\delta \sin\gamma \sin\omega)$$

It is necessary to know this angle in order to calculate how much direct sunlight is incident on a surface of arbitrary tilt and orientation.

2.8 Methods of Obtaining Solar Geometry Quantities

It is necessary to obtain various solar quantities to design eaves and other shading devices, and to determine the effects of external features such as trees and buildings. Various methods are available to calculate these quantities. These include hand calculations, solar charts, tables and computer programs.

2.8.1 Solar Charts

Solar charts give the position of the sun for any time of the day and year. Charts using standard time are available from the Department of Mapping and Surveying. They are produced for a specific latitude and longitude and two charts are required for each location due to equation of time corrections. A sample chart for June 21 to Dec. 22 in Brisbane is shown in Figure 8.

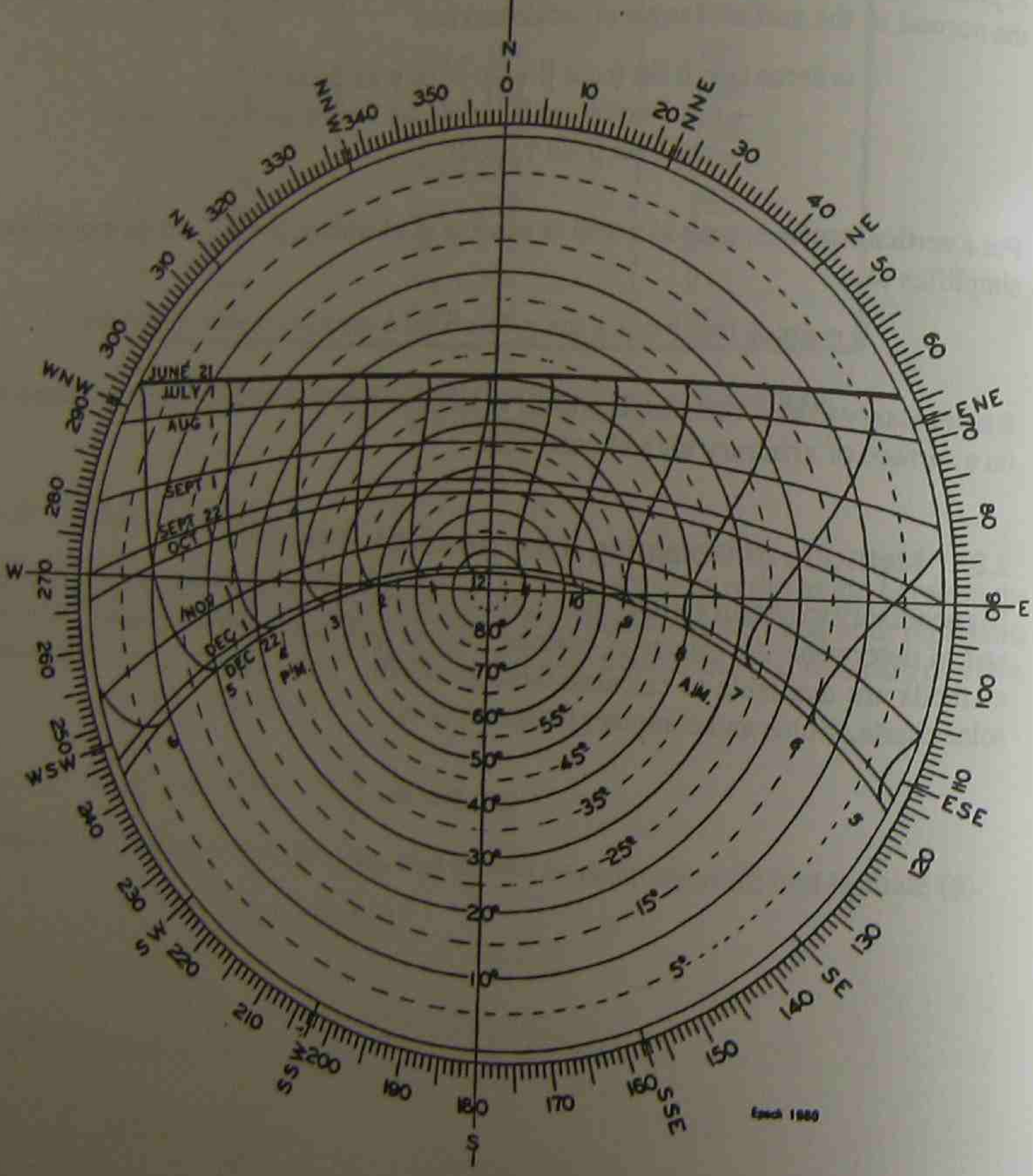


Figure 8 - Solar chart for Brisbane, June 21 to December 22. Standard time is used. (Source: Sunmap).

If solar time is used then only one chart is required for a particular latitude, however it might be necessary to convert between standard and solar time. Phillips in his book "Sunshine and Shade in Australasia" gives charts for 8 selected latitudes which cover most large cities in Australasia. A chart for latitude 35° south is shown in Figure 9. This chart can be used for Sydney, Canberra, Adelaide and Albany.

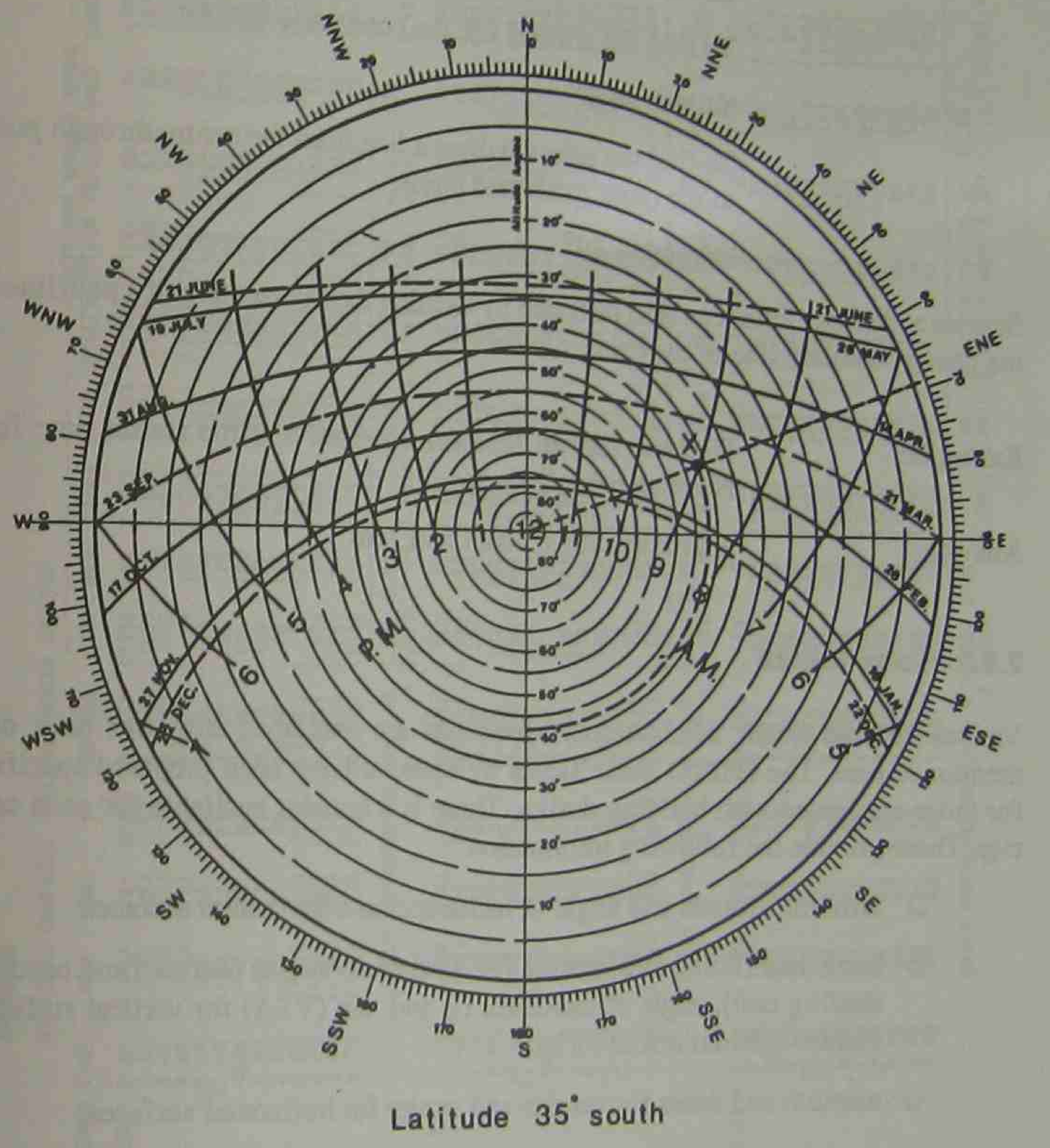


Figure 9 - Solar chart for latitude 35° south. Solar time is used. (Source: Phillips, 1983).

The centre of the chart represents the observer's position. The heavy curved lines represent the sun's path for selected dates and latitudes, and are crossed by lines indicating hours. The chart can be used to find altitude and azimuth, this is best demonstrated by an example:

Example: Find the sun's position in Sydney at 9am on 26 February.

Answer: Locate the appropriate point, which is the intersection of the 9am and 26 February lines (point X on the diagram).

To find the altitude use the concentric circles:

altitude = 42°

To find the azimuth draw a line from the centre through point X to the outer graduated circle:

azimuth = 69°

Sunrise and sunset times can also be found by locating the intersection of a path line with the heavy boundary line of the chart.

Example: Find the sunrise time for 14 April and the sunset time for 27 November for Sydney.

Answer: approximately 6.30am and 7pm

2.8.2 Solar Tables

Various sources which tabulate solar quantities are available, however only one is mentioned here. The CSIRO Solar Tables by Spencer have been prepared specifically for those concerned with building design. There is a booklet available for each capital city. These provide the following information:

- azimuth, altitude and angle of incidence on a horizontal surface.
- horizontal (HSA) and vertical (VSA) shadow angles (defined and used in the shading unit), angle of incidence (I) and tan (VSA) for vertical surfaces of various orientations.
- azimuth and times for sunrise and sunset for horizontal surfaces.
- sunrise and sunset times for vertical surfaces of various orientations.

A sample of tables for Brisbane is shown in Table 3 .

BRISBANE

VERTICAL SURFACE, FACING NORTH (SOUTH)

LATITUDE 27.5 S
GROUND REFL 0.2

						WATT PER SQUARE METRE											
STANDARD TIME		HSA	VSA	I	TAN VSA	DIR	DIF	(DIF)	TOT	TOT/25	TOT/50	TOT/100	SHGF	(SHGF)	SHGF/25	SHGF/50	SHGF/100
JAN 22	6 AM	(-72)	(28)	(73)	(0.531)	(113)	32	(44)	(157)	(137)	(118)	(80)	26	(109)	(93)	(80)	(55)
	7 AM	(-78)	(63)	(79)	(1.999)	(122)	70	(83)	(205)	(131)	(59)	(51)	57	(124)	(83)	(48)	(41)
	8 AM	(-84)	(82)	(85)	(6.931)	(66)	99	(106)	(172)	(93)	(86)	(77)	81	(101)	(75)	(70)	(63)
	9 AM	(-90)	(90)	(90)	(>9.99)	(0)	126	(126)	(126)	(118)	(111)	(101)	103	(103)	(96)	(90)	(82)
	10 AM	+81	85	86	>9.99	69	156	(149)	225	140	133	121	141	(121)	114	107	98
	11 AM	+64	83	83	8.137	110	178	(166)	288	156	148	135	179	(135)	127	120	109
	NOON	- 1	82	82	7.460	125	185	(172)	310	162	153	140	194	(140)	131	124	113
	1 PM	-64	83	83	8.173	110	177	(165)	287	156	147	135	178	(134)	126	119	109
	2 PM	-81	85	86	>9.99	68	155	(148)	223	140	132	121	140	(121)	113	107	98
	3 PM	(+90)	(90)	(90)	(>9.99)	(0)	125	(125)	(125)	(117)	(111)	(101)	102	(102)	(95)	(90)	(81)
	4 PM	(+84)	(82)	(85)	(6.694)	(67)	99	(106)	(173)	(92)	(86)	(77)	81	(102)	(74)	(70)	(62)
	5 PM	(+78)	(63)	(79)	(1.946)	(123)	69	(82)	(205)	(133)	(61)	(50)	56	(124)	(84)	(49)	(41)
	6 PM	(+72)	(27)	(72)	(0.510)	(111)	31	(43)	(154)	(135)	(117)	(80)	25	(107)	(92)	(79)	(56)
		DAILY EXPOSURE IN MJ/SQ M				1.74 (2.17)	5.41	(5.45)	7.14 (7.62)	4.89 (6.16)	4.59 (5.26)	4.14 (4.57)	4.91	(5.48)	3.96 (4.69)	3.72 (4.15)	3.35 (3.63)
FEB 22	6 AM	(-80)	(24)	(80)	(0.454)	(34)	15	(19)	(53)	(47)	(41)	(31)	12	(30)	(25)	(22)	(16)
	7 AM	(-87)	(81)	(87)	(6.251)	(28)	58	(61)	(89)	(53)	(48)	(41)	47	(53)	(43)	(39)	(33)
	8 AM	+86	83	86	8.302	46	95	(90)	141	84	78	69	85	(73)	68	63	56
	9 AM	+77	77	81	4.439	132	131	(117)	263	109	103	93	159	(95)	89	83	75
	10 AM	+65	75	77	3.637	206	162	(140)	368	153	124	114	243	(114)	118	101	92
	11 AM	+44	73	74	3.348	254	184	(157)	438	193	140	128	305	(128)	148	113	104
	NOON	+ 2	73	73	3.267	271	193	(164)	464	210	146	133	329	(134)	160	118	108
	1 PM	-41	73	74	3.336	256	185	(158)	441	195	141	129	308	(129)	149	114	104
	2 PM	-64	74	76	3.604	210	164	(142)	374	156	126	115	248	(116)	120	102	93
	3 PM	-77	77	81	4.340	138	134	(119)	272	111	105	95	166	(97)	90	85	77
	4 PM	-85	82	86	7.586	53	98	(92)	151	86	80	71	90	(75)	69	65	57
	5 PM	(+88)	(83)	(88)	(8.052)	(24)	60	(63)	(87)	(55)	(50)	(43)	49	(54)	(45)	(41)	(35)
	6 PM	(+81)	(31)	(81)	(0.591)	(38)	19	(23)	(61)	(52)	(45)	(30)	15	(34)	(28)	(24)	(17)
		DAILY EXPOSURE IN MJ/SQ M				5.64 (.45)	5.39	(4.84)	11.03 (5.29)	5.17 (4.73)	4.20 (4.42)	3.79 (3.93)	7.40	(4.08)	4.05 (3.74)	3.41 (3.49)	3.07 (3.12)
MAR 21	6 AM	(-90)	(90)	(90)	(>9.99)	(0)	3	(3)	(3)	(3)	(2)	(2)	2	(2)	(2)	(2)	(1)
	7 AM	+82	63	83	1.921	67	55	(48)	122	82	43	34	67	(39)	48	33	27
	8 AM	+75	63	76	1.921	173	100	(82)	273	176	78	62	177	(67)	116	61	50
	9 AM	+64	63	71	1.921	276	138	(109)	414	260	108	86	301	(89)	191	86	70
	10 AM	+50	63	66	1.921	358	168	(130)	526	328	131	105	406	(106)	254	105	85
	11 AM	+28	63	63	1.921	408	188	(145)	596	371	147	118	473	(118)	295	119	96
	NOON	- 2	63	63	1.921	424	195	(150)	619	385	153	123	494	(122)	308	123	99
	1 PM	-32	63	64	1.921	404	187	(144)	591	368	146	117	468	(117)	291	118	95
	2 PM	-52	63	67	1.921	349	165	(128)	514	321	129	103	395	(104)	247	103	84
	3 PM	-66	63	71	1.921	264	134	(106)	398	250	104	83	286	(86)	182	83	68
	4 PM	-76	63	77	1.921	160	96	(79)	256	164	74	59	163	(64)	107	58	48
	5 PM	-83	63	84	1.921	55	49	(43)	104	71	37	30	56	(35)	41	29	24
		DAILY EXPOSURE IN MJ/SQ M				10.58 (0.00)	5.32	(4.20)	15.90 (4.20)	10.00 (3.94)	4.15 (3.68)	3.32 (3.32)	11.84	(3.42)	7.50 (3.18)	3.31 (2.98)	2.69 (2.69)

Table 3 - A sample of Spencer's Solar Tables for Brisbane showing various solar geometry quantities for vertical surfaces. (Source: Spencer, 1979).

BRISBANE

VERTICAL SURFACE, FACING NORTH (SOUTH)

LATITUDE 27.5 S
GROUND REFL 0.2

STANDARD TIME		HSA	VSA	I	TAN VSA	WATT PER SQUARE METRE											
						DIR	DIF	(DIF)	TOT	TOT/25	TOT/50	TOT/100	SHGF	(SHGF)	SHGF/25	SHGF/50	SHGF/100
JAN 22	6 AM	(-72)	(28)	(73)	(0.531)	(113)	32	(44)	(157)	(137)	(118)	(80)	26	(109)	(93)	(80)	(55)
	7 AM	(-78)	(63)	(79)	(1.999)	(122)	70	(83)	(205)	(131)	(59)	(51)	57	(124)	(83)	(48)	(41)
	8 AM	(-84)	(82)	(85)	(6.931)	(66)	99	(106)	(172)	(93)	(86)	(77)	81	(101)	(75)	(70)	(63)
	9 AM	(-90)	(90)	(90)	(>9.99)	(0)	126	(126)	(126)	(118)	(111)	(101)	103	(103)	(96)	(90)	(82)
	10 AM	+81	85	86	>9.99	69	156	(149)	225	140	133	121	141	(121)	114	107	98
	11 AM	+64	83	83	8.137	110	178	(166)	288	156	148	135	179	(135)	127	120	109
	NOON	- 1	82	82	7.460	125	185	(172)	310	162	153	140	194	(140)	131	124	113
	1 PM	-64	83	83	8.173	110	177	(165)	287	156	147	135	178	(134)	126	119	109
	2 PM	-81	85	86	>9.99	68	155	(148)	223	140	132	121	140	(121)	113	107	98
	3 PM	(+90)	(90)	(90)	(>9.99)	(0)	125	(125)	(125)	(117)	(111)	(101)	102	(102)	(95)	(90)	(81)
	4 PM	(+84)	(82)	(85)	(6.694)	(67)	99	(106)	(173)	(92)	(86)	(77)	81	(102)	(74)	(70)	(62)
	5 PM	(+78)	(63)	(79)	(1.946)	(123)	69	(82)	(205)	(133)	(61)	(50)	56	(124)	(84)	(49)	(41)
	6 PM	(+72)	(27)	(72)	(0.510)	(111)	31	(43)	(154)	(135)	(117)	(80)	25	(107)	(92)	(79)	(56)
DAILY EXPOSURE IN MJ/SQ M						1.74 (2.17)	5.41	(5.45)	7.14 (7.62)	4.89 (6.16)	4.59 (5.26)	4.14 (4.57)	4.91	(5.48)	3.96 (4.69)	3.72 (4.15)	3.35 (3.63)
FEB 22	6 AM	(-80)	(24)	(80)	(0.454)	(34)	15	(19)	(53)	(47)	(41)	(31)	12	(30)	(25)	(22)	(16)
	7 AM	(-87)	(81)	(87)	(6.251)	(28)	58	(61)	(89)	(53)	(48)	(41)	47	(53)	(43)	(39)	(33)
	8 AM	+86	83	86	8.302	46	95	(90)	141	84	78	69	85	(73)	68	63	56
	9 AM	+77	77	81	4.439	132	131	(117)	263	109	103	93	159	(95)	89	83	75
	10 AM	+65	75	77	3.637	206	162	(140)	368	153	124	114	243	(114)	118	101	92
	11 AM	+44	73	74	3.348	254	184	(157)	438	193	140	128	305	(128)	148	113	104
	NOON	+ 2	73	73	3.267	271	193	(164)	464	210	146	133	329	(134)	160	118	108
	1 PM	-41	73	74	3.336	256	185	(158)	441	195	141	129	308	(129)	149	114	104
	2 PM	-64	74	76	3.604	210	164	(142)	374	156	126	115	248	(116)	120	102	93
	3 PM	-77	77	81	4.340	138	134	(119)	272	111	105	95	166	(97)	90	85	77
	4 PM	-85	82	86	7.586	53	98	(92)	151	86	80	71	90	(75)	69	65	57
	5 PM	(+88)	(83)	(88)	(8.052)	(24)	60	(63)	(87)	(55)	(50)	(43)	49	(54)	(45)	(41)	(35)
	6 PM	(+81)	(31)	(81)	(0.591)	(38)	19	(23)	(61)	(52)	(45)	(30)	15	(34)	(28)	(24)	(17)
DAILY EXPOSURE IN MJ/SQ M						5.64 (.45)	5.39	(4.84)	11.03 (5.29)	5.17 (4.73)	4.20 (4.42)	3.79 (3.93)	7.40	(4.08)	4.05 (3.74)	3.41 (3.49)	3.07 (3.12)
MAR 21	6 AM	(-90)	(90)	(90)	(>9.99)	(0)	3	(3)	(3)	(3)	(2)	(2)	2	(2)	(2)	(2)	(1)
	7 AM	+82	63	83	1.921	67	55	(48)	122	82	43	34	67	(39)	48	33	27
	8 AM	+75	63	76	1.921	173	100	(82)	273	176	78	62	177	(67)	116	61	50
	9 AM	+64	63	71	1.921	276	138	(109)	414	260	108	86	301	(89)	191	86	70
	10 AM	+50	63	66	1.921	358	168	(130)	526	328	131	105	406	(106)	254	105	85
	11 AM	+28	63	63	1.921	408	188	(145)	596	371	147	118	473	(118)	295	119	96
	NOON	- 2	63	63	1.921	424	195	(150)	619	385	153	123	494	(122)	308	123	99
	1 PM	-32	63	64	1.921	404	187	(144)	591	368	146	117	468	(117)	291	118	95
	2 PM	-52	63	67	1.921	349	165	(128)	514	321	129	103	395	(104)	247	103	84
	3 PM	-66	63	71	1.921	264	134	(106)	398	250	104	83	286	(86)	182	83	68
	4 PM	-76	63	77	1.921	160	96	(79)	256	164	74	59	163	(64)	107	58	48
	5 PM	-83	63	84	1.921	55	49	(43)	104	71	37	30	56	(35)	41	29	24
DAILY EXPOSURE IN MJ/SQ M						10.58 (0.00)	5.32	(4.20)	15.90 (4.20)	10.00 (3.94)	4.15 (3.68)	3.32 (3.32)	11.84	(3.42)	7.50 (3.18)	3.31 (2.98)	2.69 (2.69)

Table 3 - A sample of Spencer's Solar Tables for Brisbane showing various solar geometry quantities for vertical surfaces. (Source: Spencer, 1979).

2.8.3 Computer Programs

There are various programs available which calculate solar geometry quantities. The one we will be using in this course calculates solar position and shadow length and is called SOLPOS. This program requires latitude, tilt angle, orientation, time and date to be entered by the user and then calculates such quantities as sunrise and sunset times, azimuth, altitude, angle of incidence, horizontal light penetration and vertical shadow length. An example of the output is shown in Table 4:

```
                                   -34.00
LATITUDE.......................     90.00
TILT ANGLE.....................      0.00   S +/-180, W -90, N 0, E +90
ORIENTATION....................   22 / 8    day / month
DATE...........................     11.00
TIME...........................      7.08
TIME OF SUN-RISE...............     18.52
TIME OF SUN-SET................      8.44
DAYLIGHT HOURS.................    -81.32   W +, N 0, E -
SUNRISE AZIMUTH................    -16.05   S +/-180, W +90, N 0, E -90
AZIMUTH........................     30.81
ALTITUDE.......................     23.44   towards N +,  S -
DECLINATION....................     34.37   normal to plane and sun
ANGLE OF INCIDENCE.............      1.68   of a 1m high rod
HORIZONTAL SHADOW LENGTH.......      1.61   into a room with a 1m window
HORIZONTAL LIGHT PENETRATION...      0.62   due to 1m wide eaves
VERTICAL SHADOW LENGTH.........
```

Table 4 - Sample output from computer program SOLPOS for Sydney.

3 SOLAR RADIATION

3.1 Solar Spectrum

The electromagnetic radiation received from the sun is classified according to its wavelength:

short ultraviolet	< 0.3	µm
near ultraviolet	0.3 - 0.4	µm
visible	0.4 - 0.7	µm
near infrared	0.7 - 2.5	µm
far infrared	> 2.5	µm

The energy of radiation is inversely proportional to wavelength; the more energetic the radiation the shorter the wavelength. The wavelength characteristics for solar radiation are given in Figure 10. The curve for radiation at the top of the atmosphere is labelled air mass zero; at the earth's surface with the sun directly overhead is labelled air mass one; and with the sun making and angle of 60° with the zenith is labelled air mass two. The attenuation of solar radiation by the earth's atmosphere is due to scattering and absorption.

Scattering is caused by air molecules, water vapour and dust particles. It depends on wavelength, with shorter wavelengths (blue part of the visible spectrum) being scattered the most. This scattered or diffused radiation still reaches the earth from all parts of the skydome and is the reason for the characteristic blue colour of the sky.

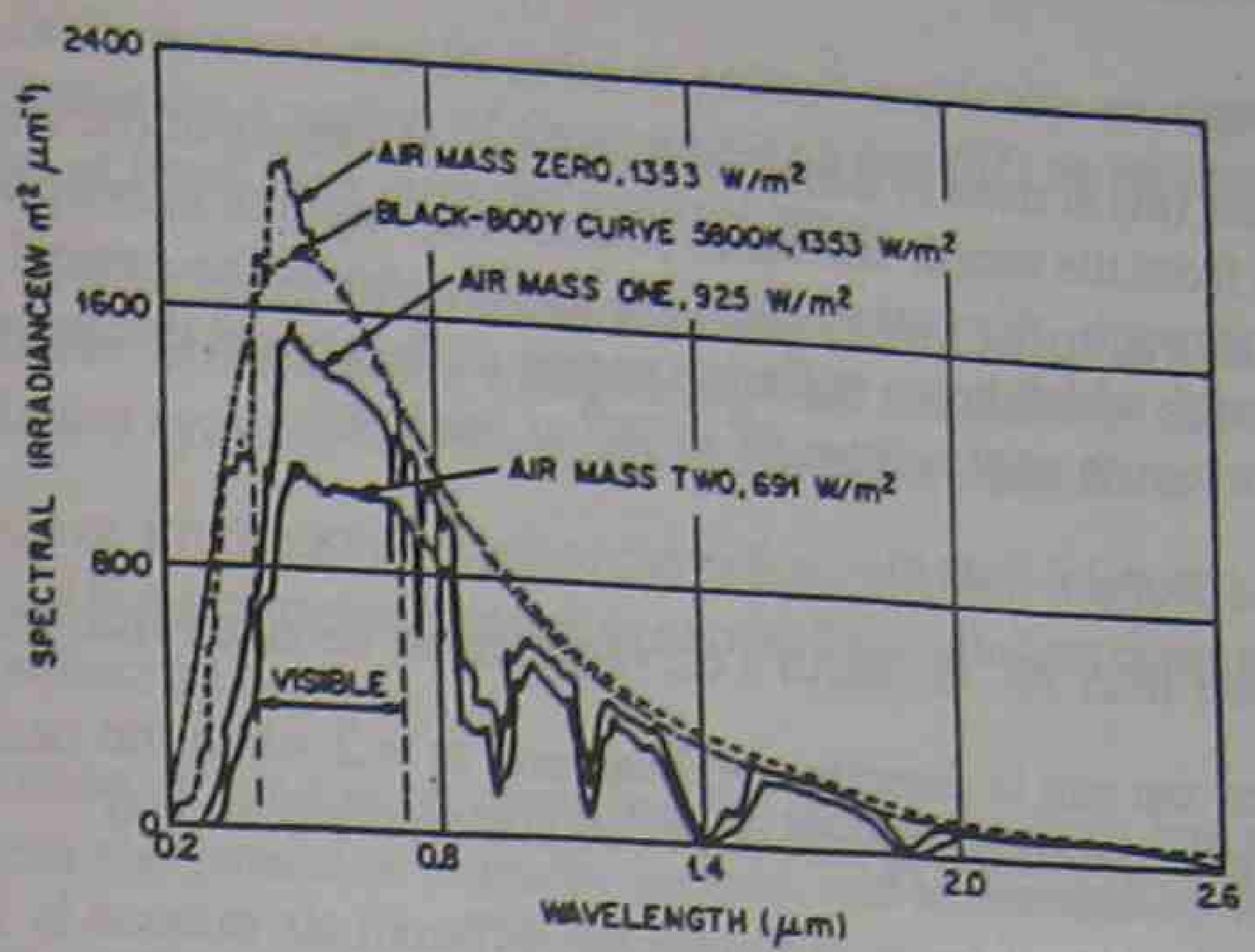


Figure 10 - Spectral irradiance for various air masses.

Absorption is caused by ozone, water vapour, carbon dioxide and oxygen and is also wavelength dependent. In the upper atmosphere ozone removes virtually all the short wavelength ultra-violet radiation reaching the earth's surface thus protecting us from the harmful affects of skin burn and eye damage. A small amount of near ultraviolet is transmitted however, and this is the cause of skin burn. Water vapour and carbon dioxide in the lower atmosphere absorb some radiation, mainly in the infrared band. The absorptance of particular gases in the atmosphere is shown in Figure 11.

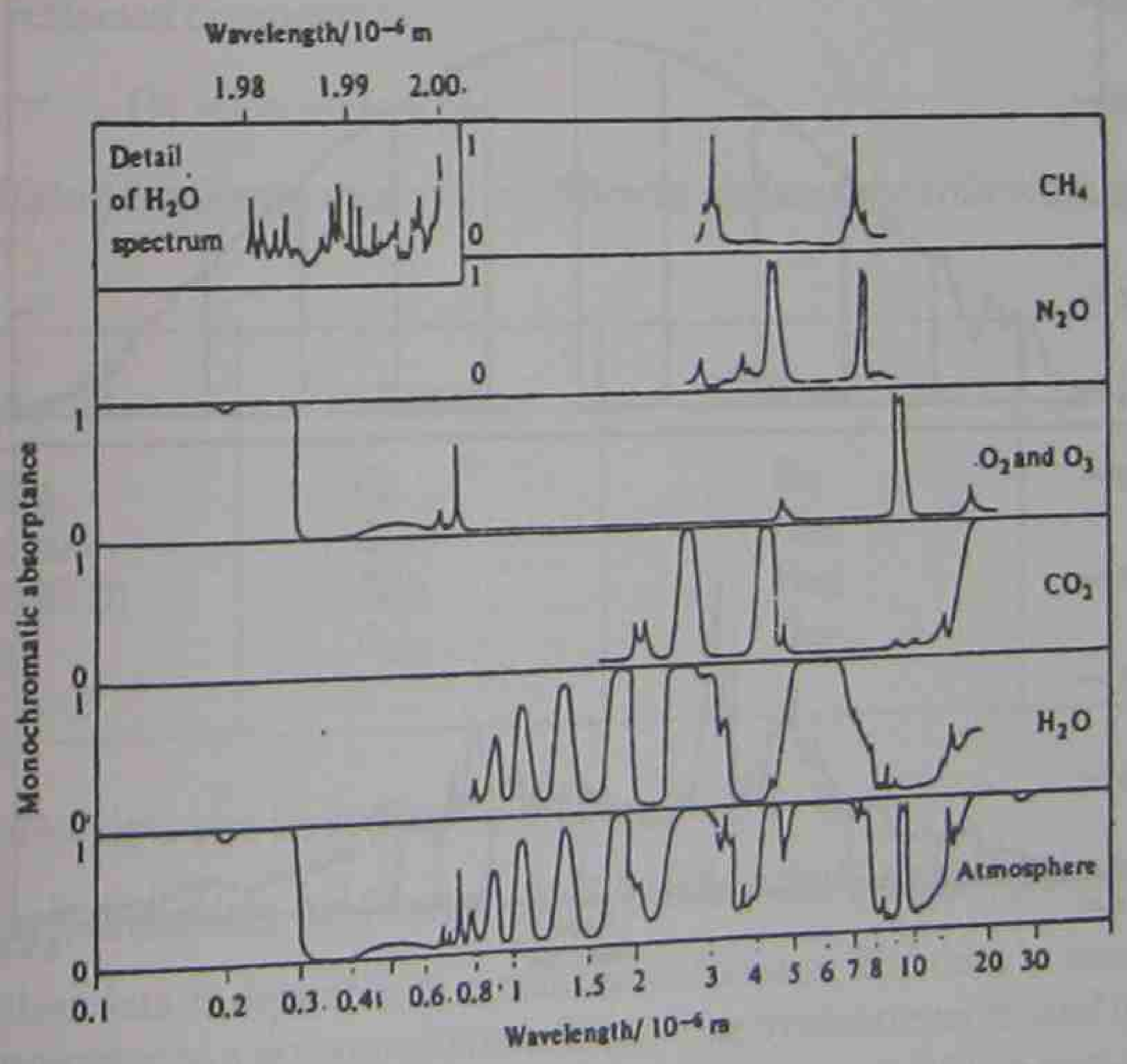


Figure 11 - Monochromatic absorptance versus wavelength of the atmosphere. (Source: Twidell and Weir, 1986).

3.2 Air Mass

The term air mass (m) is used to describe the optical thickness of the atmosphere. As the angle of the sun from the zenith increases so does the length of atmosphere that the sun's rays must pass through. Air mass is defined as the ratio of the optical thickness of the atmosphere through which beam radiation passes to the optical thickness if the sun were at the zenith. For zenith angles from 0^0 to 70^0 at sea level:

$$m = 1 / (\cos z)$$

(For angles greater than 70^0 the earth's curvature must be taken into account)

Thus m = 1 when the sun is directly overhead and m = 2 when the zenith angle is 60^0. When referring to extraterrestrial radiation (no atmosphere), m = 0.

The spectral distribution of beam radiation for different air masses is shown in Figure 10.

3.3 Solar Radiation Terminology

Irradiance (G),(often called radiation intensity) is measured in units of W/m^2 and is the power of the radiation received per unit area. It is an instantaneous value obtained from a radiation measuring instrument such as a pyranometer. Data from a pyranometer showing total irradiance plotted as a function of time for a clear day and for a cloudy day are shown in Figure 12.

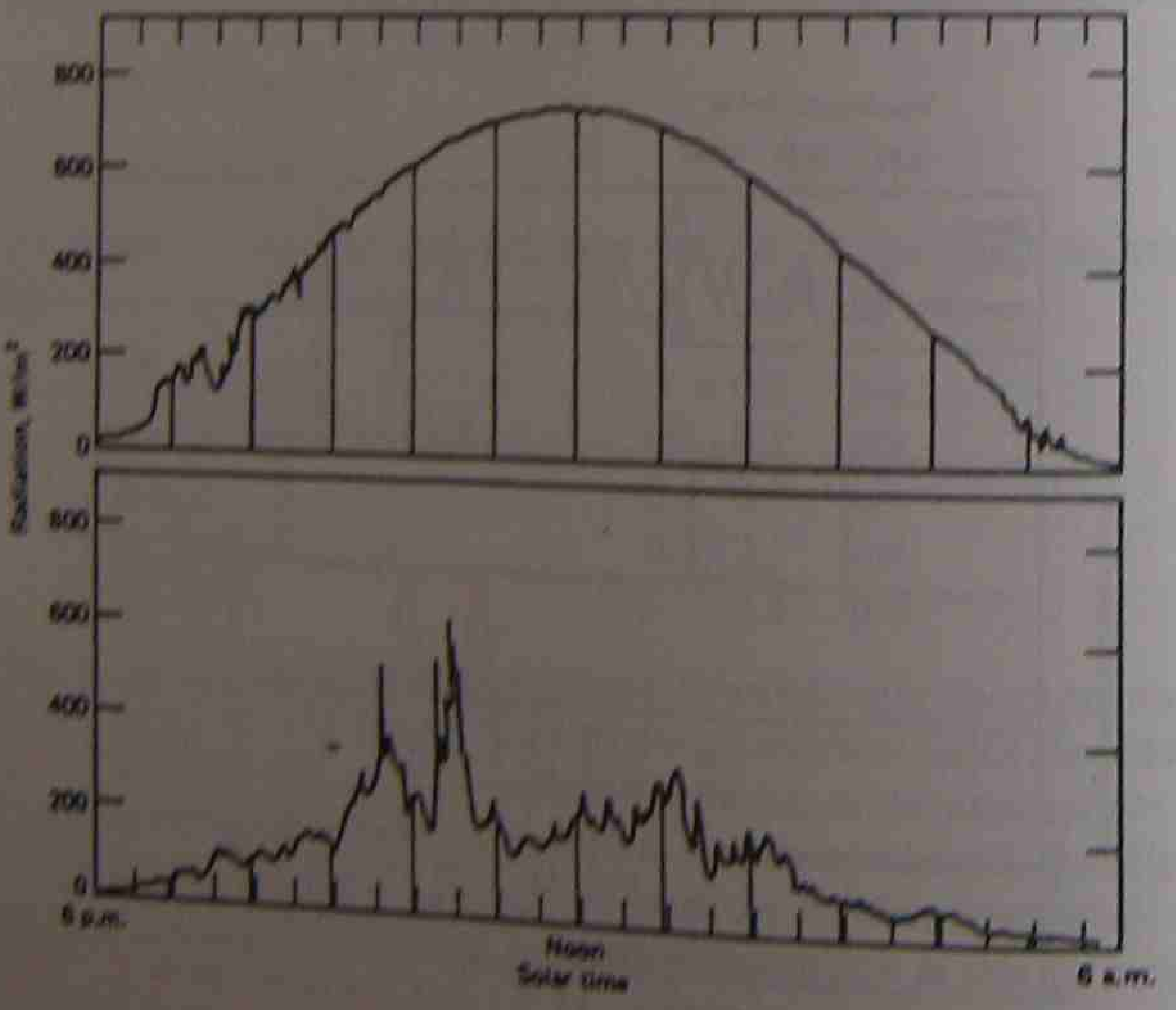


Figure 12 - Total (beam and diffuse) solar radiation on a horizontal surface versus time for a clear day and a cloudy day, latitude 43^0, for days near the equinox. (Source : Duffie and Beckman, 1980).

Irradiation (H or I), is measured in units of MJ/m^2 and is the energy of the radiation received per unit area for a period of time, usually a day (H) or an hour (I). It is found by the integration of irradiance over the required time.

Beam or direct irradiance or irradiation describes the radiation which travels directly from the sun to the surface being considered. The subscript b can be added to the appropriate radiation symbol, thus G_b refers to the beam irradiance.

Diffuse irradiance or irradiation describes the radiation which has reached a surface after being scattered by the atmosphere and thus comes from all directions of the sky. This is denoted by the subscript d.

Reflected irradiance or irradiation describes the radiation which has reached a surface by reflection from the ground or a nearby surface, and is denoted by the subscript r.

The term isotropic means evenly distributed in all directions. When applied to diffuse radiation it means that the radiation has the same intensity from all directions of the skydome.

Measured total radiation data on a horizontal surface, is referred to as global. This is the sum of the beam and diffuse radiation, there being no reflected component for a horizontal surface.

$$G_{global} = G_b + G_d$$

The diagrams shown in Figure 13 show the measured global irradiation on a horizontal plane as solar contours for January and July.

For inclined or vertical surfaces such as walls, the total radiation is the sum of the beam, diffuse and reflected components.

$$G_T = G_b + G_d + G_r$$

When specifying irradiance received on different surfaces the following subscripts will be used:

Irradiance	Beam	Diffuse	Reflected
tracking	G_b	G_d	G_r
horizontal	G_{bo}	G_{do}	-
plane (tilt β)	$G_{b\beta}$	$G_{d\beta}$	$G_{r\beta}$
vertical	G_{bv}	G_{dv}	G_{rv}

The same subscripts can be applied to irradiation (H or I).

3.4 Solar Radiation on Planes of Arbitrary Tilt and Orientation

Solar radiation data is available in a number of formats. The data is usually measured with a pyranometer on a horizontal plane. If only one pyranometer is used then horizontal global irradiance is measured. This is the sum of the beam and diffuse components. When two pyranometers are used, one is usually fitted with a shadow band and only the diffuse component is measured. By subtracting diffuse from global, the beam component is calculated.

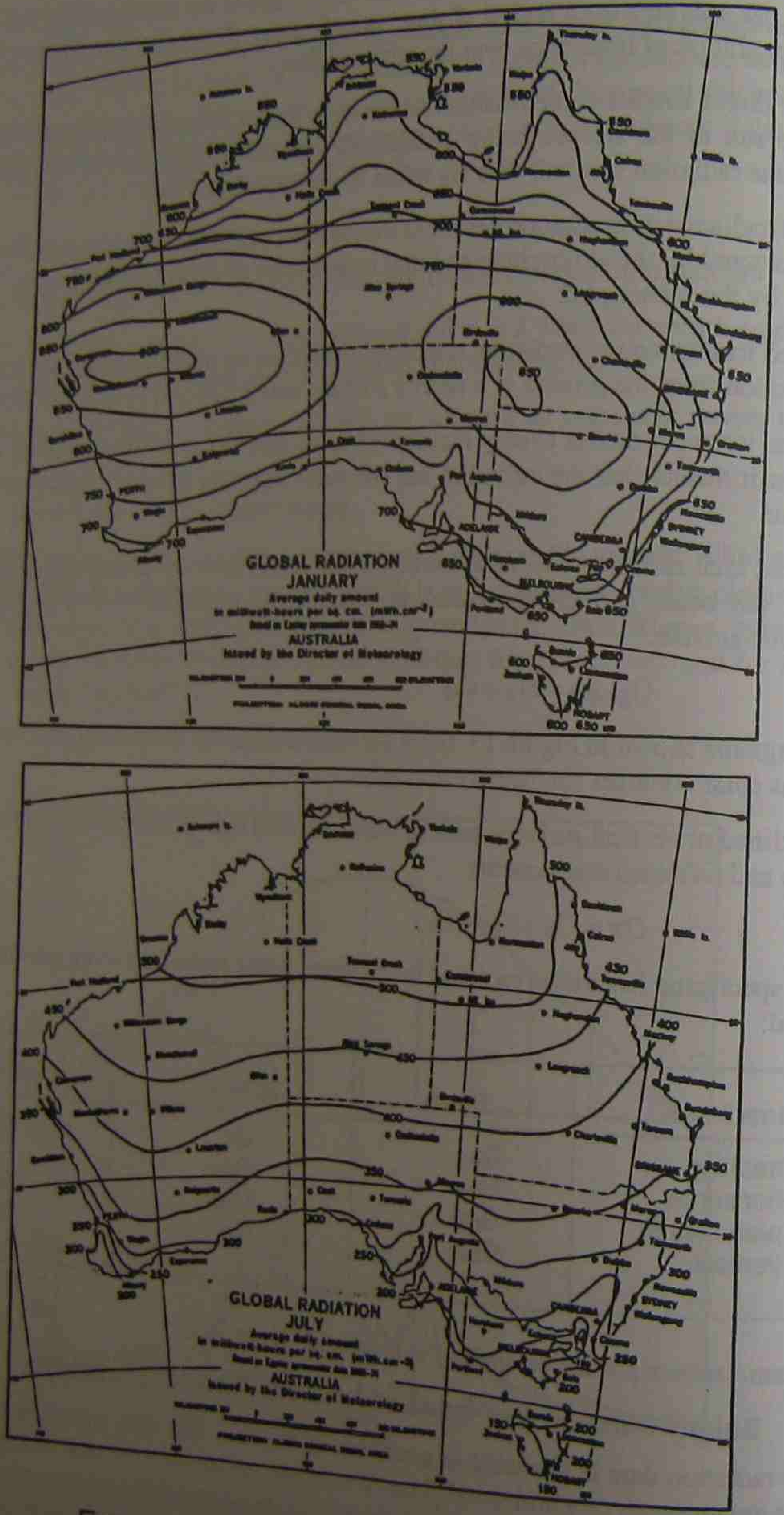


Figure 13 - Global irradiation for Australia, January and July. (Source: Bureau of Meteorology, 1975).

In order to calculate the amount of radiation on a plane of arbitrary tilt and orientation, the beam, diffuse and reflected components must be known or calculated:

$$G_{T\beta} = G_{b\beta} + G_{d\beta} + G_{r\beta}$$

For a horizontal surface:

$$G_{global} = G_{To}$$

$$= G_{bo} + G_{do}$$

3.4.1 Beam Irradiance

The beam irradiance on a plane will be a maximum when the radiation has a direction which is normal to the surface. As the angle of incidence of the radiation increases the beam irradiance will decrease. This is due to the radiation being spread over a larger area.

It can be seen from Figure 14 that a beam of light of irradiance G_b of cross section d, when projected at an angle θ onto a plane will have a cross section of d/cos θ. So the irradiance of the beam on a plane is:

$$G_{b\beta} = G_b \cos\theta$$

If the plane is horizontal, then the altitude is:

$$\alpha = 90 - \theta$$

So, $$G_{bo} = G_b \sin\alpha$$

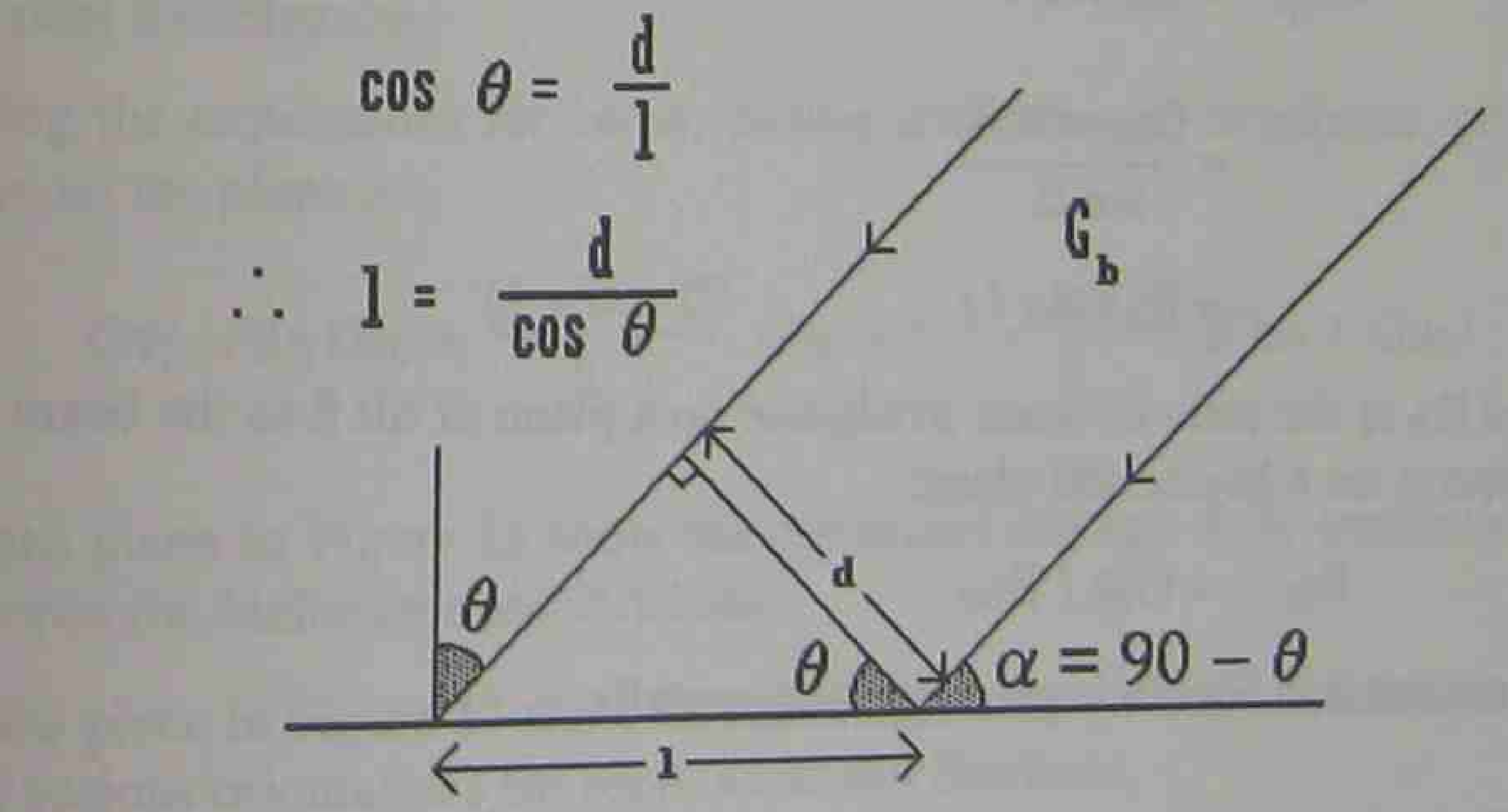


Figure 14 - The beam irradiance incident at an angle to a plane is less than the incoming beam irradiance.

It is this irradiance, G_{bo} which will be incident on a horizontal pyranometer. In order to calculate the beam irradiance, $G_{b\beta}$ on a plane of tilt β, G_b must first be calculated from G_{bo}.

From the expression above,

$$G_b = \frac{G_{bo}}{\sin \alpha}$$

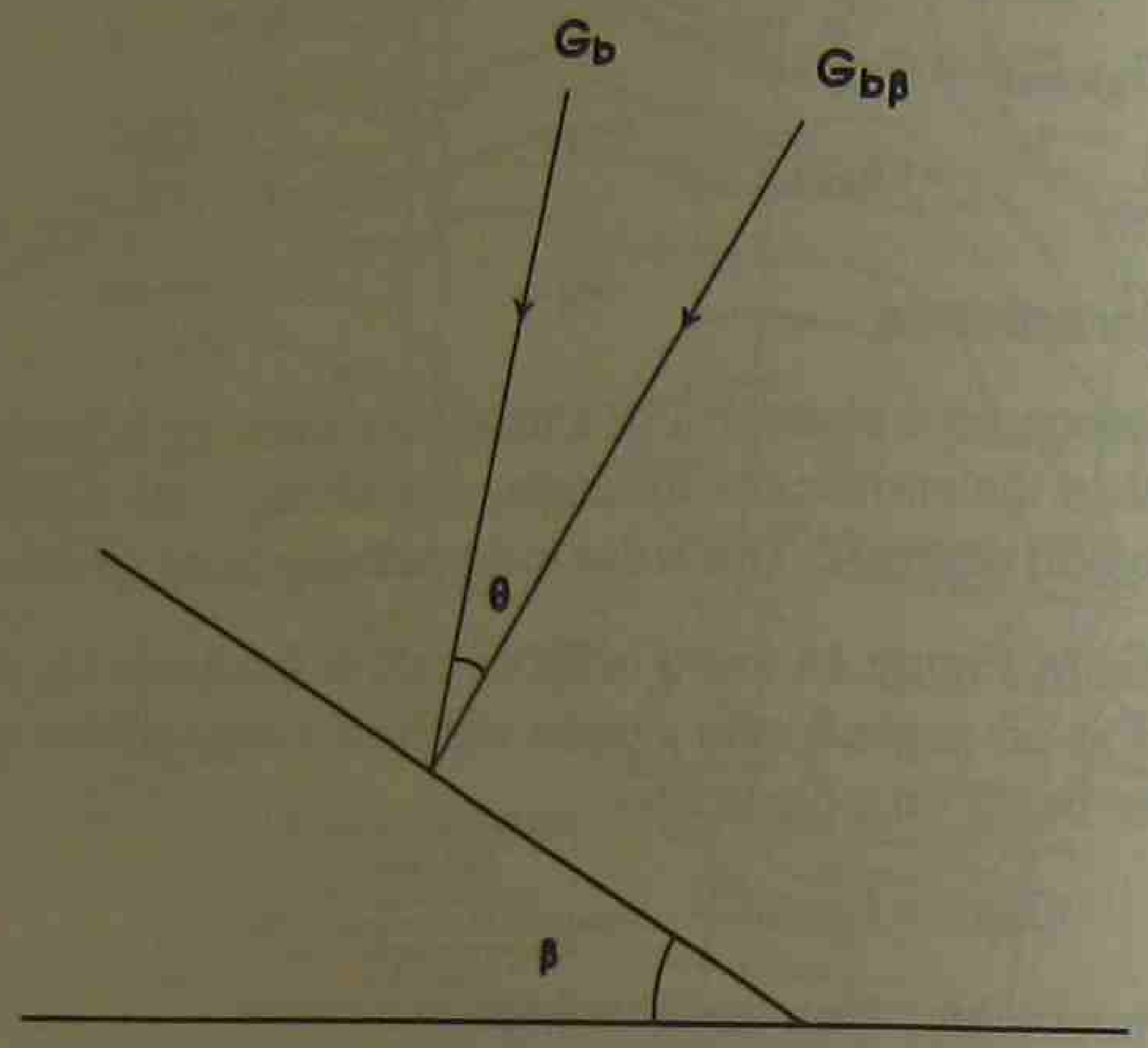


Figure 15 - Beam irradiance on a plane of tilt β.

The beam irradiance on a plane of tilt β, $G_{b\beta}$ in Figure 15 is:

$$G_{b\beta} = G_b \cos \theta$$

$$= \frac{G_{bo} \cos \theta}{\sin \alpha}$$

$$= R_b G_{bo}$$

where R_b is the ratio of beam irradiance on a plane of tilt β to the beam irradiance on a horizontal plane:

$$R_b = G_{b\beta} / G_{bo}$$

The expression for R_b is given in the appendix.

3.4.2 Diffuse Irradiation

The diffuse component of irradiance is usually considered to be isotropic. In reality, diffuse irradiance is brighter near the sun and around the horizon than for the rest of the sky. For isotropic conditions, G_{do} is always greater than $G_{d\beta}$.

It is shown in the appendix that the fraction of the sky hemisphere seen by a plane of tilt β is:

$$(1 + \cos \beta) / 2$$

So the diffuse component of the irradiance on a plane of tilt β is:

$$G_{d\beta} = G_{do} (1 + \cos \beta) / 2$$

For the special case of a vertical surface where $\beta = 90^\circ$

$$G_{d\beta} = G_{do} / 2$$

3.4.3 Reflected Irradiance

Reflected irradiance is also usually considered to be isotropic. A horizontal plane sees no reflected light from the ground. This means that a fraction ρ, of the total horizontal irradiance G_{To} is reflected towards the dome of the sky:

$$G_{r\beta} = \rho \, G_{To} = \rho \, (G_{bo} + G_{do})$$

It is shown in the appendix that the fraction of the reflected ground hemisphere seen by a plane inclined at β is:

$$(1 - \cos \beta) / 2$$

So the reflected component of irradiance on the plane is:

$$G_{r\beta} = \rho \, \frac{(1 - \cos \beta)}{2} \, (G_{bo} + G_{do})$$

The reflectance of the bare or grass covered ground is usually taken to be 0.2, while that of snow covered ground is 0.7.

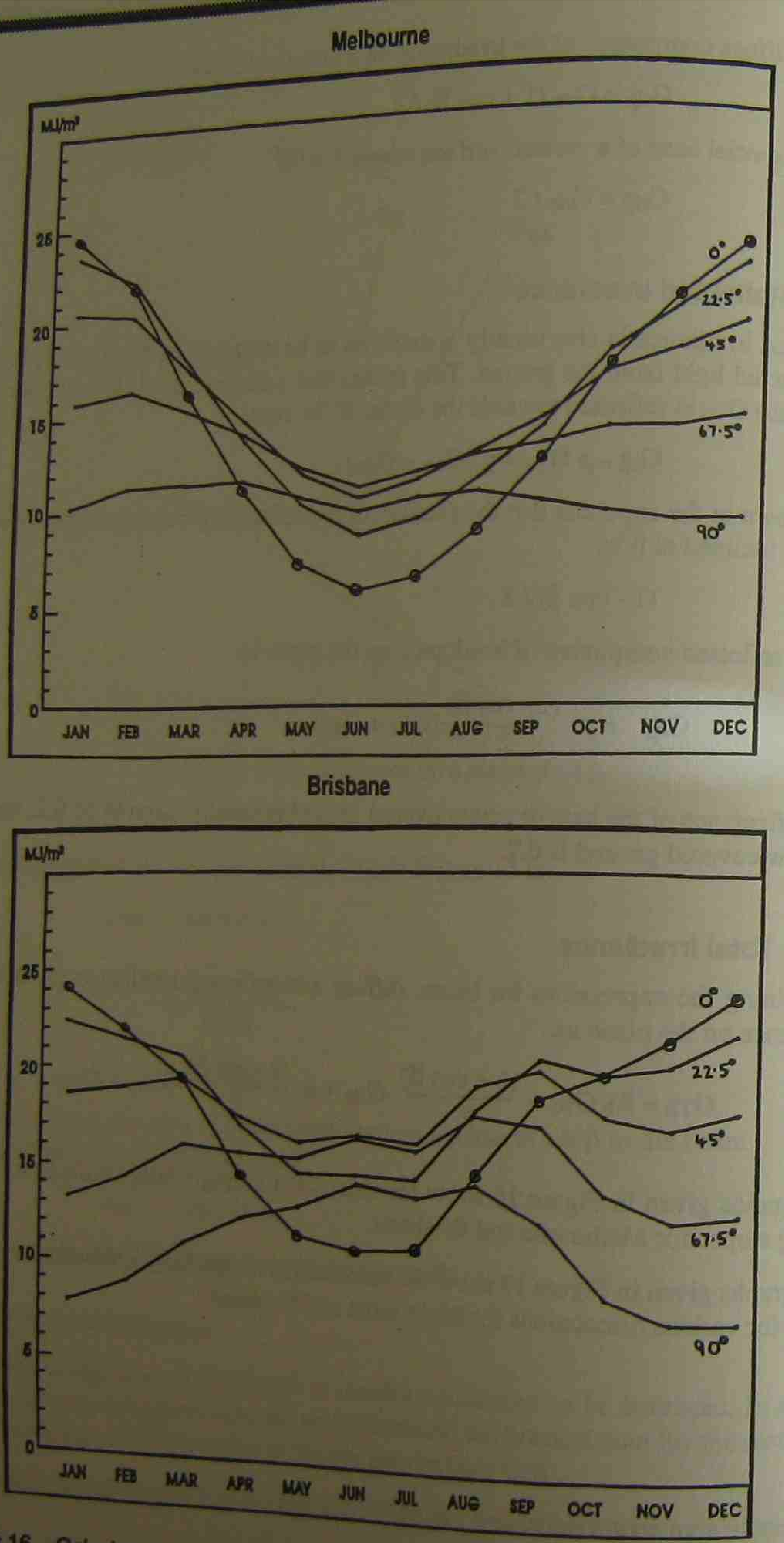
3.4.4 Total Irradiance

Combining the expressions for beam, diffuse and reflected irradiance gives the total irradiance on the plane as:

$$G_{T\beta} = R_b \, G_{bo} + \frac{(1 + \cos \beta)}{2} \, G_{do} + \rho \, \frac{(1 - \cos \beta)}{2} \, (G_{bo} + G_{do})$$

The graphs given in Figure 16 show the calculated average daily irradiation for north facing slopes for Melbourne and Brisbane.

The graphs given in Figure 17 show the calculated average daily irradiation for vertical walls for various orientations for Melbourne and Brisbane.



Figures 16 - Calculated average daily irradiation for north facing slopes of various inclination for (a) Melbourne and (b) Brisbane.

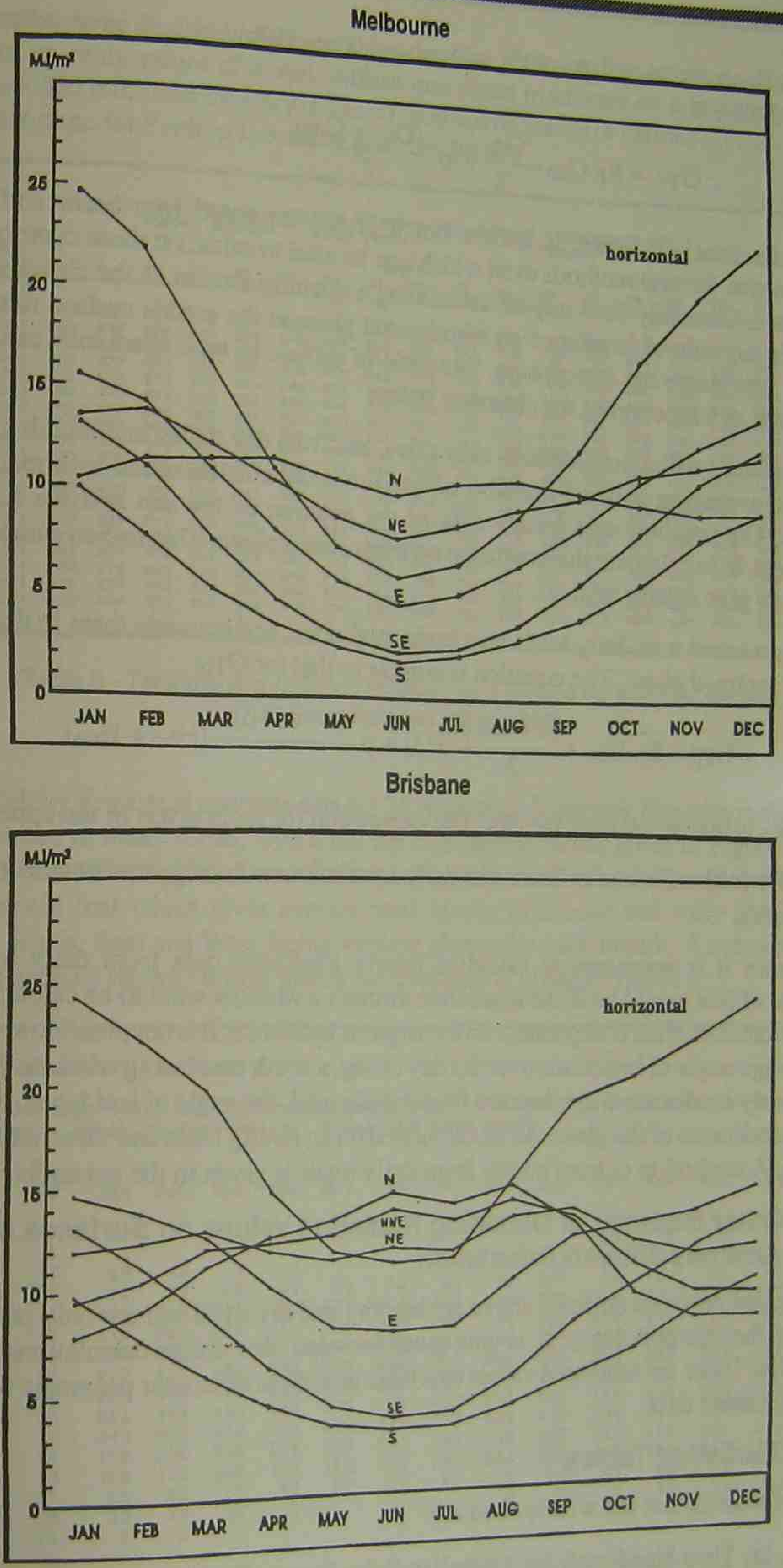


Figure 17 - Calculated average daily irradiation for vertical walls of different orientation for (a) Melbourne and (b) Brisbane.

For a vertical surface (ie. $\beta = 90^\circ$),
the irradiance is:

$$G_{Tv} = R_b G_{bo} + \frac{G_{do}}{2} + \rho \frac{(G_{bo} + G_{do})}{2}$$

Often the total irradiance is known but it is not separated into beam and diffuse components. Several methods exist which can be used to calculate these components of irradiance. Generally they rely on calculating a quantity known as the clearness index which is the ratio of irradiance on a horizontal plane at the earth's surface to that on a surface just above the atmosphere. The ratio of diffuse to total irradiance can then be calculated as a function of the clearness index.

The irradiance varies considerably over a day, and from day to day and month to month, so some averaging method must be adopted to reduce calculations to a manageable number. One method uses hourly data of the position of the sun and the horizontal irradiance, I_o to calculate the irradiance on the inclined plane. This is then summed over the day to give a daily total, H.

Another method uses daily totals on a horizontal plane and converts them to daily totals onto an inclined plane. The equation is similar to that for G_{Tb}:

$$H_{T\beta} = \overline{R_b}\, H_{bo} + \frac{(1 + \cos\beta)}{2} H_{do} + \rho \frac{(1 - \cos\beta)}{2} (H_{bo} + H_{do})$$

where $\overline{R_b}$ is integrated over the day. The expression for $\overline{R_b}$ is given in the appendix.

Generally it is sufficient to know the daily irradiation or hourly irradiance for one day each month.

Sometimes it is necessary to calculate hourly irradiance data from daily totals. An example of this would be if the irradiance through a window were to be calculated. The transmittance of glass is dependent on the angle of incidence. It is not possible to calculate the average angle of incidence over the day of say, a south east facing window. However, if an hourly irradiance is synthesized from a daily total, the angle of incidence, and hence the transmittance of the glass can be calculated on an hourly basis and then summed over the day. A method to extract hourly from daily totals is given in the appendix.

3.5 Other Methods of Obtaining Radiation Values on Surfaces of Arbitrary Tilt and Orientation

The manual methods outlined above are lengthy and involved and are only presented to explain the methodology. It is not recommended that these calculations be done manually. There are tabulated values available as well as computer programs which will calculate these data.

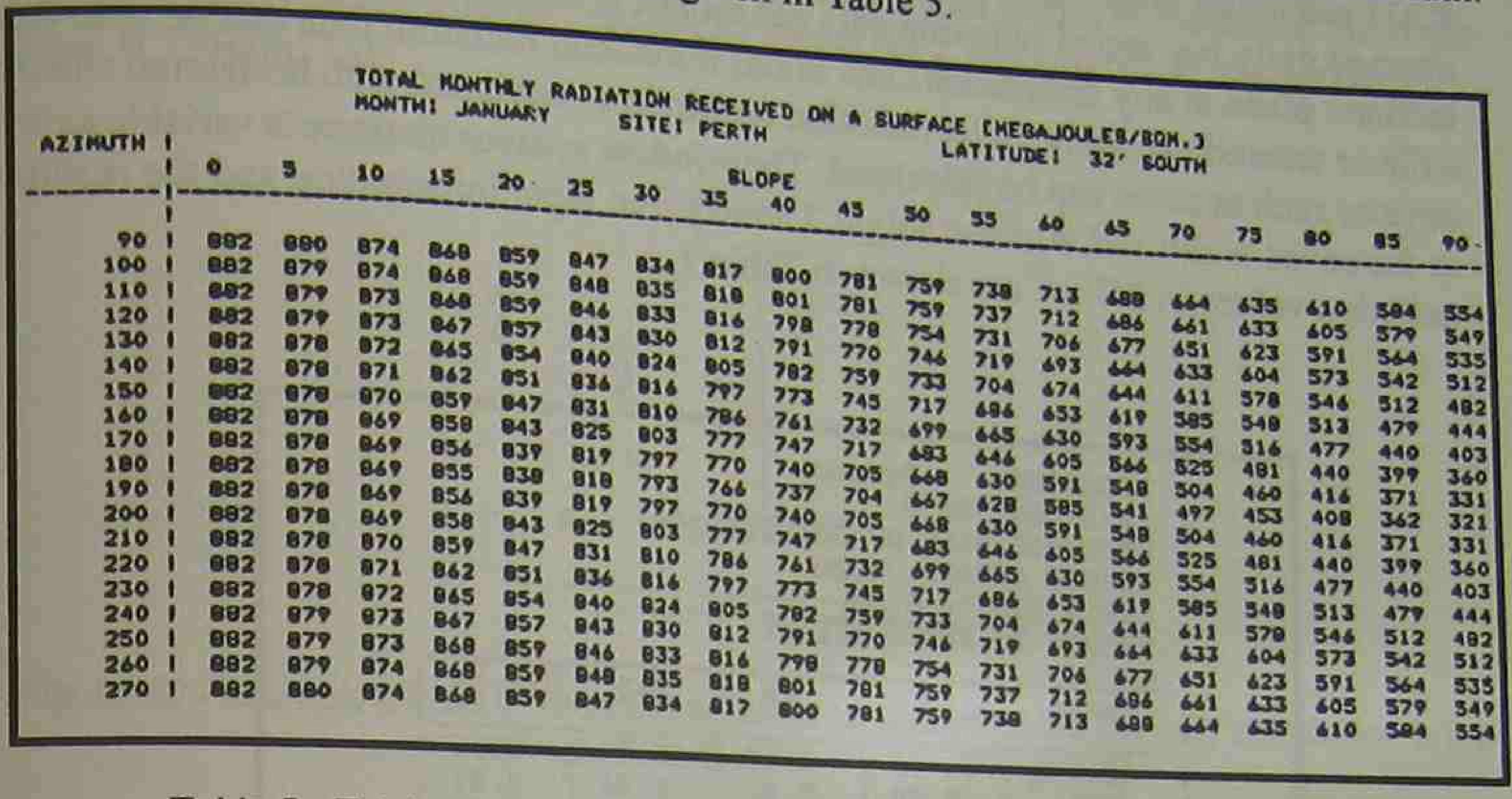
3.5.1 Radiation Tables

Two references that are widely used are:

- Data Handbook for Australian Solar Energy Designers (Roy and Miller)
- Australian Solar Radiation Data Handbook (Frick et al)

Both of these references have been mentioned previously.

The handbook by Roy and Miller contains data for 16 Australian locations. It presents tables of monthly values of global, diffuse and direct irradiance on a horizontal plane. Also included is the total monthly radiation received on planes of various tilt and azimuth. A sample page for Perth in January is given in Table 5.



TOTAL MONTHLY RADIATION RECEIVED ON A SURFACE [MEGAJOULES/SQM.]
MONTH: JANUARY SITE: PERTH LATITUDE: 32' SOUTH

AZIMUTH	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	SLOPE																		
90	882	880	874	868	859	847	834	817	800	781	759	738	713	688	664	635	610	584	554
100	882	879	874	868	859	848	835	818	801	781	759	737	712	686	661	633	605	579	549
110	882	879	873	868	859	846	833	816	798	778	754	731	706	677	651	623	591	564	535
120	882	879	873	867	857	843	830	812	791	770	746	719	693	664	633	604	573	542	512
130	882	878	872	865	854	840	824	805	782	759	733	704	674	644	611	578	546	512	482
140	882	878	871	862	851	836	816	797	773	745	717	686	653	619	585	548	513	479	444
150	882	878	870	859	847	831	810	786	761	732	699	665	630	593	554	516	477	440	403
160	882	878	869	858	843	825	803	777	747	717	683	646	605	566	525	481	440	399	360
170	882	878	869	856	839	819	797	770	740	705	668	630	591	548	504	460	416	371	331
180	882	878	869	855	838	818	793	766	737	704	667	628	585	541	497	453	408	362	321
190	882	878	869	856	839	819	797	770	740	705	668	630	591	548	504	460	416	371	331
200	882	878	869	858	843	825	803	777	747	717	683	646	605	566	525	481	440	399	360
210	882	878	870	859	847	831	810	786	761	732	699	665	630	593	554	516	477	440	403
220	882	878	871	862	851	836	816	797	773	745	717	686	653	619	585	548	513	479	444
230	882	878	872	865	854	840	824	805	782	759	733	704	674	644	611	578	546	512	482
240	882	879	873	867	857	843	830	812	791	770	746	719	693	664	633	604	573	542	512
250	882	879	873	868	859	846	833	816	798	778	754	731	706	677	651	623	591	564	535
260	882	879	874	868	859	848	835	818	801	781	759	737	712	686	661	633	605	579	549
270	882	880	874	868	859	847	834	817	800	781	759	738	713	688	664	635	610	584	554

Table 5 - Total monthly radiation received on a surface for Perth in January.
(Source: Roy and Miller, 1980).

The work by Frick et al contains data for 24 Australian locations. Here the radiation data is presented in many forms, with a full list of available tables given in Figure 20 of the student notes for Unit 2. Data that is particularly useful for solar efficient building designers is that which gives average total hourly irradiance and daily irradiation on North, South, East and West facing vertical planes for each month. A sample page for North and East facing vertical planes for Brisbane is given in Tables 6.

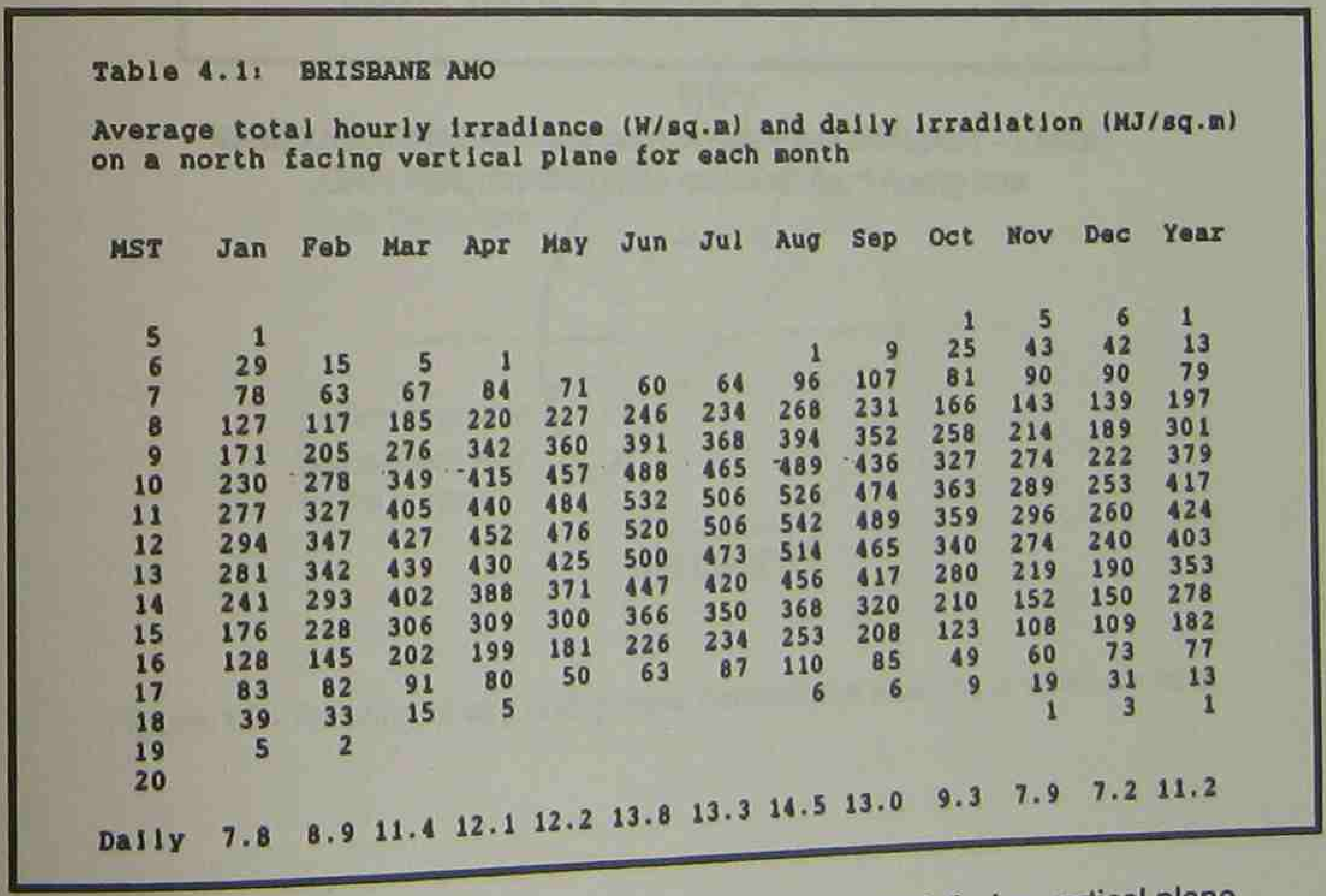


Table 4.1: BRISBANE AMO

Average total hourly irradiance (W/sq.m) and daily irradiation (MJ/sq.m) on a north facing vertical plane for each month

MST	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5	1									1	5	6	1
6	29	15	5	1				1	9	25	43	42	13
7	78	63	67	84	71	60	64	96	107	81	90	90	79
8	127	117	185	220	227	246	234	268	231	166	143	139	197
9	171	205	276	342	360	391	368	394	352	258	214	189	301
10	230	278	349	415	457	488	465	489	436	327	274	222	379
11	277	327	405	440	484	532	506	526	474	363	289	253	417
12	294	347	427	452	476	520	506	542	489	359	296	260	424
13	281	342	439	430	425	500	473	514	465	340	274	240	403
14	241	293	402	388	371	447	420	456	417	280	219	190	353
15	176	228	306	309	300	366	350	368	320	210	152	150	278
16	128	145	202	199	181	226	234	253	208	123	108	109	182
17	83	82	91	80	50	63	87	110	85	49	60	73	77
18	39	33	15	5				6	6	9	19	31	13
19	5	2									1	3	1
20													
Daily	7.8	8.9	11.4	12.1	12.2	13.8	13.3	14.5	13.0	9.3	7.9	7.2	11.2

Table 6 - Hourly irradiance and daily irradiation on a north facing vertical plane.
(Source: Frick et al, 1987).

3.5.2 Computer Programs

There are various programs available which calculate solar radiation quantities. Program RAD calculates solar radiation on surfaces of arbitrary tilt and orientation RAD uses average daily horizontal radiation data per month to calculate the solar radiation on an inclined plane at any orientation. The initial horizontal radiation data can be read from a file or entered manually. Solar radiation on windows equipped with horizontal shading devices such as eaves can be calculated. The window to eaves distance is variable as well as the eaves width and window height.The required input information and the resultant radiation values in MJ/m^2 are shown in Table 7.

```
    LOCATION:    Sydney
    LATITUDE:-34.0
    VERTICAL WALL OF ORIENTATION:    0
    WINDOW HEIGHT: 2.20
    EAVES WIDTH: 0.80
    WINDOW TO EAVES HEIGHT: 0.20

  ----------------------------------------------------
  | month      H        HW       HWS     HWS-HW   |
  |--------------------------------------------------|
  |  JAN   | 21.90 |  8.82 |  6.13 |  2.69 |
  |  FEB   | 18.80 |  9.21 |  5.54 |  3.67 |
  |  MAR   | 16.10 | 10.58 |  7.00 |  3.58 |
  |  APR   | 13.40 | 13.17 | 10.42 |  2.75 |
  |  MAY   | 10.50 | 14.39 | 12.51 |  1.88 |
  |  JUN   |  8.10 | 12.67 | 11.37 |  1.30 |
  |  JUL   | 10.30 | 15.78 | 14.01 |  1.77 |
  |  AUG   | 12.10 | 13.78 | 11.42 |  2.36 |
  |  SEP   | 16.50 | 12.92 |  9.22 |  3.70 |
  |  OCT   | 18.60 |  9.80 |  5.83 |  3.97 |
  |  NOV   | 22.50 |  9.30 |  6.04 |  3.25 |
  |  DEC   | 24.20 |  9.21 |  6.45 |  2.76 |
  |________|_______|_______|_______|_______|
  |  AV    | 16.09 | 11.65 |  8.84 |  2.81 |
  |________|_______|_______|_______|_______|

  H   : horizontal insolation
  HW  : insolation on unshaded vertical window
  HWS : insolation on shaded vertical window
```

Table 7 - Required input information and resultant output table and graph from radiation computer program RAD.

---

4 APPENDIX

4.1 Diffuse and Reflected Irradiance on Planes

For isotropic conditions the same irradiance exists for all angles of incidence. So if ray 1 of solid angle $\delta\theta$ contributes irradiance D, then ray 2 will contribute irradiance D cos θ, (Figure 18).

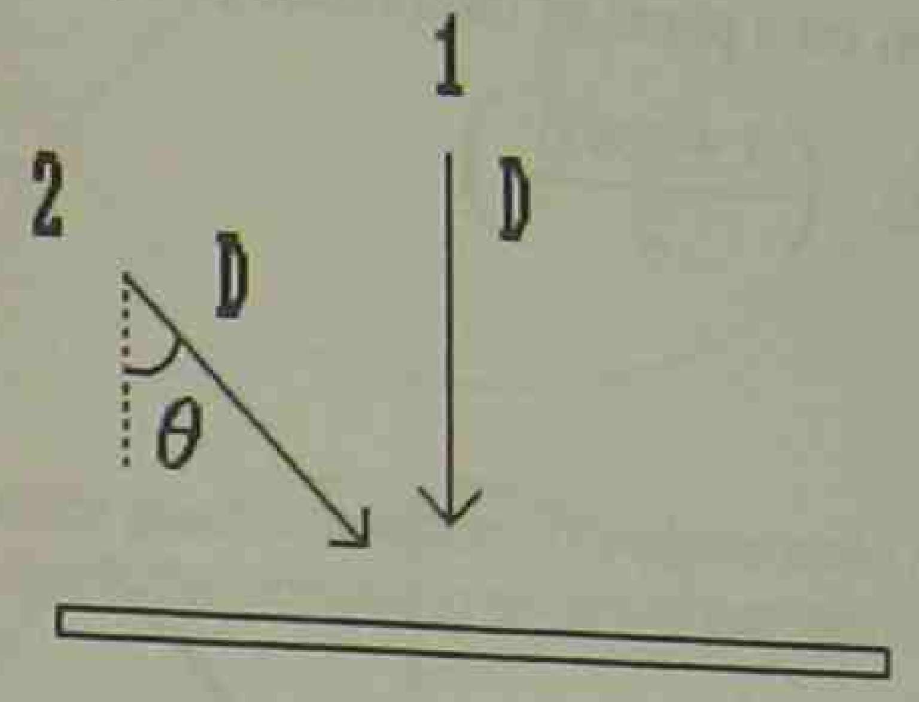


Figure 18 - Isotropic diffuse or reflected radiation assumes that the intensity of radiation is the same from all parts of the sky or of the ground.

Summing over the whole hemisphere of the sky the diffuse irradiance on a horizontal plane is:

$$G_{do} = \sum_{-90}^{90} D\cos\theta\,\delta\theta = \int_{-90}^{90} D\cos\theta\,d\theta = 2\,D$$

A plane inclined at an angle β will see a portion of the sky hemisphere and a portion of the ground hemisphere as shown in Figure 19:

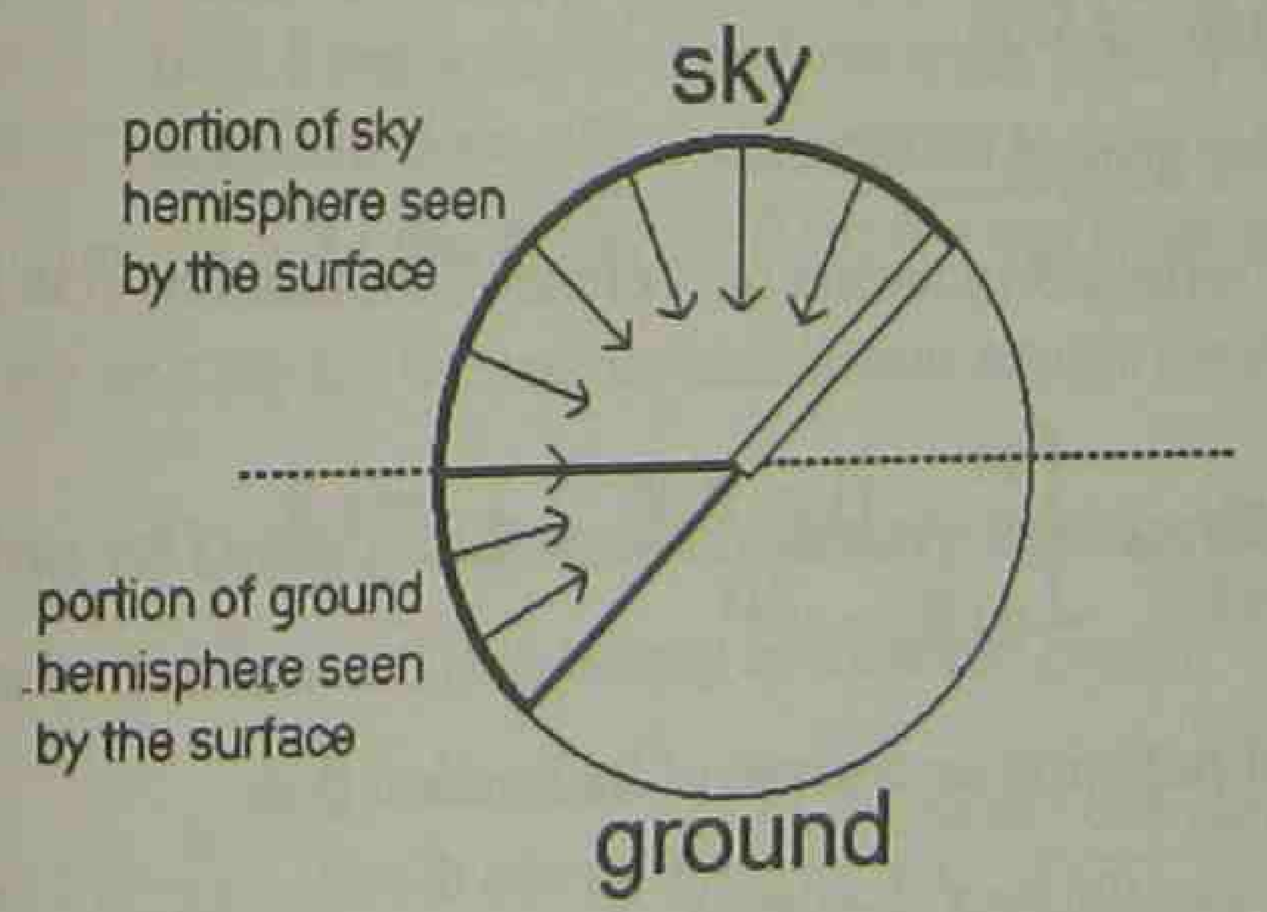


Figure 19 - Portions of sky and ground hemisphere seen by a tilted surface.

4.1.1 Diffuse Irradiance

The fraction of diffuse radiation on the plane of inclination β is (Figure 20):

$$\frac{G_{d\beta}}{G_{do}} = \int_{-90}^{90-\beta} \frac{D\cos\theta\, d\theta}{2D} = \frac{1+\cos\beta}{2}$$

Thus the diffuse radiation on a plane of inclination β is:

$$G_{d\beta} = G_{do}\left(\frac{1+\cos\beta}{2}\right)$$

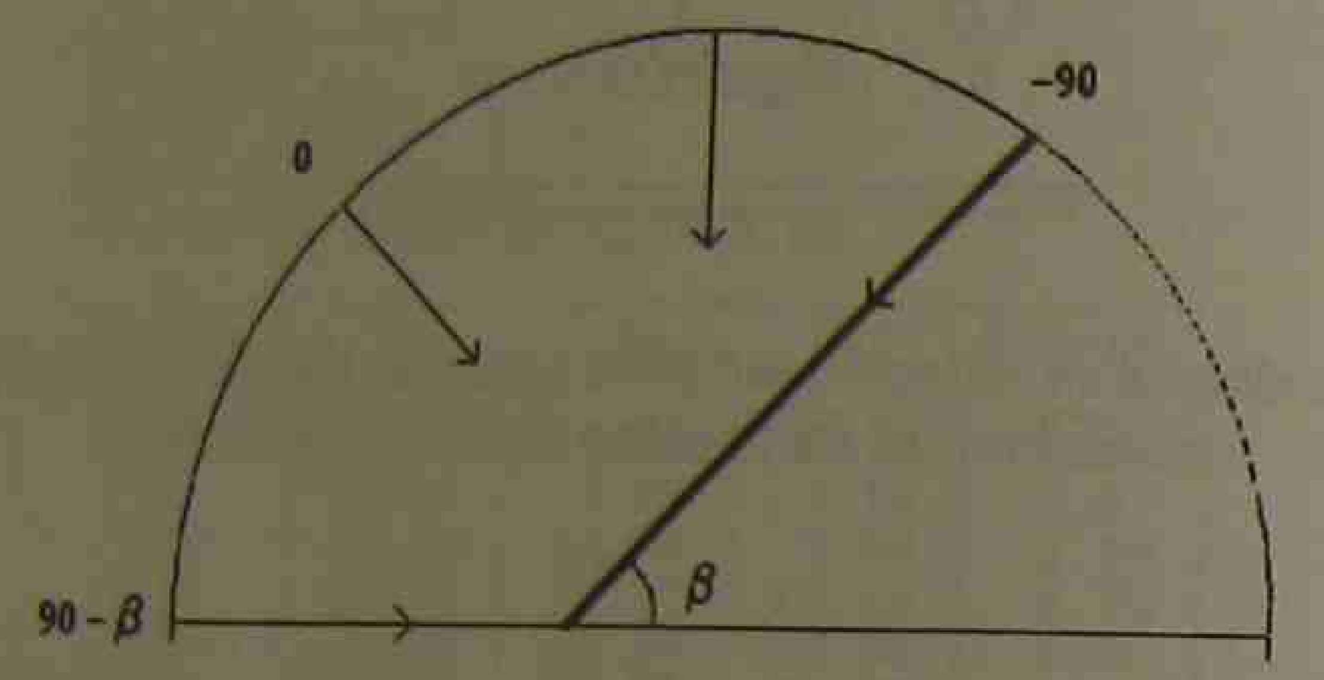


Figure 20 - Isotropic diffuse sky radiation. The plane of tilt β sees radiation from the sky from an angle parallel to the horizon to an angle parallel to the plane.

4.1.2 Reflected Irradiance

The total reflected radiation from the ground is:

$$G_{r180} = \rho\, G_{To}$$

where ρ is the ground reflectance

So the fraction of reflected radiation on a plane of inclination β is (Figure 21):

$$\frac{G_{r\beta}}{G_{r180}} = \int_{90-\beta}^{90} \frac{D\cos\theta\, d\theta}{2D} = \frac{1-\cos\beta}{2}$$

Thus the reflected radiation on a plane of inclination β is

$$G_{r\beta} = \rho\, G_{To}\left(\frac{1-\cos\beta}{2}\right)$$

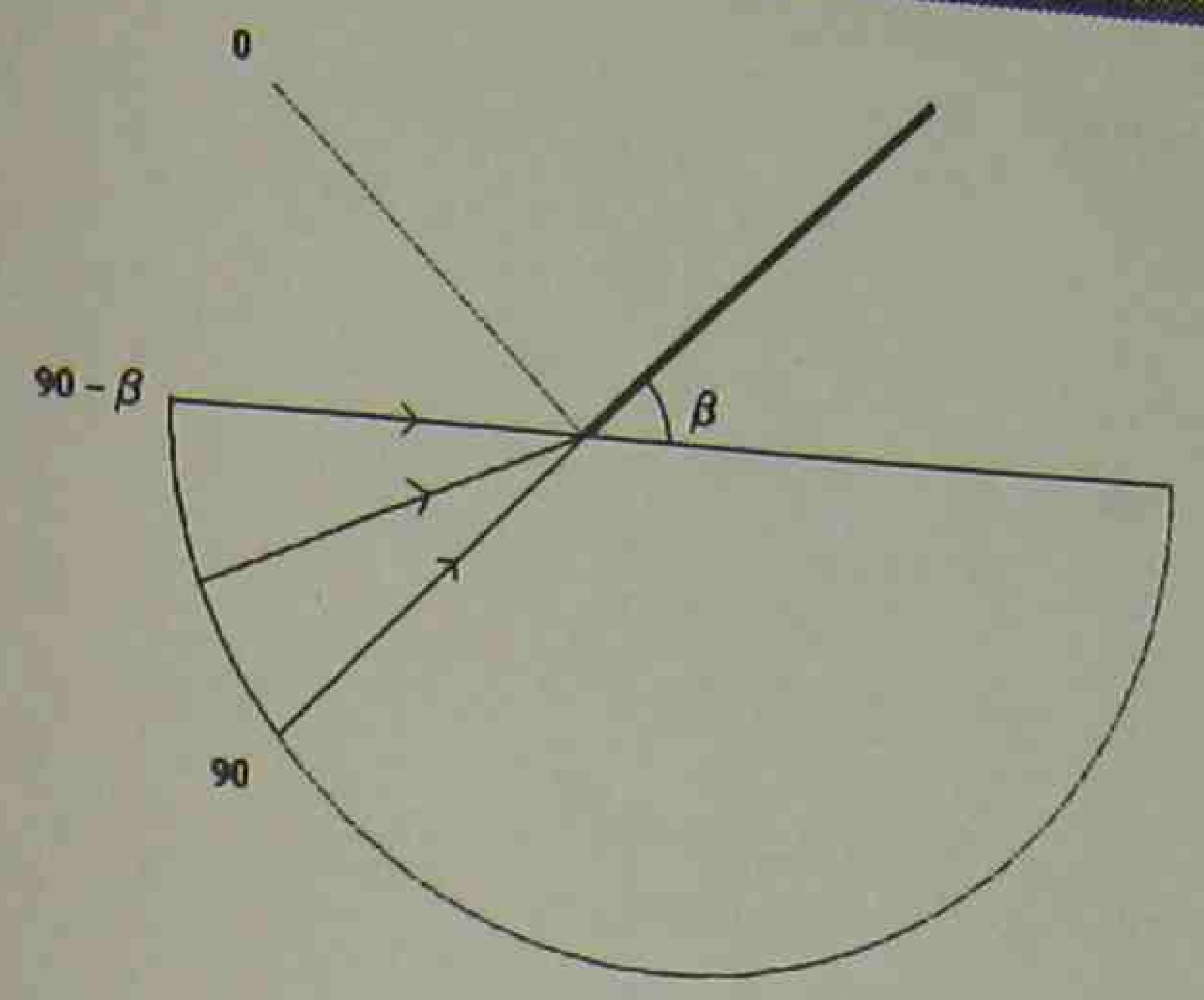


Figure 21 - Isotropic reflected ground radiation. The plane sees reflected radiation from an angle parallel to the horizon to an angle parallel to the plane.

4.2 Conversion of Beam Components of Irradiance

For instantaneous or hourly irradiance G or I:

$$R_b = \frac{\cos\theta}{\sin\alpha}$$

$$= \frac{(\sin\delta\sin\phi\cos\beta + \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega - \cos\delta\sin\phi\sin\beta \cos\gamma\cos\omega - \cos\delta\sin\beta\sin\gamma\sin\omega)}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta}$$

For daily irradiance, H:

$$\overline{R_b} = \frac{(\sin\delta\sin\phi\cos\beta + \sin\delta\cos\phi\sin\beta\cos\gamma)(\omega_1 - \omega_2)\pi/180 + (\cos\delta\cos\phi\cos\beta - \cos\delta\sin\phi\sin\beta\cos\gamma(\sin\omega_2 - \sin\omega_1) + \cos\delta\sin\beta\sin\gamma(\cos\omega_2 - \cos\omega_1)}{2(\omega_{ss}\pi/180\sin\delta\sin\phi + \cos\delta\cos\phi\sin\omega_{ss})}$$

where ω_1 and ω_2 are the sunrise and sunset angles for the arbitrary surface

4.3 Conversion of Daily Irradiance to Hourly Irradiance

To convert from daily irradiance (H) to hourly irradiance (I) use:

$$I = H\frac{\pi}{180}(a + b\cos\omega)\left(\frac{\cos\omega - \cos\omega_{ss}}{\sin\omega_{ss} - (\pi/180)\,\omega_{ss}\cos\omega_{ss}}\right)$$

where:

$a = 0.409 + 0.5016\sin(\omega_{ss} - 60)$

$b = 0.6609 - 0.4767\sin(\omega_{ss} - 60)$

ω - hour angle

ω_{ss} - sunset hour angle

4.4 List of Symbols

Angles:

α - altitude
ψ - azimuth
ϕ - latitude
z - zenith angle
δ - declination
ω - hour angle
β - tilt
γ - orientation
θ - incidence angle

Radiation quantities:

G - irradiance (W/m^2)
H - daily irradiation (MJ/m^2)
I - hourly irradiation (MJ/m^2)

Subscripts for G, H and I are:

type of radiation:
b - beam
d - diffuse
r - reflected
T - total

type of surface:
o - horizontal
β - plane tilted at an angle b to the horizontal
v - vertical

Other Quantities:

m - air mass
ρ - reflectance
R_b - ratio of beam irradiance on a plane of tilt β to irradiance on a horizontal plane
$\overline{R_b}$ - above ratio integrated over a day
ω_1, ω_2 - sunrise and sunset hour angles for an arbitrary surface
ω_{sr}, ω_{ss} - sunrise and sunset hour angles for a horizontal surface

Unit 4

Thermodynamic Principles and Heat Flow

1 INTRODUCTION

The thermal performance of a building is dependent on the physical properties of the building structure as well as the environmental conditions inside and outside the building.

The insulating properties of the building envelope determine the rate of heat flow between the building and its environment. The amount of mass within the insulating envelope determines the time lag between the temperature peaks inside the building and outside, as well as moderating the extent of the temperature swings inside the building. This unit is principally concerned with the investigation of the factors which affect the rate of heat flow to and from the building.

2 BASIC PRINCIPLES

2.1 Laws of Thermodynamics

The mechanisms of heat flow are governed by the laws of thermodynamics. An understanding of these laws underpins the understanding of the thermal behaviour of buildings.

Every body has a property called temperature. When two bodies are found to be in thermal equilibrium their temperatures are equal. So in order for heat to flow from one body to another a temperature difference must exist. This is the **zeroth** law of thermodynamics.

The **first law** of thermodynamics is often called the law of conservation of energy, i.e energy can not be created or destroyed. When work is done on a body then that body has its energy increased. The increase in internal energy of a body:

$$\Delta U = Q - W$$

where Q - heat added to the body
W - work done by the body on its surroundings

The **second law** of thermodynamics is concerned with the amount of heat that can be changed to work. The transfer of thermal energy or heat always occurs in the direction of decreasing temperature, i.e., heat must flow from a hot body to a cold body. As a consequence it is not possible to change heat completely into work in an environment with a temperature above absolute zero.

2.2 Heat and Temperature

Heat (Q) is the form of energy transferred between two bodies as a result of a difference in their temperatures. It is a form of energy appearing as motion of the atoms, molecules and ions of which a substance is composed.

Heat has the same unit as energy, i.e., the Joule (J). However kilojoule (kJ), megajoule (MJ) and kilowatt-hour (kWh) are often used.

$$1 \text{ kWh} = 3.6 \text{ MJ}$$

Temperature (T) is a measure of the kinetic energy of the atoms, molecules and ions of which a substance is composed.

Units of temperature are Kelvin (K) or degrees Celsius (^oC). The Kelvin is the S.I. unit and must be used in equations involving T. However if the change in temperature (ΔT) is required, as is often the case, then either Kelvin or degrees Celsius may be used. Degrees Celsius is more commonly used for everyday measurement of temperatures. The Kelvin scale has its zero (called absolute zero) when all atoms, molecules and ions cease to move. This is at a temperature of -273^oC. The Celsius scale uses the freezing point of water as its zero. A change in temperature of 1K equals a change in temperature of 1^oC. To convert from one scale to the other, the following formula is used:

$$T\,(K) = T\,(^oC) + 273.16$$

Specific heat capacity (c) is the amount of heat energy required to raise the temperature of a mass of 1kg by 1K. The heat transferred to a body (without producing a change in state) which results in an increase in temperature from $T_{initial}$ to T_{final} is

$$\begin{aligned} Q &= m\,c\,(T_{final} - T_{initial}) \\ &= m\,c\,\Delta T \end{aligned}$$

where
Q - heat energy (J)
m - mass (kg)
c - specific heat capacity (J/kgK)
ΔT - change in temperature (K)

The specific heat capacity is also a measure of the amount of heat that a body can release for a corresponding drop in temperature. The thermal mass of a material is related to its specific heat capacity. The specific heat capacity of some common building materials are given in Table 1.

3 HEAT FLOW

3.1 Heat Flow Rate

The heat flow rate (P) is the amount of heat that is transferred per unit time. Heat flow rate is often called heat flux. The unit of P is Joule/second (J/s) which is a Watt (W). The heat flow rate through an area A across which there exists temperature difference ΔT is:

$$P = h\,A\,\Delta T$$

where h - heat transfer coefficient (W/m^2K)

(The symbol Q is often used for heat flow rate, however this text will use the symbol P as heat flow rate is a power quantity)

Material Name	Cond. W/m/K	Density kg/m3	Sp. Heat J/kg/K
adobe (mud brick)	1.250	2050.00	1000.00
aluminium	210.000	2680.00	880.00
brick	1.150	2000.00	800.00
carpet + underlay	0.050	100.00	1200.00
cement rendering	0.600	1400.00	1000.00
concrete 1:2:4	1.440	2400.00	880.00
concrete aerated	0.130	500.00	1000.00
concrete block hollow	1.000	980.00	880.00
cork tiles	0.079	465.00	1800.00
fibreboard (caneite)	0.058	290.00	1507.00
fibro cement sheet	0.320	1490.00	840.00
glass	1.050	2510.00	840.00
granite	2.900	2650.00	900.00
hardboard	0.220	1025.00	1675.00
insulation cellulose	0.039	42.00	1000.00
insulation fibreglass	0.043	12.00	880.00
insulation polystyrene	0.039	16.00	340.00
insulation polyurethane	0.025	24.00	450.00
insulation rockwool	0.035	40.00	920.00
particle board	0.121	640.00	2000.00
plaster rendered	0.500	1440.00	880.00
plasterboard	0.170	880.00	1050.00
plywood	0.140	530.00	1500.00
roof tiles	0.810	1922.00	921.00
sandstone	1.300	2000.00	920.00
slate	1.500	2650.00	750.00
soil compacted	1.210	1540.00	1260.00
steel	47.500	7850.00	500.00
strawboard (stramit)	0.081	320.00	1050.00
timber hardwood	0.200	860.00	2090.00
timber pine	0.100	506.00	2090.00
vinyl floor tiles	0.790	2050.00	840.00
water	0.600	1000.00	4190.00
weatherboard	0.140	478.00	2090.00

Table 1 - The conductivity, density and specific heat capacity of some common building materials.

To be able to understand how to control heat flow through building structures it is necessary to have a knowledge of the heat transfer processes. There are three types of heat transfer; conduction, convection and radiation. These are discussed below.

3.2 Conduction

Thermal conduction is the mechanism whereby energy transfer takes place due to the transfer of kinetic energy between particles at the atomic level. In metals thermal conduction takes place through the motions of free electrons. Liquids and non electrically conducting solids conduct heat primarily via longitudinal oscillations of the lattice structure. Gases conduct via elastic collisions of molecules.

The rate of heat flow through a solid block with a uniform cross sectional area is given by the following relationship:

$$P = \frac{k A \Delta T}{d}$$

where
P - heat flow rate (W)
k - thermal conductivity (W/mK)
A - area (m^2) of the uniform cross section perpendicular to the heat flow
ΔT - temperature difference (K)
d - path length or thickness (m)

Other terms which are used in conjunction with thermal conduction are:

Resistivity (Res) is the reciprocal of the conductivity and is a measure of the insulation ability of a particular material.

$$Res = 1/k \ \ (mK/W)$$

Resistance (R) is the often called "R-value" and is a measure of the insulating ability of a particular material of a particular thickness (d).

$$R = d \times Res = d/k \ \ (m^2K/W)$$

Conductance (C) is the reciprocal of the resistance and is a measure of the conduction ability of particular material of a particular thickness.

$$C = 1/R \ \ (W/m^2K)$$

This gives the **heat flow rate** for a solid due to conductance as:

$$P_{cond} = C A \Delta T$$

Example: A mud brick wall has the following dimensions; height 2.4m, length 5.0m and thickness 300mm. If the two wall surfaces are 19°C and 11°C respectively calculate:

(a) the rate of heat flow through the wall
(b) the R-value of the wall

Solution:

(a) $C = k/d$
$= 1.25/0.3$ (k from Table 1)
$= 4.17\ W/m^2K$

$A = L.W$
$= 5 \times 2.4$
$= 12\ m^2$

$P = C A \Delta T$
$= 4.17 \times 12 \times 8$
$= 400W$

(b) $R = d/k$
$= 0.3/1.25$
$= 0.24\ m^2K/W$

3.3 Convection

Thermal convection involves energy transfer in a fluid due to mixing of layers at different temperatures. Heat transfer in fluids involves both convection and conduction. Reference to convection heat flow rates often includes the conduction component as well.

Natural convection occurs when fluid in contact with a hot surface is heated and rises due to its expansion and resultant lower density. This is then replaced by cooler fluid of lower density which is then heated etc.

The heat flow rate for combined convection and conduction is:

$$P_{conv/cond} = h_c A \Delta T$$

where h_c - combined conduction and convection heat transfer coefficient (W/m^2K)

The heat transfer coefficient for heat flowing across an air gap depends on average temperature, gap distance (approximately constant after 100mm), fluid type and direction of heat flow.

Natural convection assumes an airspeed of less than 0.1m/s. The following values of h_c apply:

$h_c = 3.0$ for horizontal heat flow
$= 4.3$ for heat flow upwards
$= 1.5$ for heat flow downwards

Forced convection heat transfer occurs when fluid currents are produced by some external source such as the wind, blowers or pumps. The heat transfer coefficient for forced convection is:

$$h_c = 5.8 + 4.1v$$

where v is airspeed (m/s)

3.4 Radiation

Thermal radiation or radiant energy is energy emitted by a body as a consequence of its temperature alone. Radiant energy is energy in the form of electromagnetic waves or photons. Unlike conduction or convection there is no heat transfer due to matter. In a vacuum this energy travels at a constant speed, (the speed of light), irrespective of its frequency.

The energy associated with a photon is directly proportional to its frequency i.e.,

$$E_v = h\nu$$

where h - Planck's constant
ν - photon frequency

Frequency and wavelength are related by the speed of light:

$$C = \lambda\nu$$

where λ - wavelength

A radiating body loses heat by emitting photons which have a range of energies, and therefore a range of frequencies. This frequency distribution, which is referred to as an emission spectrum, is dependent on temperature. The higher the temperature of the source, the greater will be the emission of high energy photons; i.e., photons of high frequency or low wavelength. The wavelength at which a body radiates most strongly, i.e., λ_{max} is given by Wiens law:

$$\lambda_{max} T = 2898\ \mu mK$$

So as a body cools, its emission spectrum shifts in the direction of longer wavelengths.

The sun emits short wavelength infrared, visible and ultraviolet radiation, while the earth emits long wavelength infrared radiation. The graphs of Figure 1 show the emission spectra of bodies at different temperatures.

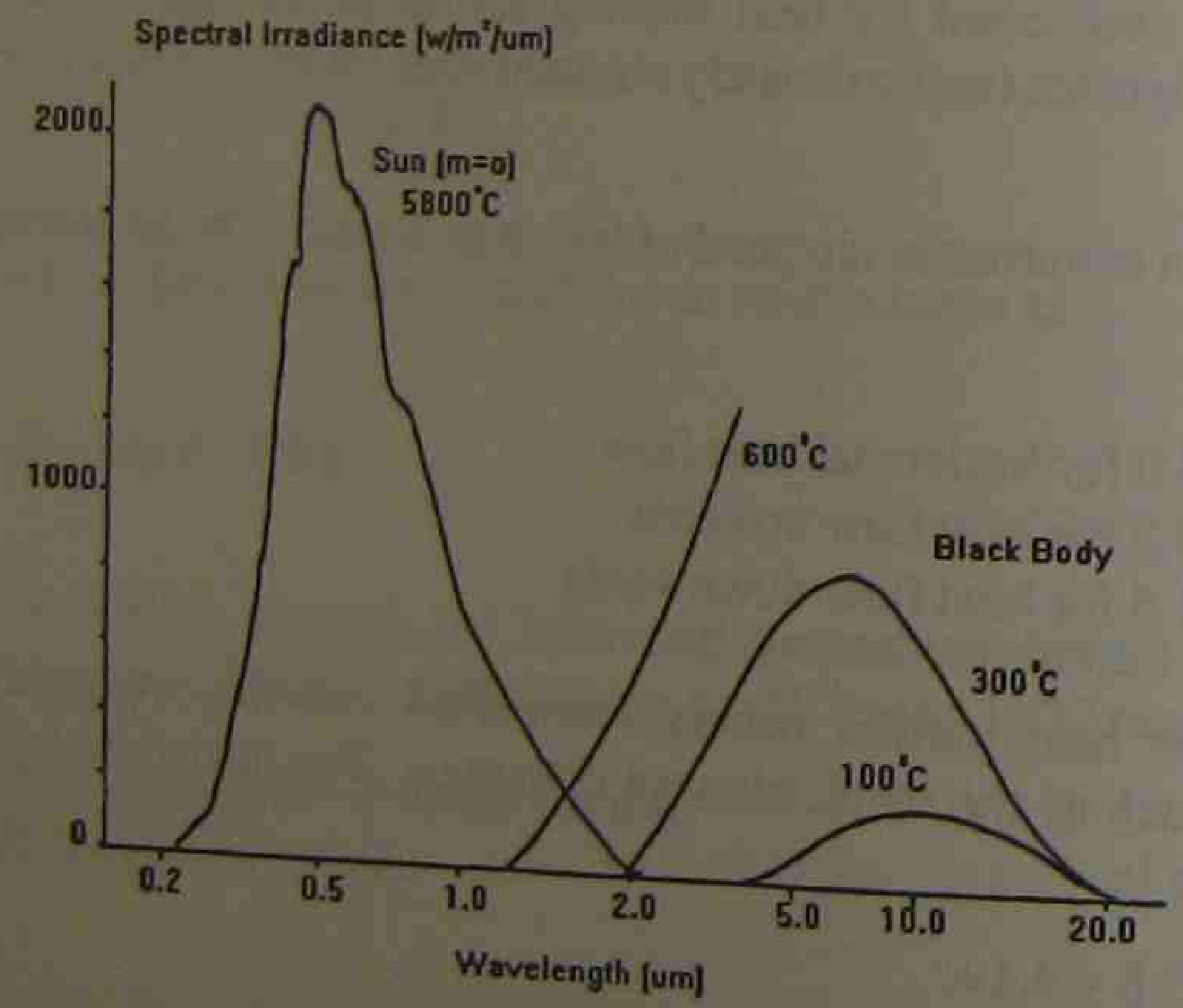


Figure 1 - The emission spectra of bodies at different temperatures.

A **black body** is a body or surface that absorbs all the radiant energy incident upon it and emits the maximum possible amount of thermal radiant energy for a body at that temperature.

The **emissive power** of a black body depends only on its temperature and is described by the Stefan - Boltzmann law.

$$P_r = \sigma A T^4$$

where σ - Stefan-Boltzmann constant ($5.7 \times 10^{-8}\ W/m^2K^4$)
A - surface area (m^2)
T - temperature (K)

Optical properties of surfaces, such as emittance, absorptance and reflectance are wavelength dependent. Often the wavelength range is not stated. Emittance generally refers to long wavelength properties of a material, i.e., its ability to emit heat. Absorbtance generally refers to short wavelength properties, i.e., the ability to absorb light.

Emittance (ε), is a measure of the ability of a surface to radiate. It is the ratio of the thermal radiation emitted from a surface to that emitted by a black body (perfect radiating body) at the same temperature. The thermal emittances of some common building materials are shown in Table 2.

material	emittance
copper (bright)	0.03
aluminium (foil)	0.05
galv. iron (oxidized)	0.28
granite	0.44
white paint	0.90
black paint	0.90
lamp black	0.98

Table 2 - Emittances of some common building materials.

Reflectance (ρ), is a measure of the ability of a surface to reflect radiation. It is the ratio of the thermal radiation reflected from a surface to that which falls on it. The reflectance of surfaces over a range of wavelengths, from shortwave light to longwave heat is shown in Figure 2.

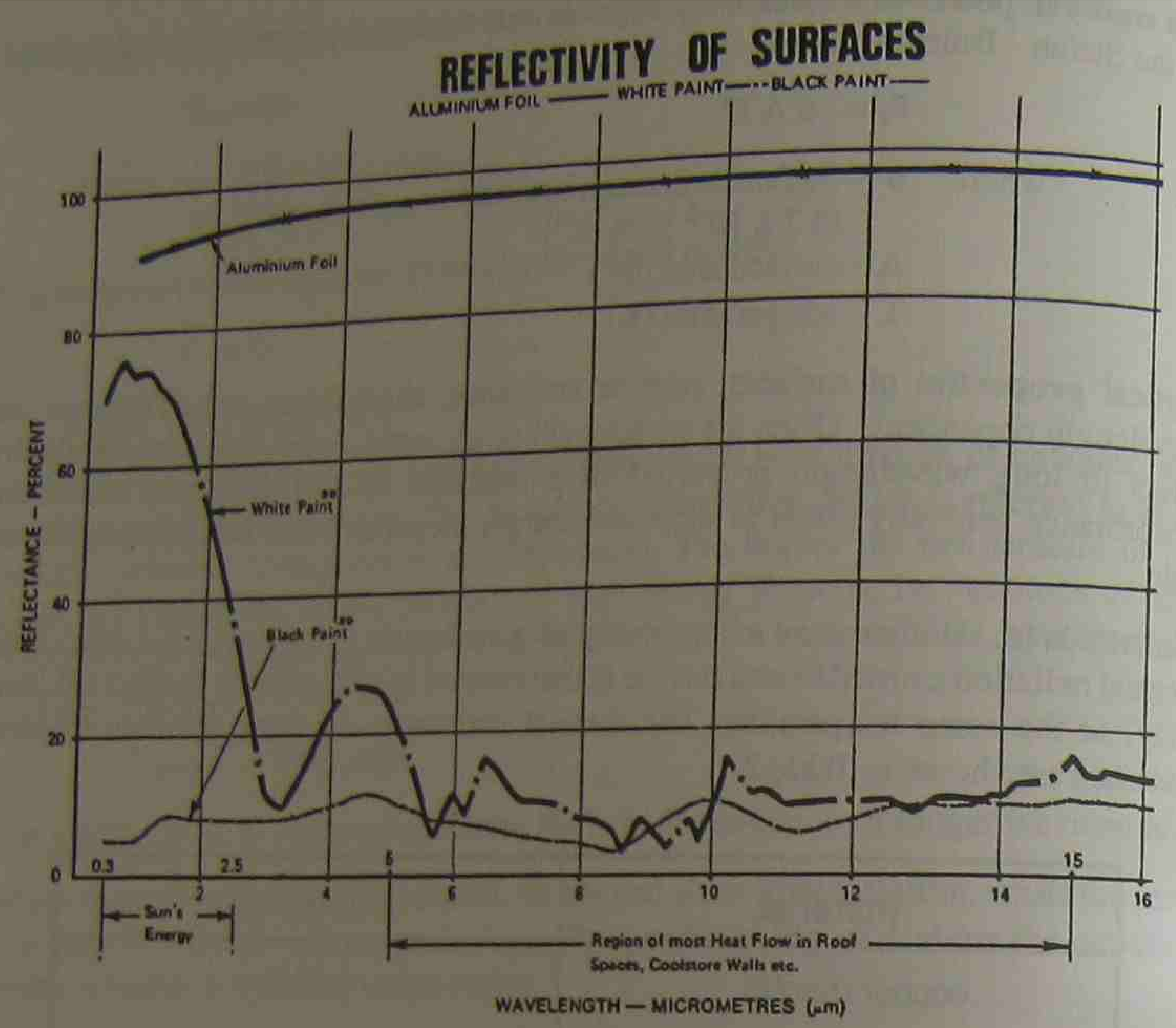


Figure 2 - Reflectance of surfaces as a function of wavelength. (Source: Hassell, 1977).

Absorptance (α), is a measure of the ability of a surface to absorb radiation. It is the ratio of the thermal radiation absorbed by a surface to that absorbed by a black body (perfectly absorbing body) at the same temperature. The solar absorptances of some common building materials are shown in Table 3.

material	absorptance
copper (bright)	0.2
aluminium (bright)	0.15
galv.iron (oxidized)	0.8
white paint	0.3
black paint	0.9

Table 3 - Solar absorptances for some common building materials.

The optical properties of materials, emittance, absorptance and reflectance as they are used here refer to the total value when summed over all the wavelengths over which the radiation acts. Solar absorptance for example refers to the ability of a surface to absorb all the radiation wavelengths of the sun's emission spectrum.

Note that many texts dealing with the thermal properties of materials confuse the suffixes *-ivity* and *-ance*. The convention that should be used is that for a pure material, with an optically smooth surface, the intrinsic properties are referred to as emissiv*ity*, absorptiv*ity* and reflectiv*ity*. All other optical properties of materials are referred to as either emitt*ance*, absorpt*ance* or reflect*ance*.

The rate of heat radiation transfer between a small object (1) at temperature T_1 to a large surrounding black body enclosure (2) at temperature T_2 is derived from the Stefan-Boltzmann relation:

$$P_{rad} = \sigma \varepsilon A (T_1^4 - T_2^4)$$

where σ - Stefan-Boltzmann constant (5.7×10^{-8} W/m^{2}K^4)
ε - emittance of surface
A - surface area of object 1 (m^2)

The rate at which an object absorbs solar radiation is given by:

$$P_A = \alpha A G$$

where α - absorptance
A - surface area (m^2)
G - irradiance (W/m^2)

The equations for radiation gain from the sun and radiation loss to the environment use total integrated values of α and ε. The reflectance of an opaque material at a specific wavelength λ is given by:

$$\rho\lambda = 1 - \alpha\lambda$$

and $$\alpha\lambda = \varepsilon\lambda$$

These relationships are true at each wavelength, so the equations:

$$\rho_{solar} = 1 - \alpha_{solar}$$

and $$\alpha_{thermal} = \varepsilon_{thermal}$$

are only true for total integrated values for the spectral distribution for which the measurements were made.

Many materials behave differently as thermal emitters of long wavelengths than as solar absorbers of shorter wavelengths. Hence for these materials:

$$\alpha_{solar} \neq \alpha_{thermal}$$

This is illustrated by the graphs of Figure 2. Aluminium foil and black paint are both examples of materials that behave in a similar way over a relatively large wavelength range, where:

$$\rho_{solar} \approx \rho_{thermal}$$

so, $\alpha_{solar} \approx \varepsilon_{thermal}$

White paint however, behaves quite differently. This is because the short wavelength or solar properties of a material are determined by the pigment, which is quite different for black and white paint. The long wavelength or thermal properties depend on the binder, which in the case of paint is similar.

So if a building material that reflects both light and heat, and emits little heat is required aluminium could be used. If the material is to absorb a lot of sunlight but also emit heat fairly rapidly black paint could be used. If the required properties are to reflect sunlight but emit heat fairly rapidly white paint could be used. Figure 3 compares the solar and far infrared characteristics of some building materials.

The heat flow rate for radiation is derived from the Stefan-Boltzmann relation for a small object radiating to a surrounding surface and can be approximated to:

$$P_{rad} = h_r \, A \, \Delta T$$

where h_r - radiation heat transfer coefficient in (W/m^{2}K)
- depends on temperature and emittance
- 5.4 x ε for a surface of emittance, ε at 20°C radiating to an air temperature of 10°C

ΔT - temperature difference

A - area of the object

3.5 Surface Conductance

Combining all heat losses from a surface at temperature T_s to the air at temperature T_a the total heat flow rate is obtained as:

$$P_{Total} = P_{cond/conv} + P_{rad}$$

$$= (h_c + h_r) \; A \; \Delta T$$

where $h_c + h_r$ - surface conductance

$\Delta T = T_s - T_a$

When a building loses heat via conduction and convection it does so to the air and thus the air temperature, T_a is used in the equation for ΔT. However, when a building loses heat via radiation from the roof it does so to the sky. The walls lose heat to the sky and the ground. The ground can be assumed to be at air temperature. The sky temperature can be found from:

$$T_{sky} = 0.0552 \, T_a \times 1.5$$

Making the approximation that $T_{sky} = T_a$ underestimates the heat loss but simplifies calculations.

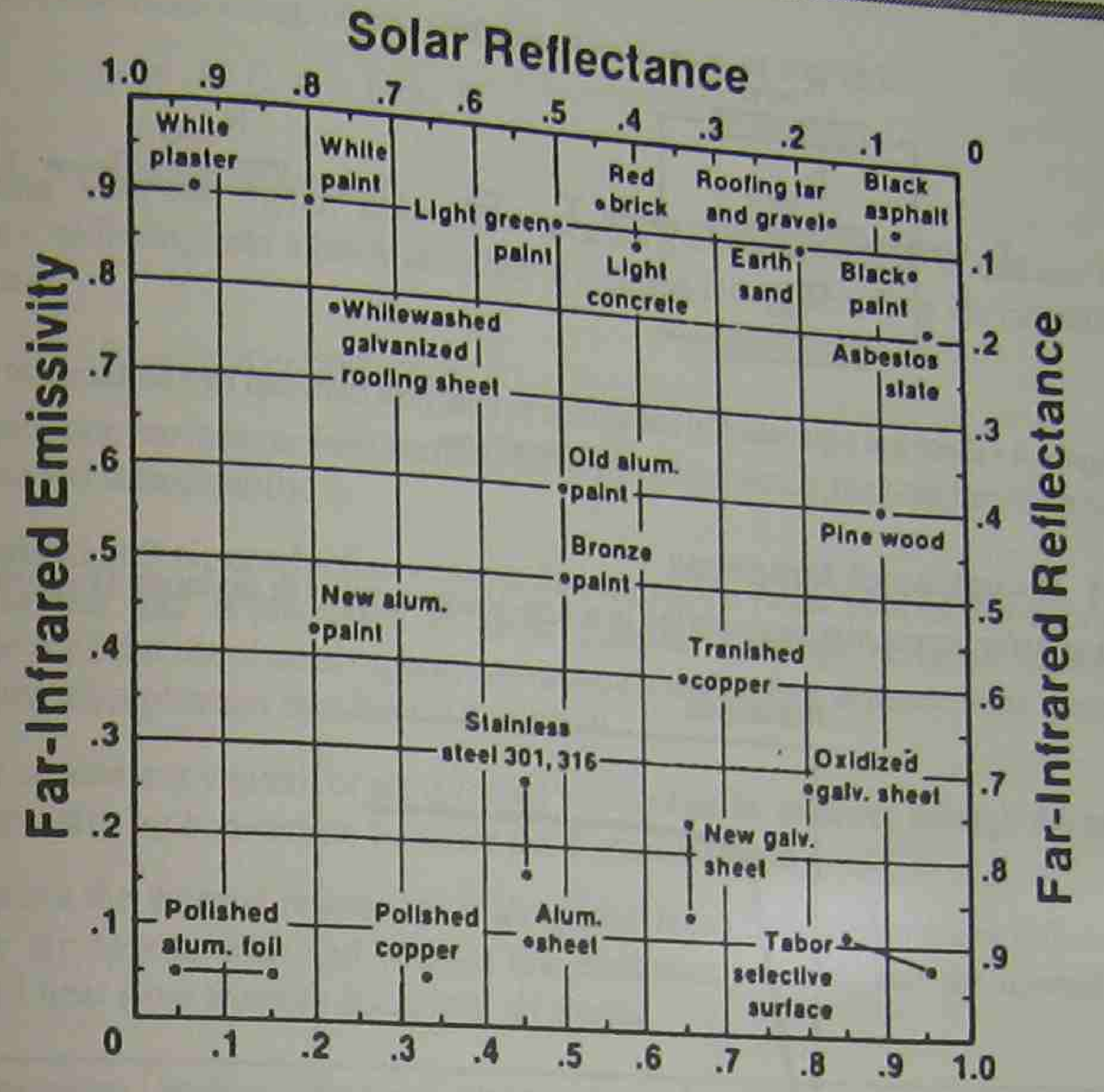


Figure 3 - Solar and far infrared characteristics of some building materials. (Source: Florida Solar Energy Centre).

4 HEAT LOSS OR GAIN THROUGH BUILDING SECTIONS

The heat loss or gain through a building element is determined by:

- ☐ the area of the element
- ☐ the air speed on either side of the element
- ☐ the resistance to heat flow of the element as determined by the materials and air spaces making up the element.

If either side of the element is absorbing heat from a radiant source, or is radiating heat to a temperature other than air temperature then a correction factor is used to determine an effective air temperature.

4.1 R - values

The resistance to heat flow between two surfaces at different temperatures is a parallel combination of radiation, conduction and convection. The relatively small range of temperatures to which buildings are subject allow these three resistances to be combined as a single resistance, often known as the R-value. Figure 4 shows the electrical equivalent of these thermal resistances.

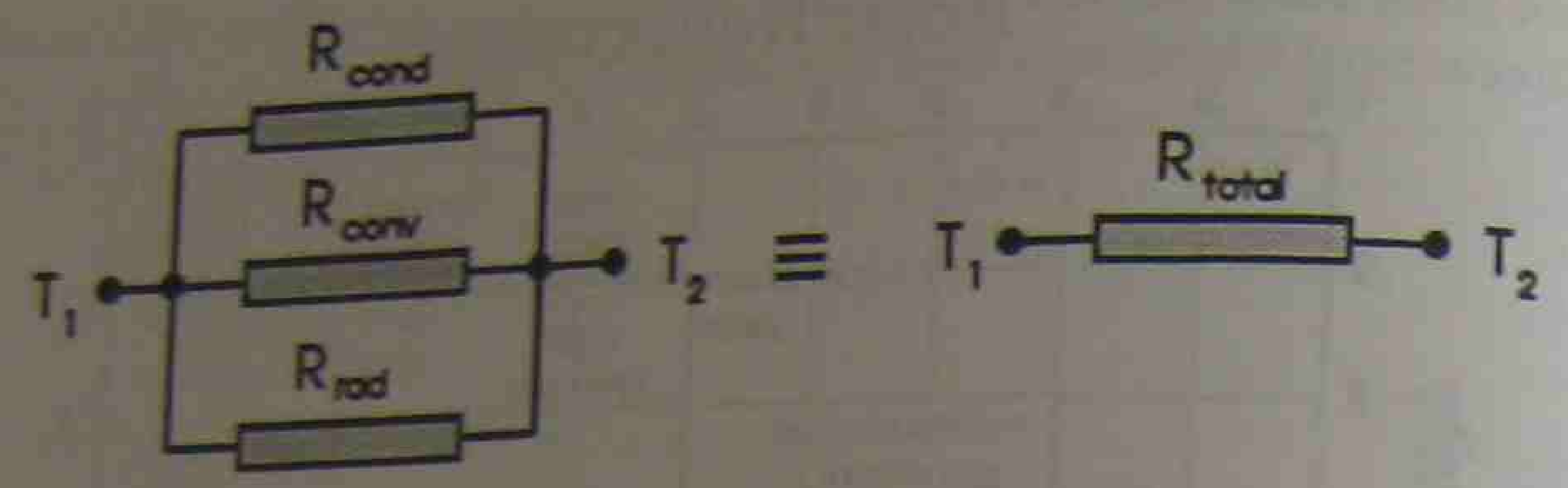


Figure 4 - Electrical equivalent of resistance to heat flow between two surfaces at different temperatures.

4.1.1 R - values of Airspaces

Heat transfer across airspaces varies in a non-linear way with distance (Figure 5).

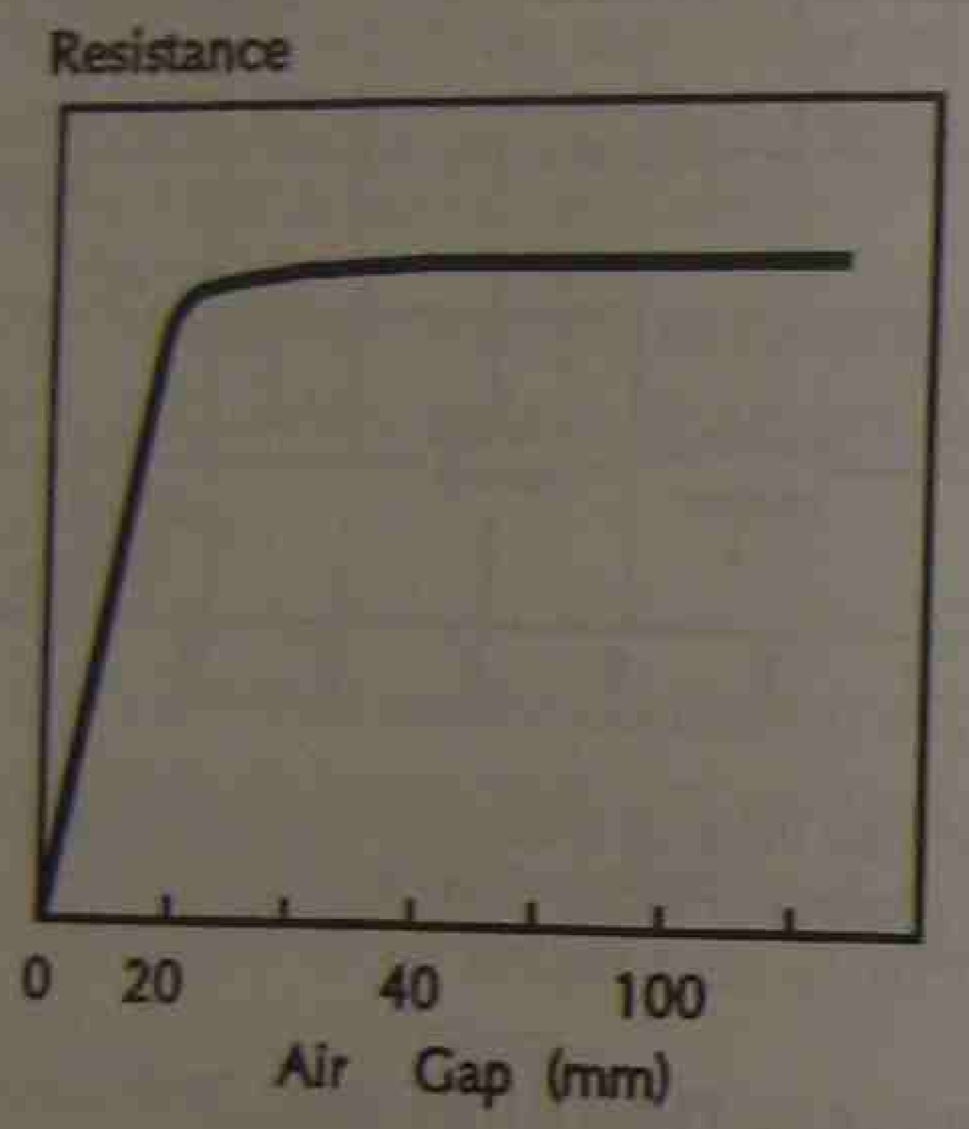


Figure 5 - Graph of heat transfer across an airspace versus air gap width.

The radiation component of heat transfer across an air gap depends on the emittances of the surfaces on either side (Figure 6).

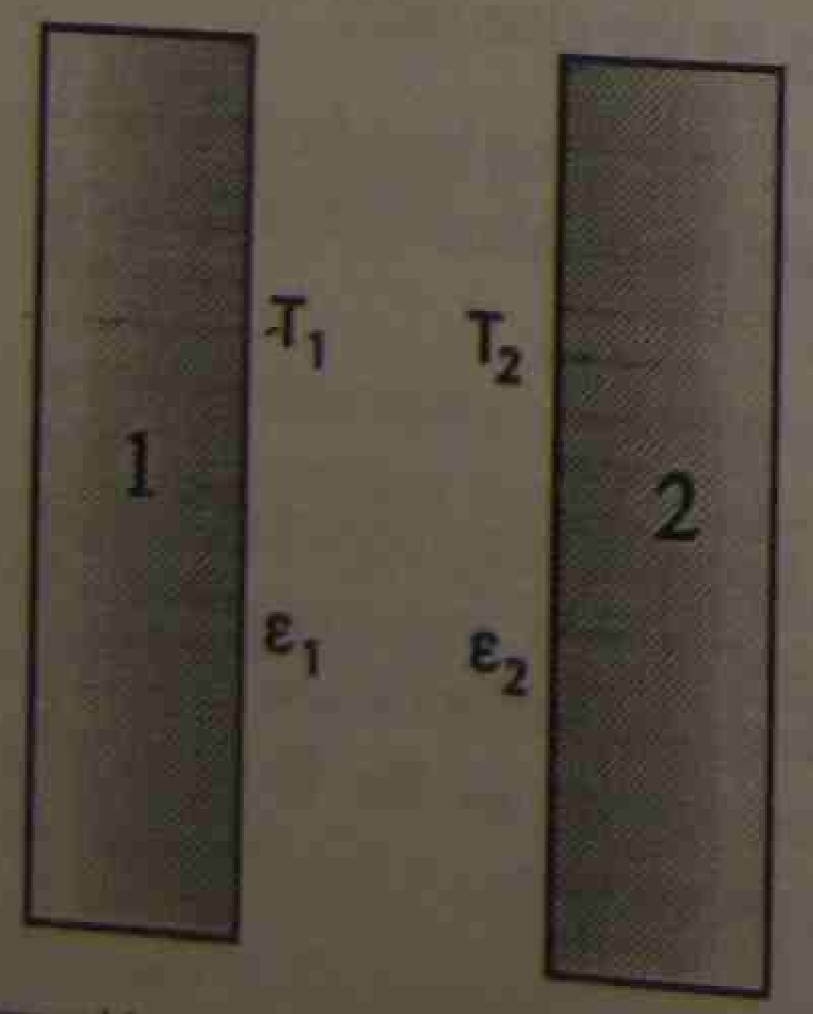


Figure 6 - Air gap formed by two surfaces with temperatures and emittances of T_1, ε_1 and T_2, ε_2 respectively.

The effective emittance (ε_f), of two surfaces of emittance ε_1 and ε_2 is:

$$\varepsilon_f = 1 / (1/\varepsilon_1 + 1/\varepsilon_2 - 1)$$

Substituting into the Stefan Boltzmann relation (which considers a surface with emittance ε radiating into a black absorber (ε =1), the rate of heat flow via radiation is obtained as:

$$P = \sigma A \varepsilon_f (T_2^4 - T_1^4)$$

When either one surface, or both surfaces have a low emittance, the heat flow across the gap is reduced significantly.

The combined still air conduction - convection resistance varies from zero to a constant amount as the gap is increased to about 100mm. Although radiation transfer is independent of the tilt of an air space, convection transfer does depend on the direction of heat flow except when that flow is horizontal.

When air spaces are vented, or air is forced to circulate in, or move through the space, the heat transfer by convection becomes the dominant factor.

Table 4 gives the thermal resistances of air spaces. It can be seen that major differences occur for air spaces with and without low emittance surfaces, and for upward and downward heat flow through horizontal air spaces.

Nature of bounding Surfaces	Position of airspace	Direction of heat flow	Resistance ($m^2 . K/W$)	
			20 mm width	100 mm width
High emittance surfaces	Horizontal	Up	0.15	0.17
		Down	0.15	0.17
	45° Slope	Up	0.17	0.17
		Down	0.15	0.16
	Vertical	Horizontal	0.15	0.16
One surface of low emittance	Horizontal	Up	0.39	0.48
		Down	0.57	1.42
	45° Slope	Up	0.49	0.53
		Down	0.57	0.77
	Vertical	Horizontal	0.58*	0.61
Two surfaces of low emittance	Horizontal	Up	0.41	0.51
		Down	0.63	1.75
	45° Slope	Up	0.52	0.56
		Down	0.62	0.85
	Vertical	Horizontal	0.62*	0.66

* For vertical airspaces greater than 20 mm, with horizontal heat flow, the value of resistance for 100 mm should be used.

Table 4 - Thermal resistance of air spaces. (Source: AIRAH handbook, 1989).

Any vertical building elements which contain air spaces such as walls, doors and double glazed windows will have the same resistance value for air spaces with similar mean temperatures irrespective of heat flow direction. So the same R- value is used for summer or winter. However, floors or roofs incorporating air spaces must be assigned different values depending on whether summer or winter conditions exist. The resistance to heat flow down is more than for heat flow up. This difference is accentuated when the radiative heat flow component is reduced by using low emittance surfaces such as aluminium foil.

This appears to be contradicted by the tables for air spaces with high emittance surfaces; However, the resistance of an air space increases as the temperature decreases, and the values for heat flow up are for winter conditions with an average air space temperature of 10°C and the heat flow down values are for summer conditions with an average air space temperature of 30°C.

Clearly, these values which are fairly accurate for ceilings, will show a greater error for floors where the heat flow is in the opposite direction. Similarly, for vertical air spaces the winter resistance would be slightly greater than for summer. However, reasonable accuracy can be obtained with the simplified tables shown.

Reflective foil insulation in its basic form is just building paper with one or both sides coated with aluminium foil. Placing reflective foil within an air space effectively creates two air spaces. If the foil is double sided then each air space will have one low emittance surface. The thermal resistance of an air space with a low emittance surface on one side will increase between two and eight times, depending on its slope and the direction of heat flow. So creating two such air spaces can significantly reduce heat transfer. In practice, the top surface of horizontal or sloped reflective foil will eventually be covered by a layer of dust which will effectively turn it into a high emittance surface. For this reason the upper air space formed by a low emittance surface is regarded as having a lower surface of high emittance. Only when double sided foil is used in a vertical plane can both sides be considered to have a low emittance in the longer term.

4.1.2 R-values of Pitched Roof Spaces

Roof spaces formed by a pitched roof with a flat ceiling cannot be treated as an ordinary air space. Table 5 lists some experimentally found thermal resistances for these spaces.

	Direction of heat flow	Resistance ($m^2 . K/W$)	
		Heat emittance surfaces	Low emittance sarking
Ventilated roof space	Up	0.11	0.34
	Down	0.46	1.36
Non-ventilated roof space	Up	0.18	0.56
	Down	0.28	1.09

Table 5 - Thermal resistance of pitched roof spaces. (Source: AIRAH handbook, 1989).

Clearly, pitched roof spaces are more effective in retarding heat flow into the building in summer than they are in keeping heat in the building in winter. Ventilated spaces are more effective than non ventilated spaces in summer and less effective than non ventilated spaces in winter. Roof spaces which have reflective sarking under the roofing material are at least three times more effective in providing thermal insulation than roof spaces where it is not installed.

Tiles, shingles or similar types of roofing material allow the wind to penetrate easily into the attic space or between the sarking, if installed, and the tiles. For this reason, if sarking is present, the air gap between it and the tiles is given a thermal resistance of zero for calculation purposes. If sarking is absent, the roof space is treated as being fully ventilated.

4.1.3 R-values of Bulk Materials

Bulk materials have R-values directly proportional to their thickness. For example the resistance to heat flow of 3 bricks is 3 times the resistance of 1 brick, (Figure 7).

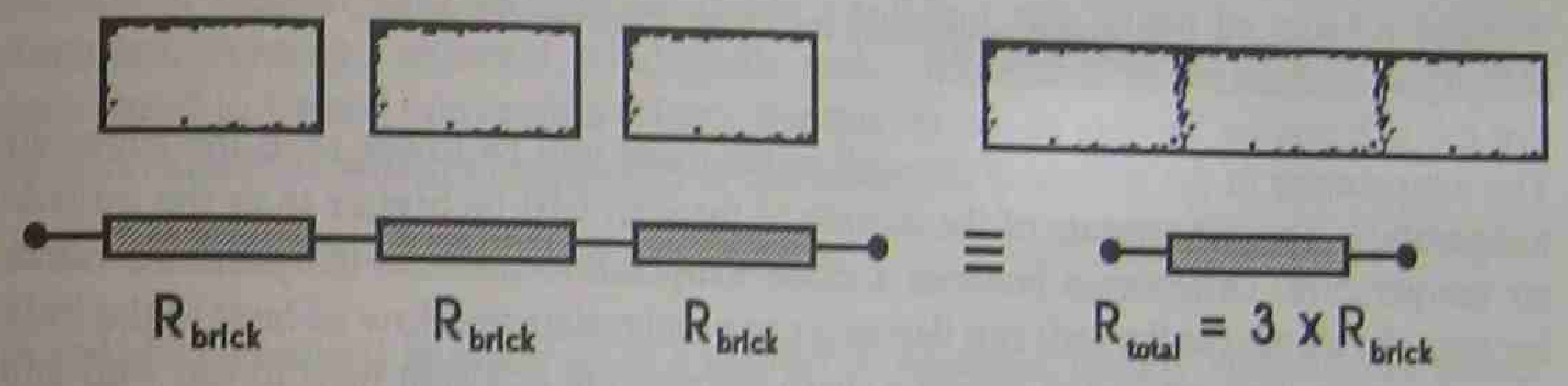


Figure 7 - The resistance to heat flow of three bricks is three times the resistance of one brick.

R-values of materials of a particular thickness can be found in table form in a variety of handbooks. If an unlisted thickness is required, the R-value can be calculated from the conductivity:

$$R = d/k$$

as is outlined in section 3.2.

4.1.4 R-values of Surfaces (Internal and External)

Consider a wall which partitions the inside and outside of a building. If the outside air temperature is lower than the inside then heat will flow down the temperature gradient from the inside to outside (Figure 8).

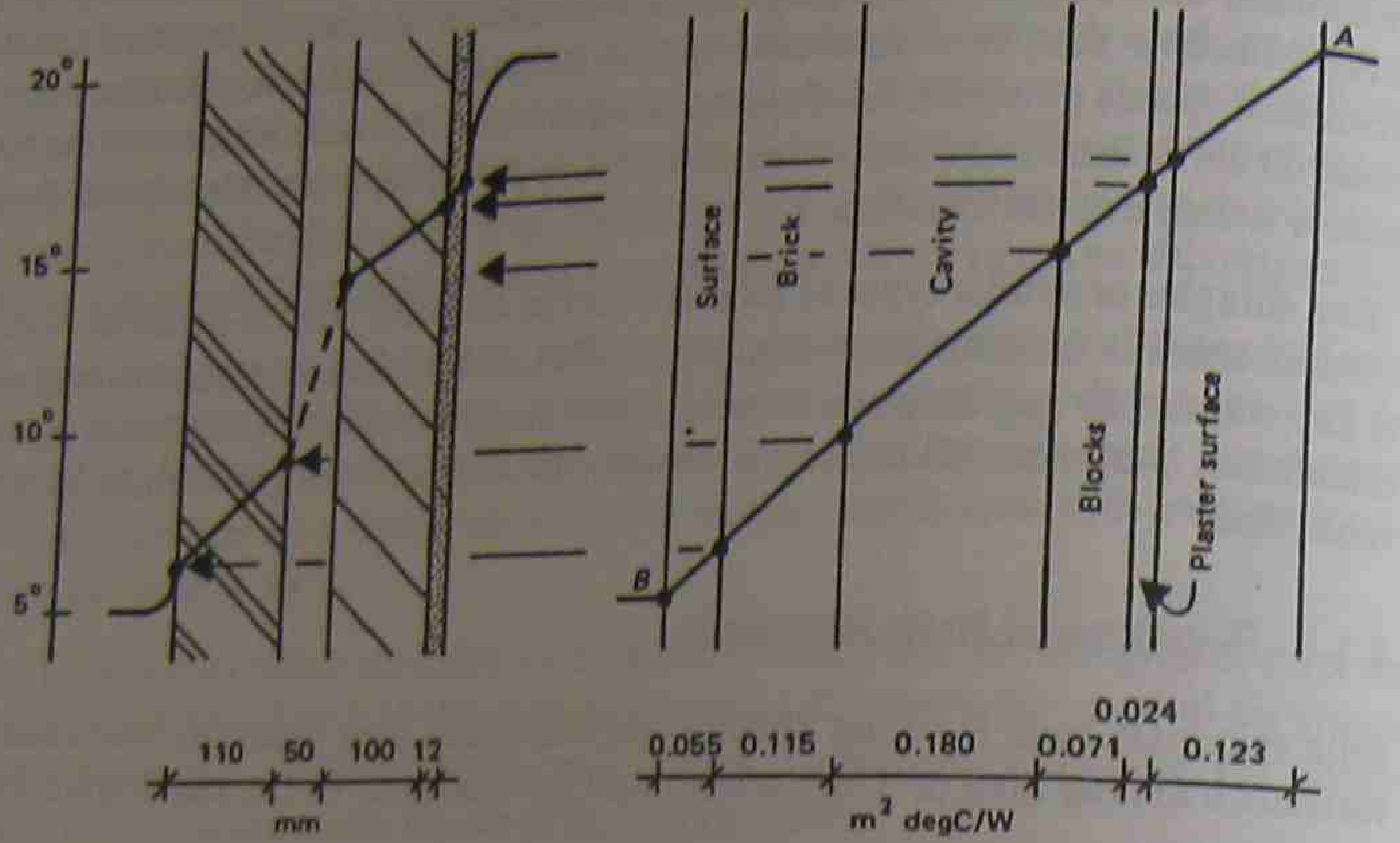


Figure 8 - Temperature gradient for a wall. (Source: Szokolay, 1980).

The temperature of the surface of the wall in the room will be lower than the room air temperature. The temperature of the outside of the wall will be higher than the outside air temperature. Differences between surface temperature and air temperature occur because the air next to the wall acts like an air gap and resists the flow of heat to the bulk of ambient air. This resistance causes a sharp temperature gradient next to the wall and is treated as an air film effect which is commonly referred to as an air film resistance.

The air film resistance is dependent on the emittance of the surface, the direction of heat flow (for all but vertical surfaces) and the amount of air movement next to the surface. If air movement is forced past the surface (eg. wind outside, fans inside) the heat losses are dominated by the forced convection coefficient (h_c), which is independent of heat flow direction. This factor is usually used on its own to determine the surface resistance if the air speed is greater than about 5m/s:

$$R_o = 1/h_c$$
$$= 1/(5.8 + 4.1v)$$

where v - air speed (m/s)

Table 6 shows the surface resistance for still air, R_i (inside surfaces of buildings) and for moving air R_o (outside surfaces of buildings).

Clearly, low emittance surfaces offer better insulating properties in still air conditions. However, in practice nearly all common building surfaces have a high emittance of about 0.90. The exceptions are aluminium, galvanised iron and aluminium paint which have values of 0.11, 0.28 and 0.50 respectively (when they have been out in the weather for a time).

Wind Speed (m/s)	Position of Surface	Direction of heat flow	Resistance (m^2.K/W)	
			High emittance surface	Low emittance surface
Still air	Horizontal	Up	0.11	0.23
		Down	0.16	0.80
	45° Slope	Up	0.11	0.24
		Down	0.13	0.39
	22.5° Slope	Up	0.11	0.24
		Down	0.15	0.60
	Vertical	Horizontal	0.12	0.30
6	Any position	Any direction	0.03	
3	Any position	Any direction	0.04	

Table 6 - Surface resistances. (Source: AIRAH handbook, 1989).

Although still air can be expected inside a building, this would be rare for external surfaces. Average external windspeeds make differences in emittances negligible compared to forced convection effects. For this reason, an external air speed of 3.5 m/s is often selected which corresponds to a resistance of 0.04 m^2K/W.

4.2 U-values of Building Sections

A building element is made up of a number of materials, usually including air spaces. The wall shown in Figure 9 can be represented by a number of thermal resistances, including inside and outside air film resistances. This is equivalent to having a single resistance, R_T, equal in value to the sum of the individual resistances.

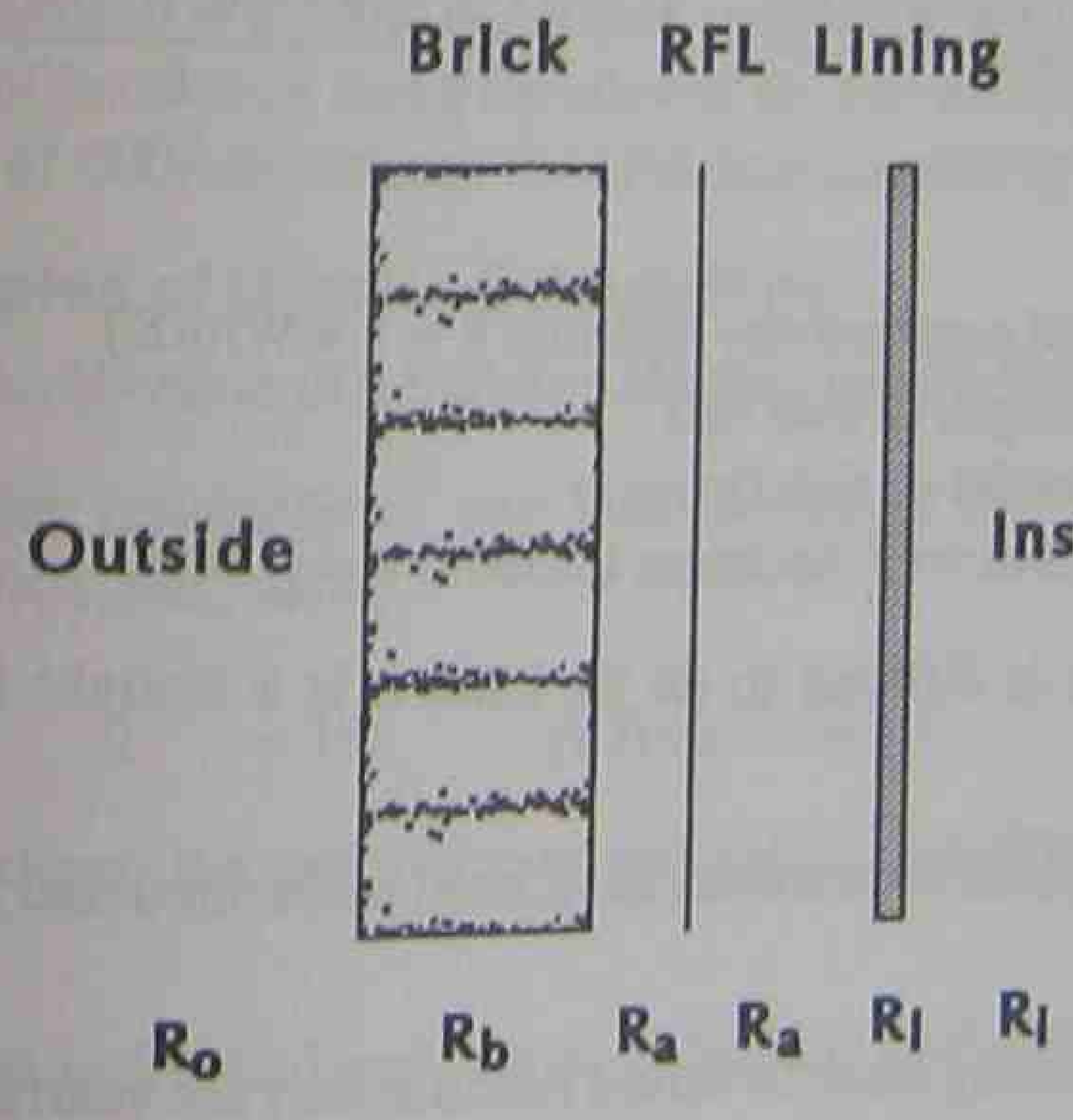


Figure 9 - Various thermal resistances for a brick veneer wall with reflective foil insulation.

The overall heat transfer coefficient, or U-value, is calculated from this resistance:

$$U = \frac{1}{R_T}$$

$$= \frac{1}{R_o + R_b + R_a + R_a + R_l + R_i}$$

where U - overall heat transfer coefficient or U-value (W/m^2K)
R - resistances of materials, air gaps or surfaces (m^2K/W)

The U-value gives the rate of heat transfer through a particular building element of 1 m^2 area with a temperature difference across it of 1K.

4.3 U-values of Concrete Slabs on Ground

Concrete slabs when laid on soil must be treated differently to other building elements when calculating U-values.

Concrete slabs have nearly all of their external surfaces in contact with the soil, and so will not lose or gain heat to air temperature but to soil temperature. The earth under a slab is cooler than the mean air temperature in summer and is warmer than the air in winter. So the heat transfer in and out of the slab on ground is considerably less than heat transferred by a suspended concrete slab. This results in the majority of heat losses occuring from the edges of the slab to the air. Since U-values are measures of heat transfer per unit area, the total heat loss per °C temperature difference must be calculated first and then divided by the area to give the U-value. To do this the dimensions of the slab must be known. A rather complex looking equation which calculates all of this is:

$$U = \frac{k}{\pi ab}\left\{a \ln\left(\frac{4a}{v}\right) + b \ln\left(\frac{4b}{v}\right) + 2\,(a^2 + b^2)^{1/2} - a - b\right.$$

$$\left. - b \ln\left[\frac{(a^2+b^2)^{1/2} + b}{a}\right] - a \ln\left[\frac{(a^2+b^2)^{1/2} + a}{b}\right]\right\}$$

where k - ground conductivity (assume k = 1.4 W/mK)
a - half length of slab (m)
b - half width of slab (m)
v - effective wall thickness (assume v = 0.3m) .

Although this calculation is difficult to do by hand it is a straight forward computer calculation.

Some calculations for specific dimensions have been performed and are included in Table 7.

Care must be taken when using these U-values because they are yearly averages and may not be completely accurate for any particular month.

Floor dimensions (m)	Floor U-value (W/m^2K)
100 x 100	0.099
100 x 60	0.125
100 x 40	0.156
100 x 20	0.239
60 x 60	0.149
60 x 40	0.178
60 x 20	0.259
60 x 10	0.397
40 x 40	0.206
40 x 20	0.282
40 x 10	0.416
40 x 6	0.579
20 x 20	0.350
20 x 10	0.472
20 x 6	0.632
20 x 4	0.795
10 x 10	0.576
10 x 6	0.731
10 x 4	0.884
10 x 2	1.268
6 x 6	0.855
6 x 4	0.996
6 x 2	1.355
4 x 4	1.126
4 x 2	1.462
2 x 2	1.751

Table 7 - Theoretical calculations of the steady state heat losses through a slab-on-ground floor.

Studies of the effects of edge insulation on heat transfer from slabs suggest that 25mm of vertical insulation to a depth of 150mm reduces the total flow by between 17 and 22%. Using 50mm of insulation along the edge of the slab and then horizontally under the slab for a distance of 600mm reduces the total heat transfer by 32 to 37%.

4.4 Examples of U-value Calculations

To calculate the U-value of a building element use the following steps:

(i) Find the resistance of any bulk materials, such as brick, glass, wood, bulk insulation, etc., using:

$R = 1/k$ (k from Table 1)

(ii) Write down the resistance of individual elements using (i) and the resistance tables.

(iii) Sum the individual resistances to find the total resistance R_T.

(iv) Find the U-value using:

$U = 1/R_T$

Example 1: U-value calculation
on the outside of the frame (Figure 10).

Use the following:
thickness of bricks = 110mm
air gap adjacent to bricks = 20mm
air gap adjacent to plasterboard = 100mm
thickness of plasterboard = 10mm

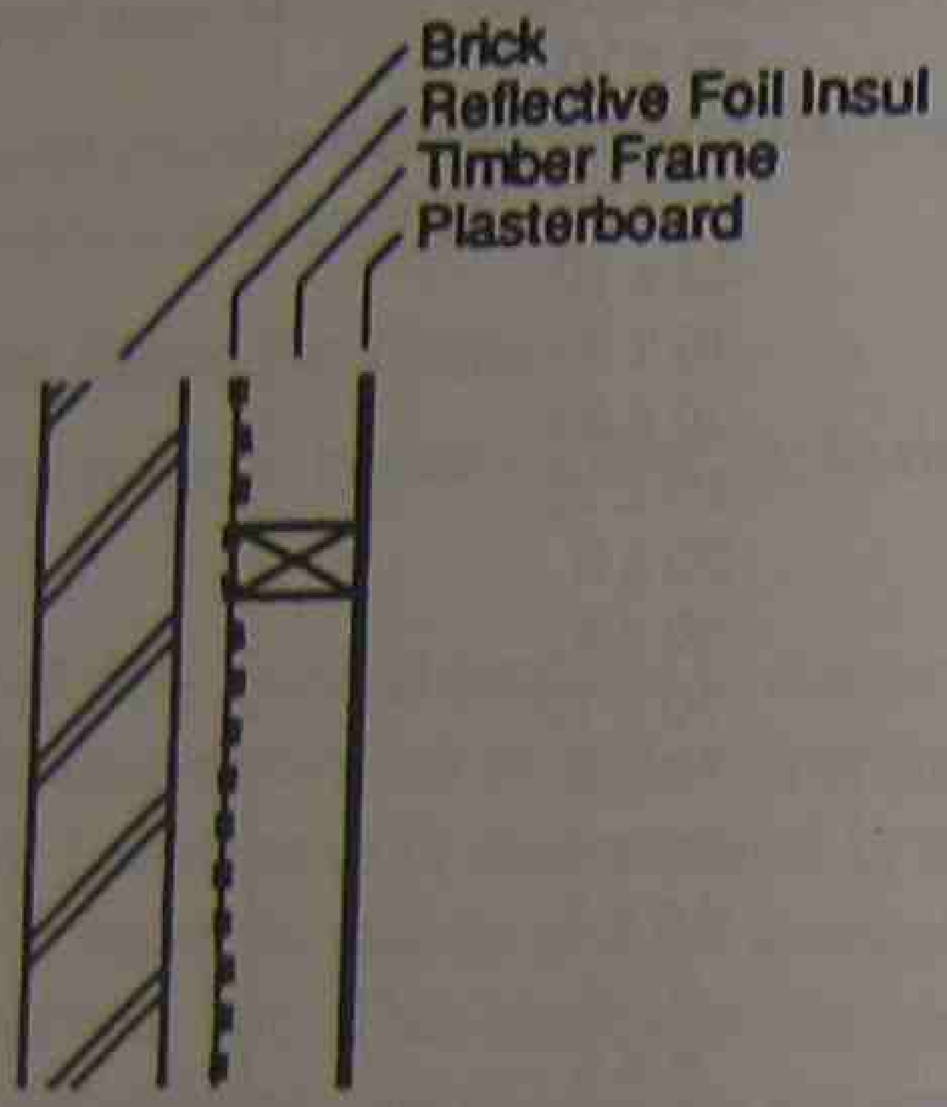


Figure 10 - Brick veneer with reflective foil insulation.

Procedure:

(i) Find the resistance of the bulk materials:

$R_{bricks} = d/k$
$= 0.11/1.15 = 0.10\ m^2K/W$

$R_{plaster} = d/k$
$= 0.01/0.17 = 0.06\ m^2K/W$

(ii) Write down resistance of individual elements from outside to inside:

ELEMENT	RESISTANCE	SOURCE
outside air film	0.04	Table 6
brickwork, 110mm	0.10	part (i)
air gap, 20mm, 1 side rfl	0.58	Table 4
air gap, 100mm, 1 side rfl	0.61	Table 4
plasterboard, 10mm	0.06	part (i)
inside air film	0.12	Table 6

(iii) Find total resistance; $R_T = 1.51\ m^2K/W$

(iv) Find the U-value:

$U = 1/R_T$
$= 1/1.51 = 0.66\ W/m^2K$

Example 2: U-value calculation for a pitched metaldeck roof with reflective foil insulation and raked ceiling with R1.5 bulk insulation (Figure 11).

Use the following:
thickness of steel = 1mm
air gap adjacent to metaldeck = 20mm
air gap adjacent to insulation = 20mm
thickness of plasterboard = 13mm

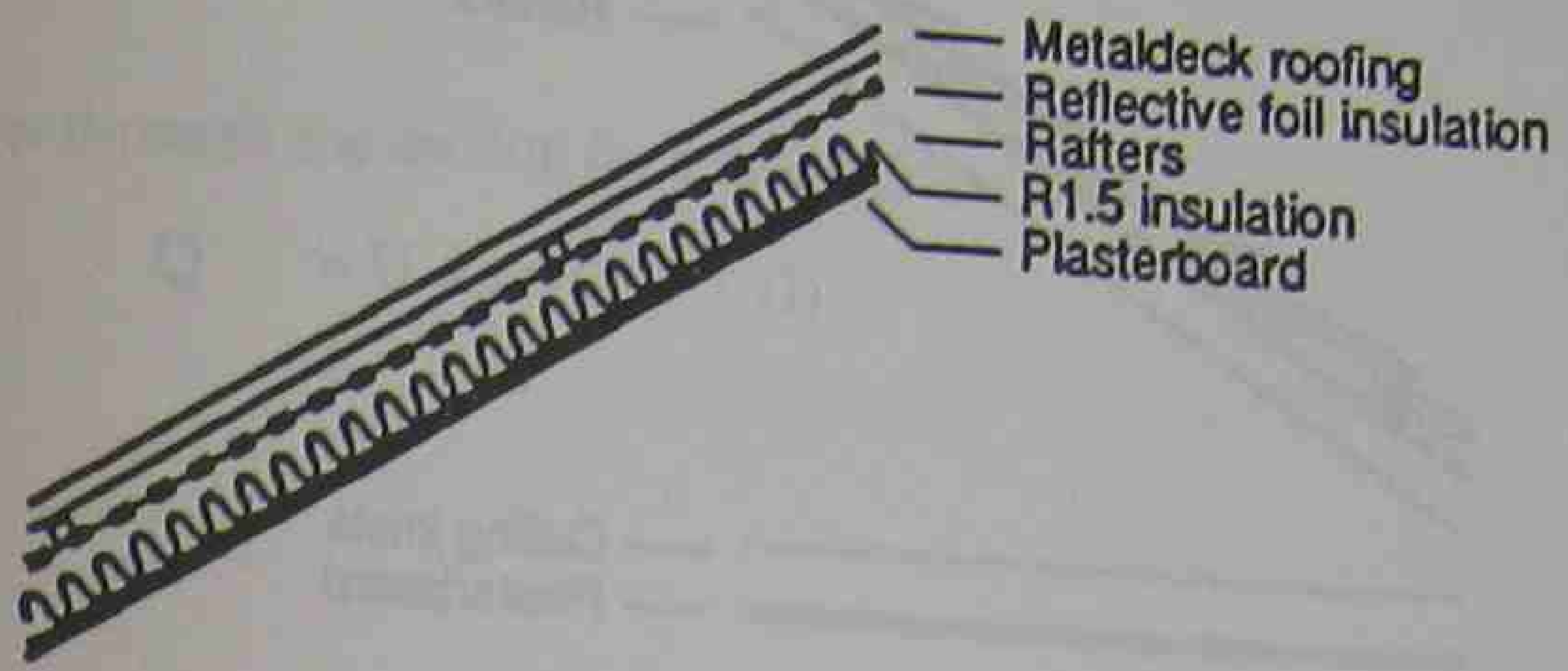


Figure 11 - Metaldeck roof with reflective foil insulation and raked ceiling with R1.5 insulation.

Procedure:

(i) Find the resistance of the bulk materials:

$R_{steel} = d/k$
$= 0.001/47.5 = 0.00002\ m^2K/W$

(As a result the resistance of a metal roof can always be taken as zero)

$R_{plaster} = d/k$
$= 0.013/0.17 = 0.08\ m^2K/W$

(ii) Write down resistance of individual elements for both summer and winter conditions from outside to inside:

ELEMENT	RESISTANCE		SOURCE
	SUMMER	WINTER	
outside air film	0.04	0.04	Table 6
steel, 1mm	0.00	0.00	part (i)
air gap, 20mm no rfl	0.15	0.17	Table 4
air gap, 20mm 1 side rfl	0.57	0.49	Table 4
insulation, R1.5	1.50	1.50	
plasterboard, 13mm	0.08	0.08	part (i)
inside air film	0.16	0.11	Table 6

(iii) Find total resistance; $R_T = 2.50$ $2.39\ m^2K/W$

(iv) Find the U-value:

U-value $= 1/R_T$
$= 1/2.50$ $= 0.40\ W/m^2K$ summer
$= 1/2.39$ $= 0.42\ W/m^2k$ winter

Example 3: U-value calculation for a pitched and vented tiled roof with reflective foil laminate under the tiles (Figure 12).

Use the following:
thickness of tiles = 19mm
thickness of plasterboard = 13mm

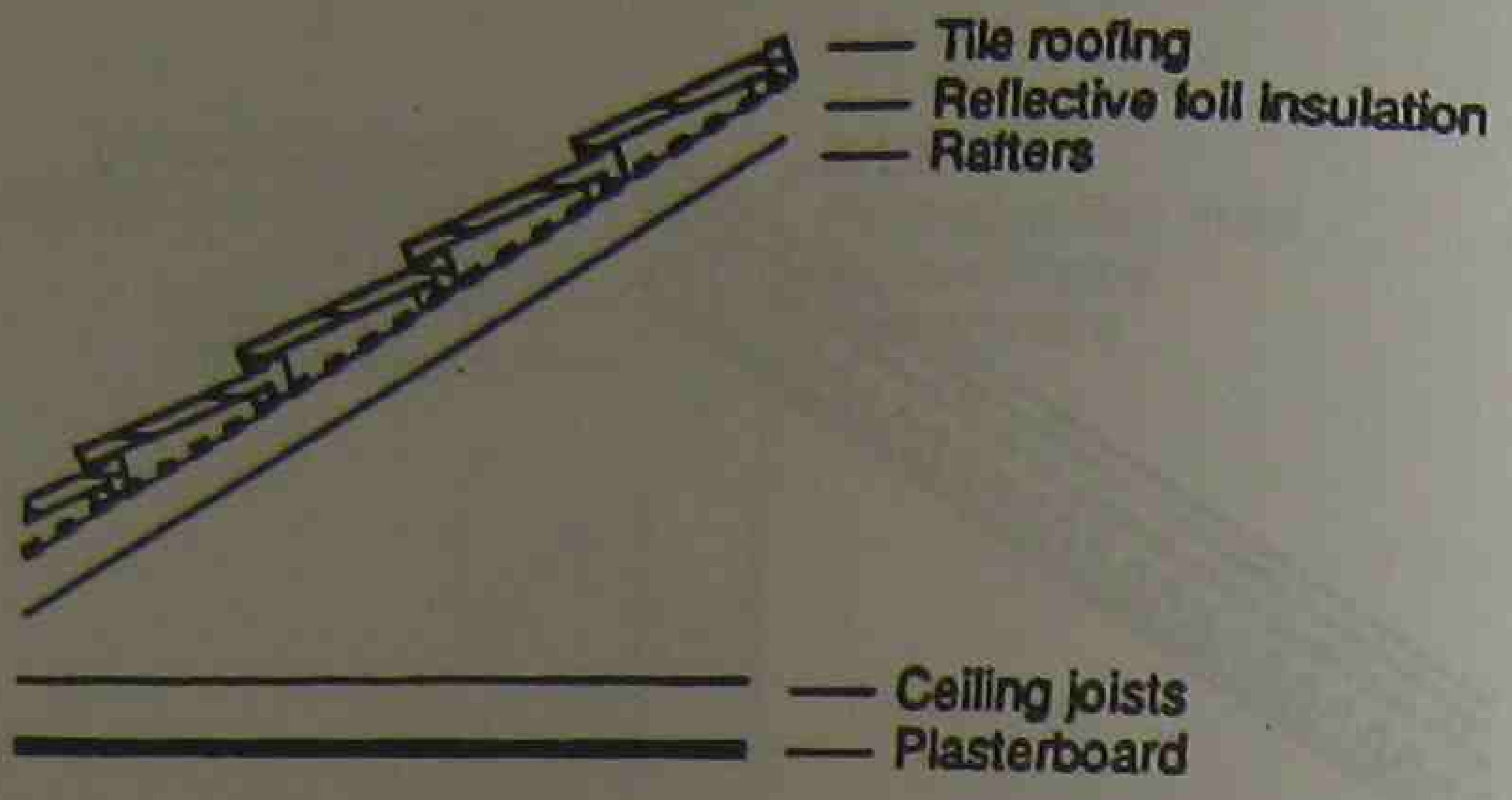


Figure 12 - Tiled roof with reflective foil insulation under tiles.

Procedure:

(i) Find the resistance of the bulk materials:

$$R_{tiles} = d/k = 0.019/0.81 = 0.02\ m^2K/W$$

$$R_{plaster} = d/k = 0.013/0.17 = 0.08\ m^2K/W$$

(ii) Write down resistance of individual elements for both summer and winter conditions from outside to inside:

ELEMENT	RESISTANCE SUMMER	RESISTANCE WINTER	SOURCE
outside air film	0.04	0.04	Table 6
tiles, 19mm	0.02	0.02	part (i)
roof cavity, vented, rfl	1.36	0.34	Table 5
plasterboard, 12mm	0.08	0.08	part (i)
inside air film	0.16	0.11	Table 6

(iii) find total resistance; $R_T = 1.66$ $0.59\ m^2K/W$

(iv) Find the U-value:

$$U\text{-value} = 1/R_T$$

$$= 1/1.66 = 0.60\ W/m^2K \quad \text{summer}$$

$$= 1/0.59 = 1.69\ W/m^2K \quad \text{winter}$$

The diagrams in the appendix show the U-values of common building elements. Values have been generated using the computer program UVAL, but they could easily be calculated using the method outlined above.

4.5 Total Heat Flow Rate

The total heat flow rate (loss or gain) through a building section of area A, with a heat transfer coefficient U for a temperature difference ΔT is:

$$P = U A \Delta T \quad (W)$$

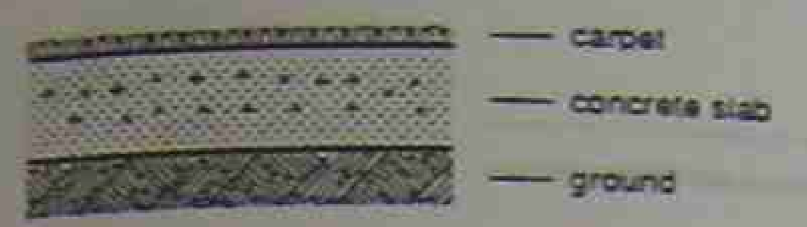
The heat flow through the section for a time t(s) is:

$$Q = U A t \Delta T \quad (J)$$

Appendix

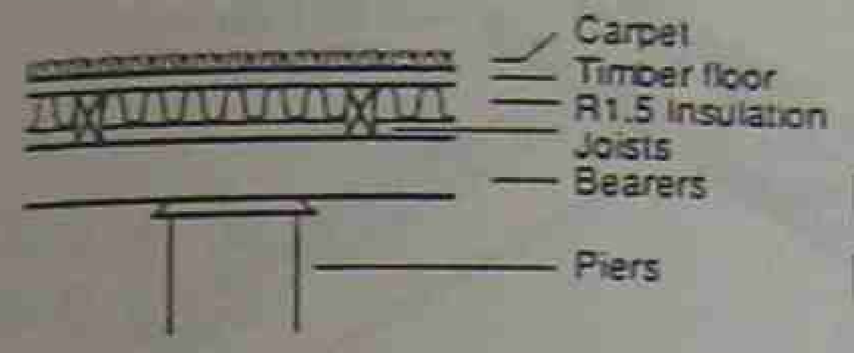
U-values of Building Elements

FLOOR DETAILS



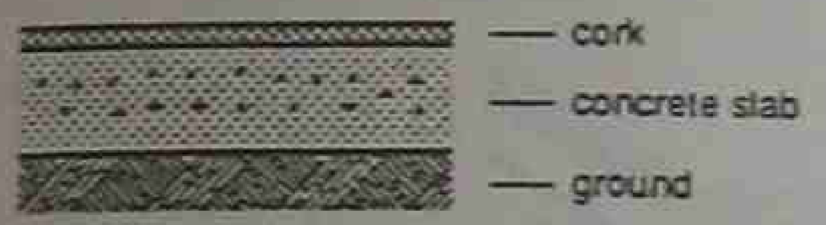
$U_i = 0.41$
$U_o = 0.40$

F 1 Carpet on a concrete slab on ground



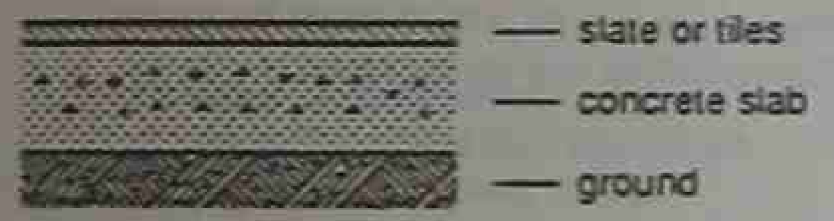
$U_i = 0.40$
$U_o = 0.39$

F 2 Carpet on timber with R1.5 insulation



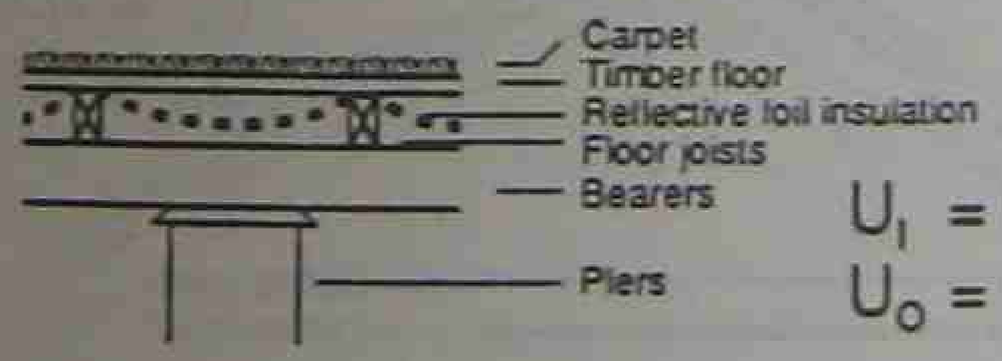
$U_i = 0.49$
$U_o = 0.47$

F 3 Cork tiles on a concrete slab on ground



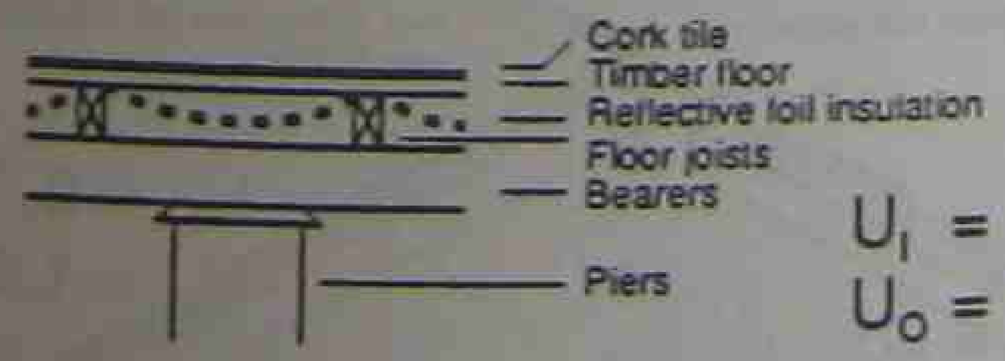
$U_i = 0.52$
$U_o = 0.49$

F 4 Slate or ceramic tiles on a concrete slab on ground



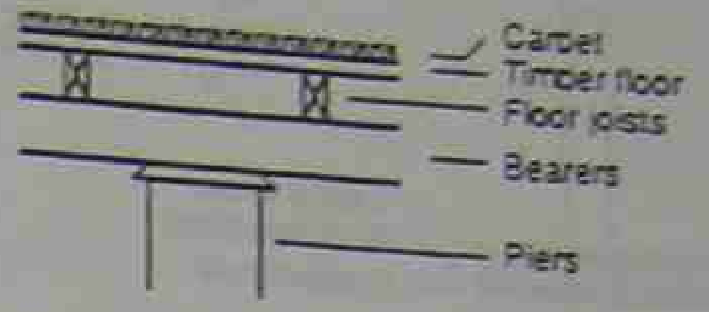
$U_i = 0.82$
$U_o = 0.69$

F 5 Carpet on timber with reflective foil insulation



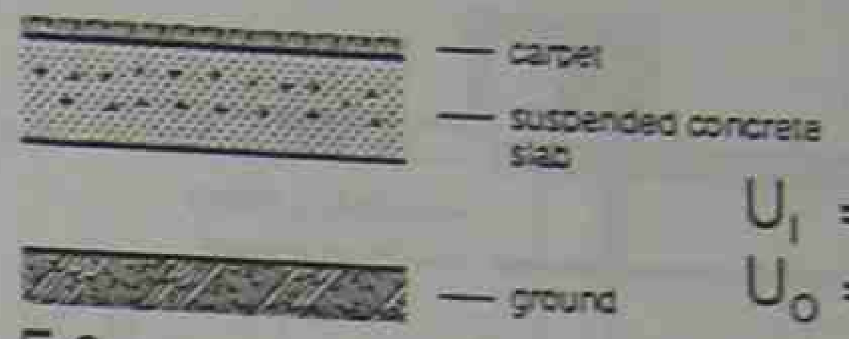
$U_i = 1.15$
$U_o = 0.91$

F 6 Cork tile on timber with reflective foil insulation



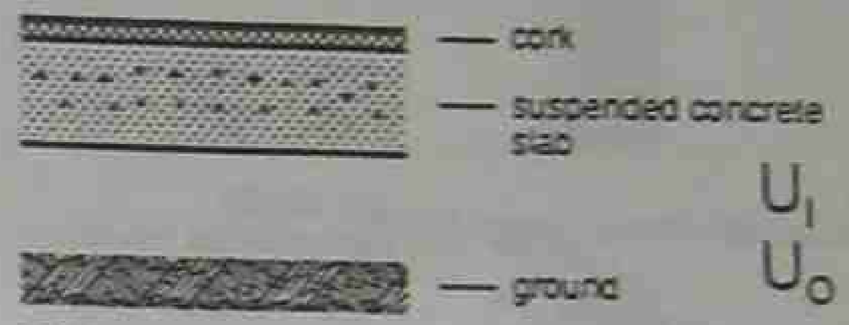
$U_i = 1.20$
$U_o = 1.13$

F 7 Carpet on timber uninsulated



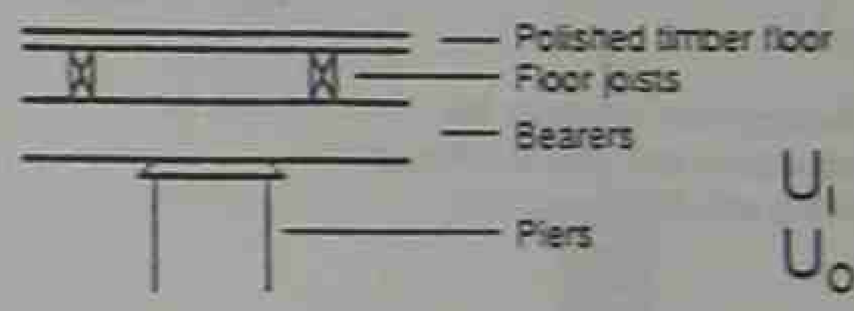
$U_i = 1.29$
$U_o = 1.21$

F 8 Carpet on suspended slab



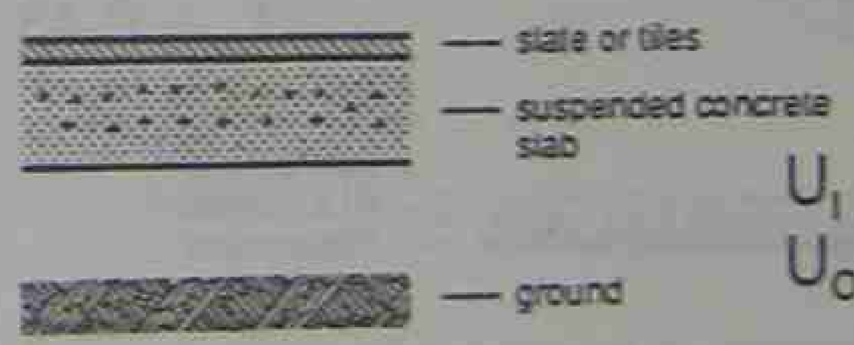
$U_i = 2.63$
$U_o = 2.32$

F 9 Cork tiles on suspended slab



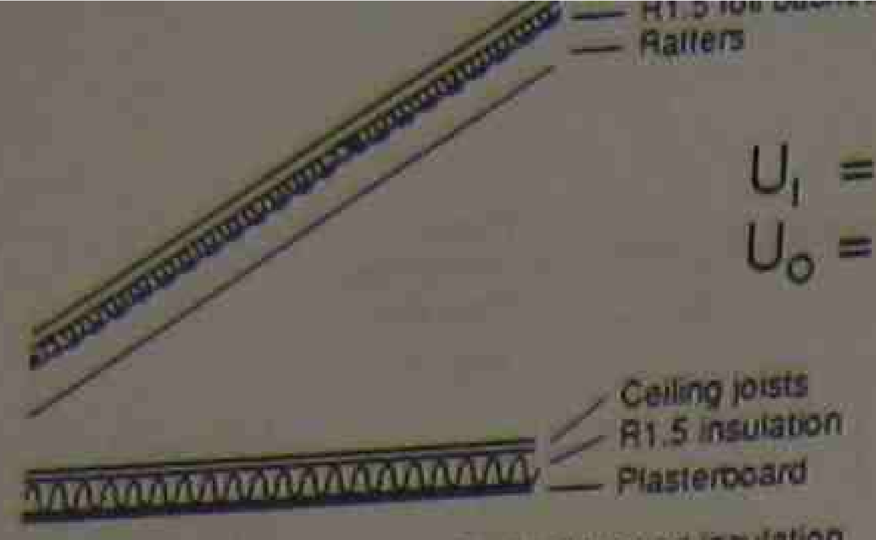
$U_i = 3.64$
$U_o = 3.08$

F 10 Polished timber uninsulated



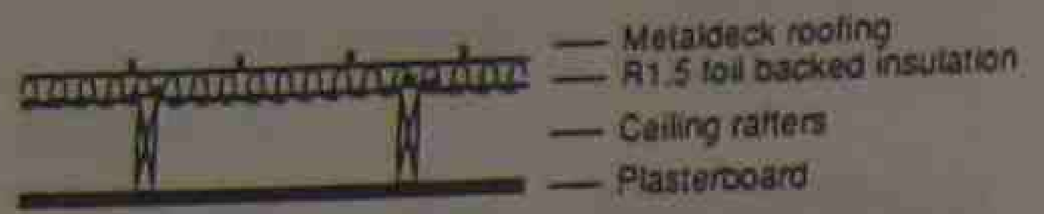
$U_i = 3.69$
$U_o = 3.12$

F 11 Slate or ceramic tiles on suspended slab



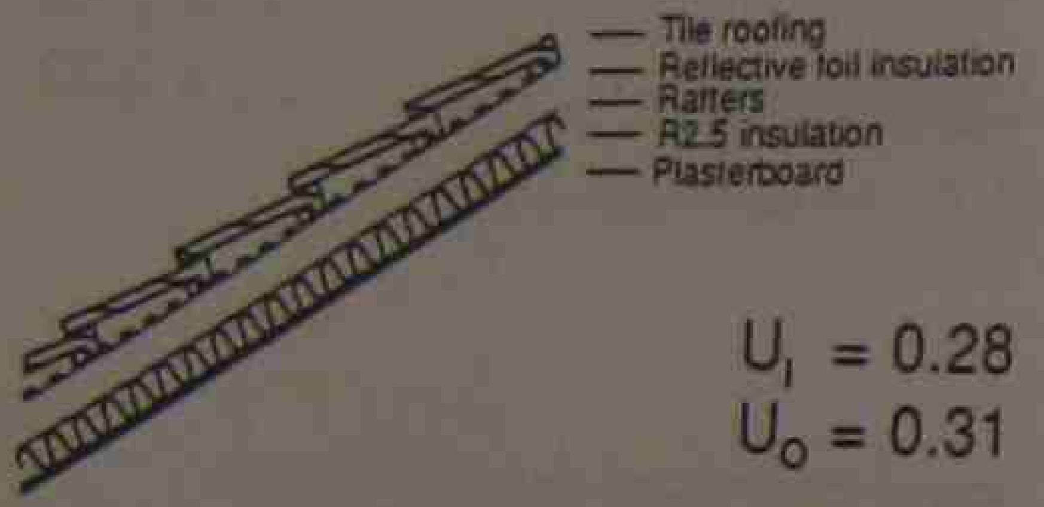
$U_I = 0.22$
$U_O = 0.25$

R 1 Metaldeck roof with R1.5 foil backed insulation and R 1.5 insulation above ceiling



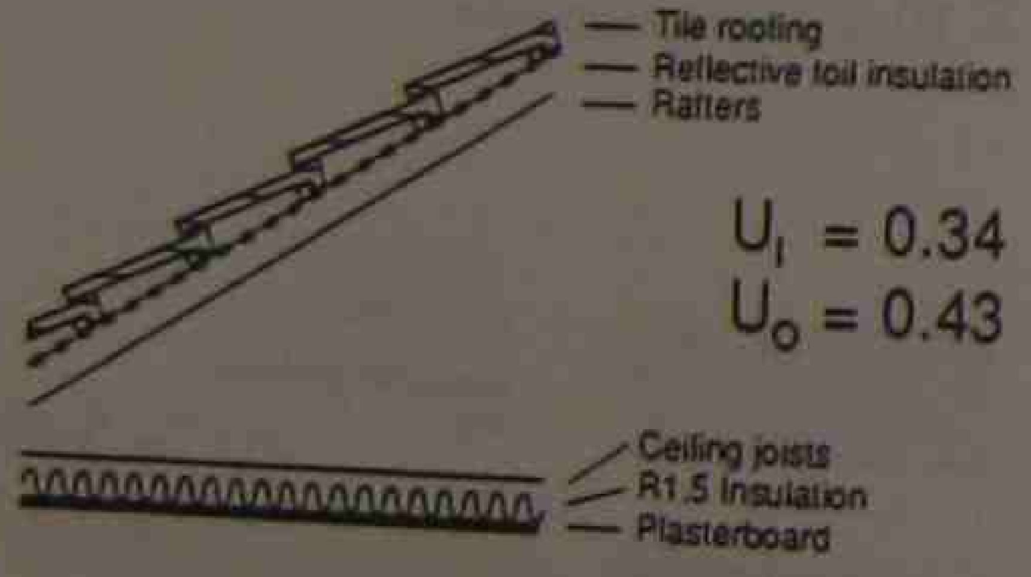
R 2 Flat metaldeck roof with R1.5 foil backed insulation

$U_I = 0.24$
$U_O = 0.31$



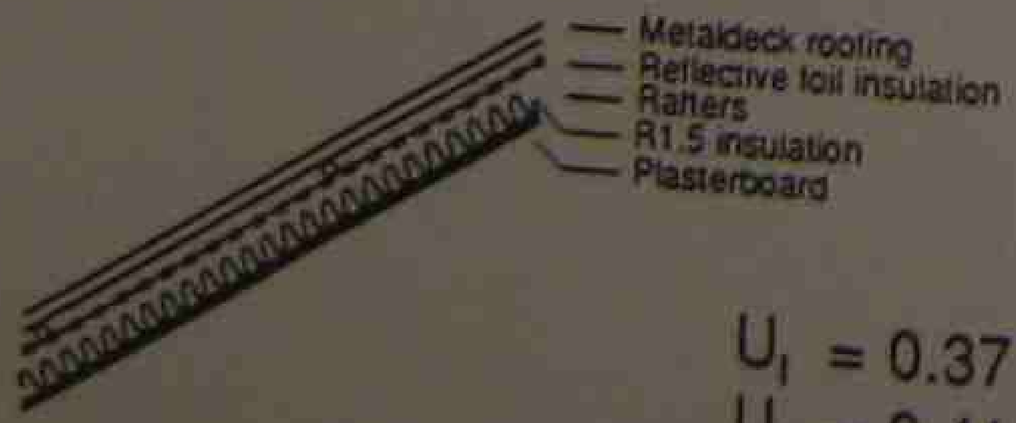
$U_I = 0.28$
$U_O = 0.31$

R 3 Tiled roof with reflective foil insulation under tiles and Raked ceiling with R2.5 insulation



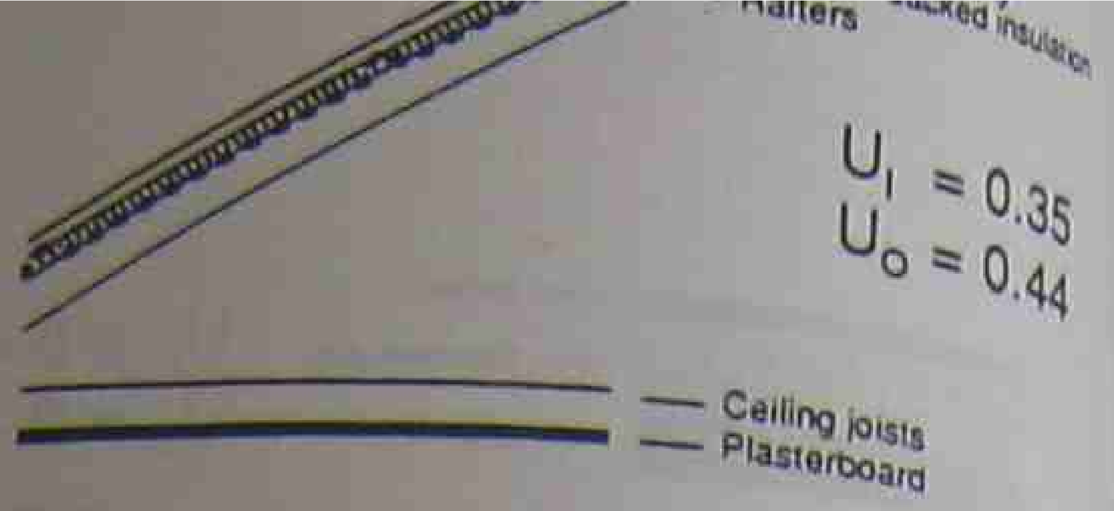
$U_I = 0.34$
$U_O = 0.43$

R 4 Tiled roof with reflective foil insulation under tiles and R1.5 insulation above ceiling



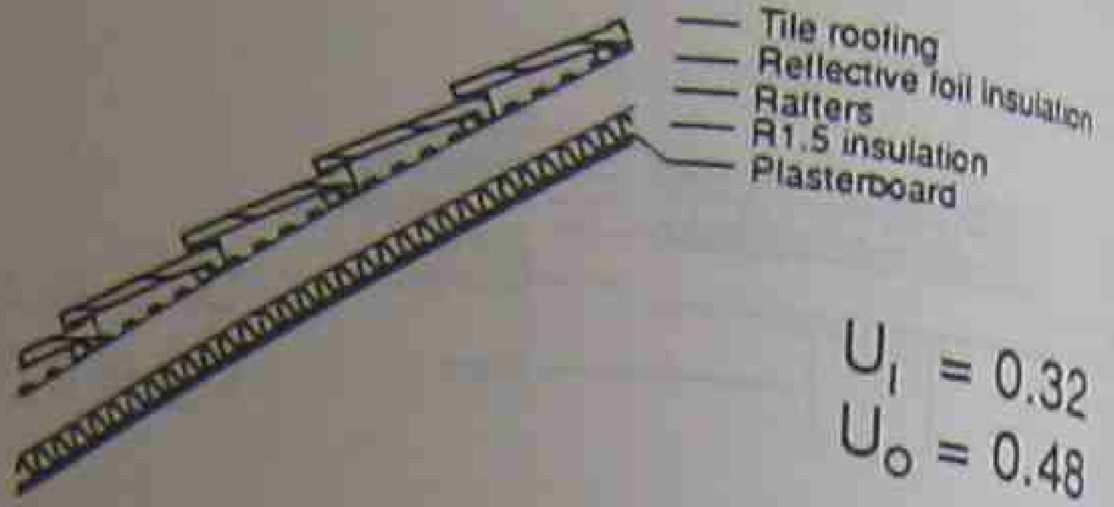
$U_I = 0.37$
$U_O = 0.41$

R 5 Metaldeck roof with reflective foil insulation and Raked ceiling with R1.5 insulation



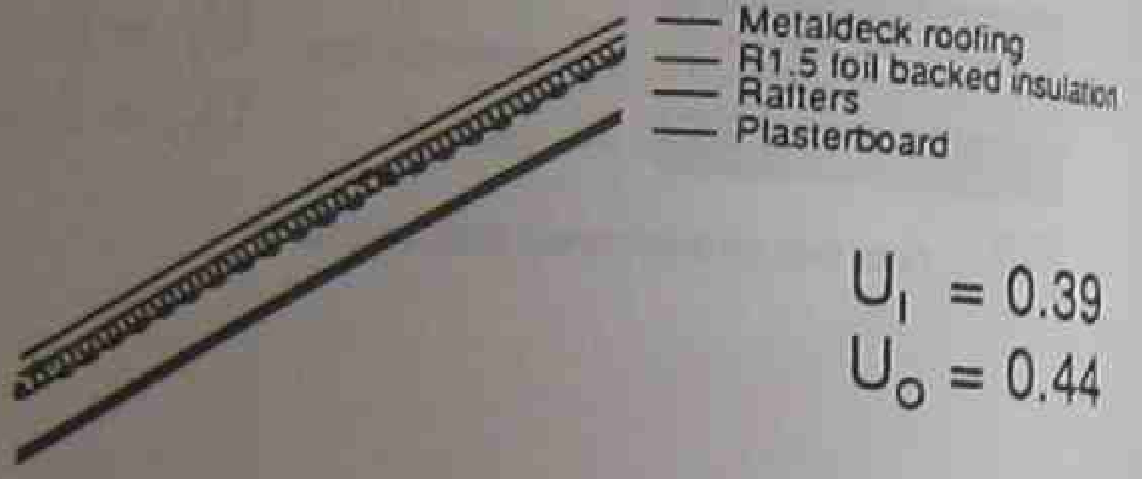
$U_I = 0.35$
$U_O = 0.44$

R 6 Metaldeck roof with R1.5 foil backed insulation



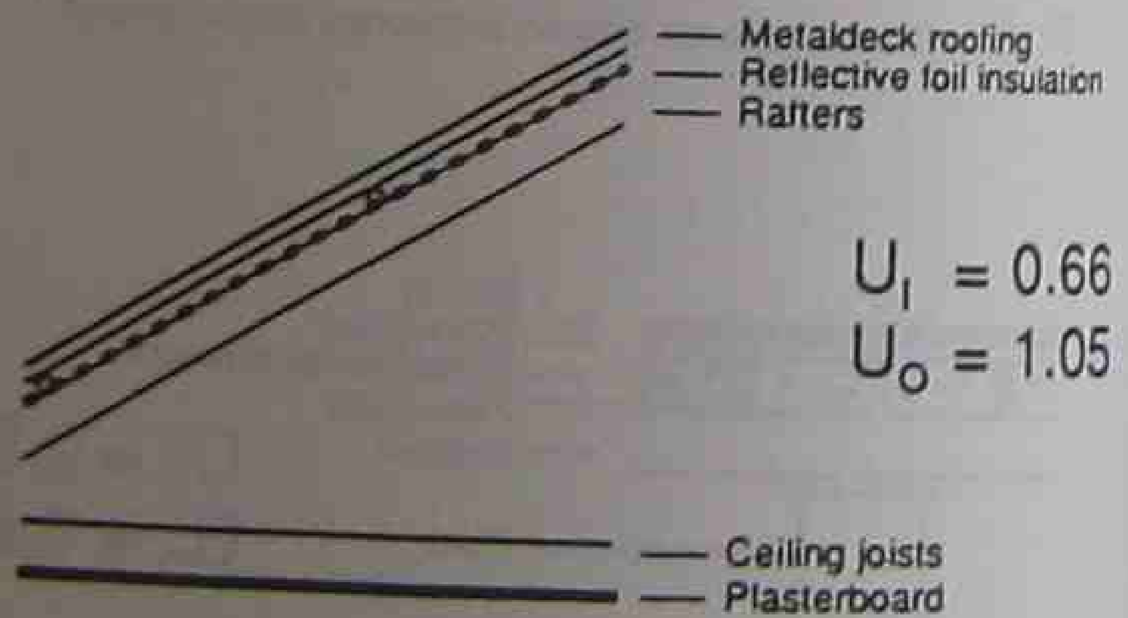
$U_I = 0.32$
$U_O = 0.48$

R 7 Tiled roof with reflective foil insulation under tiles and Raked ceiling with R1.5 insulation



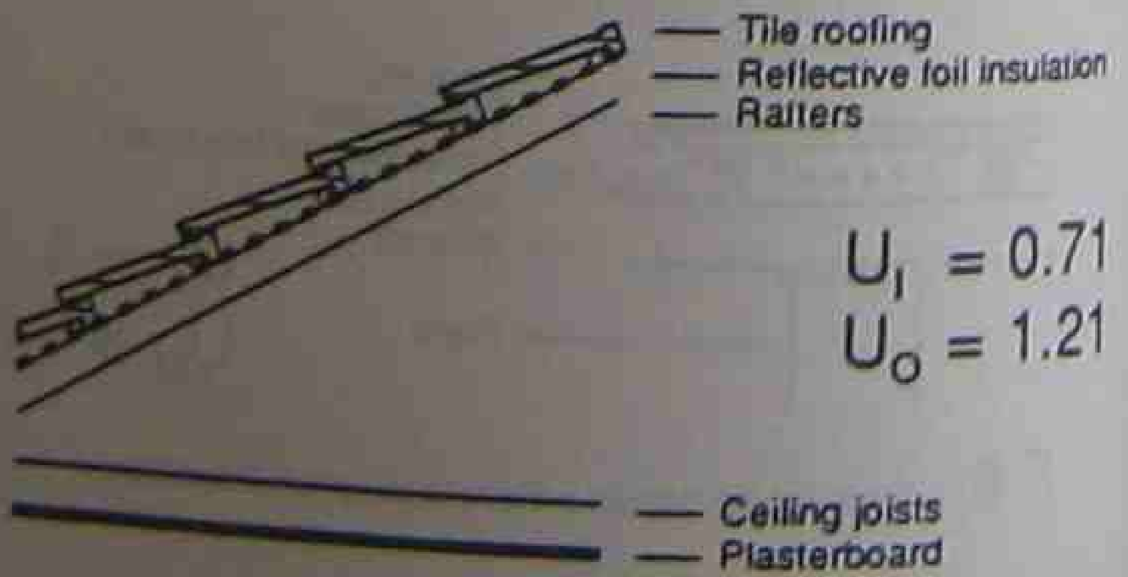
$U_I = 0.39$
$U_O = 0.44$

R 8 Metaldeck roof with R1.5 foil backed insulation and Raked ceiling with no insulation



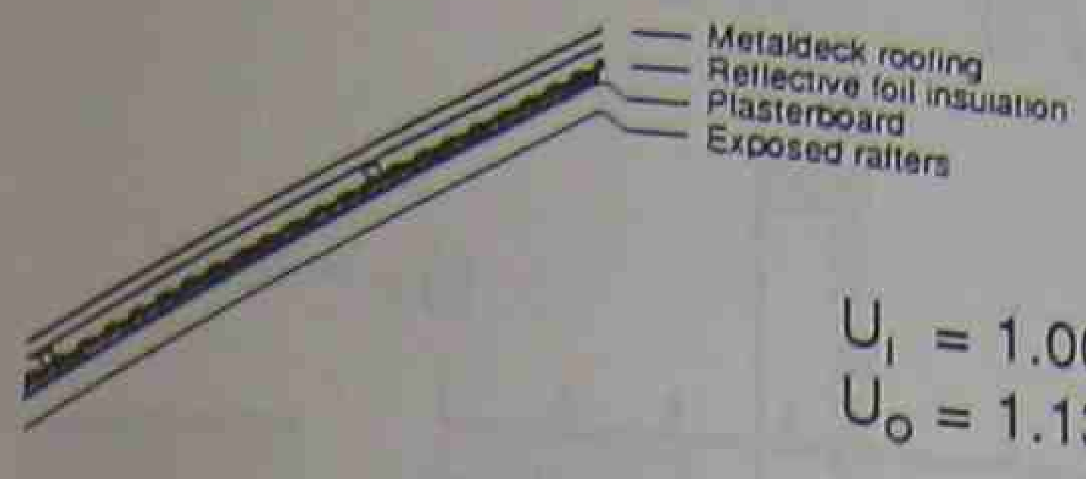
$U_I = 0.66$
$U_O = 1.05$

R 9 Metaldeck roof with reflective foil insulation



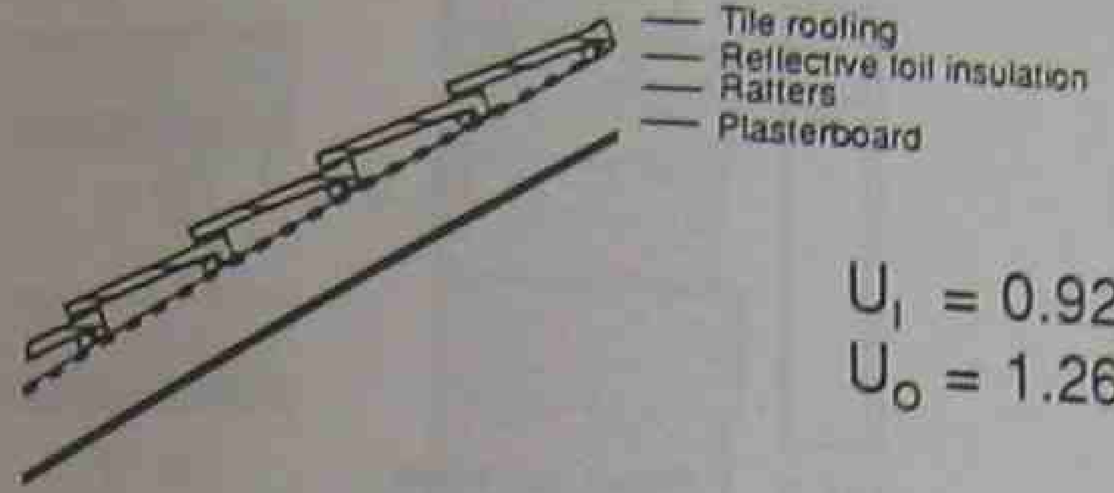
$U_I = 0.71$
$U_O = 1.21$

R 10 Tiled roof with reflective foil insulation under tiles



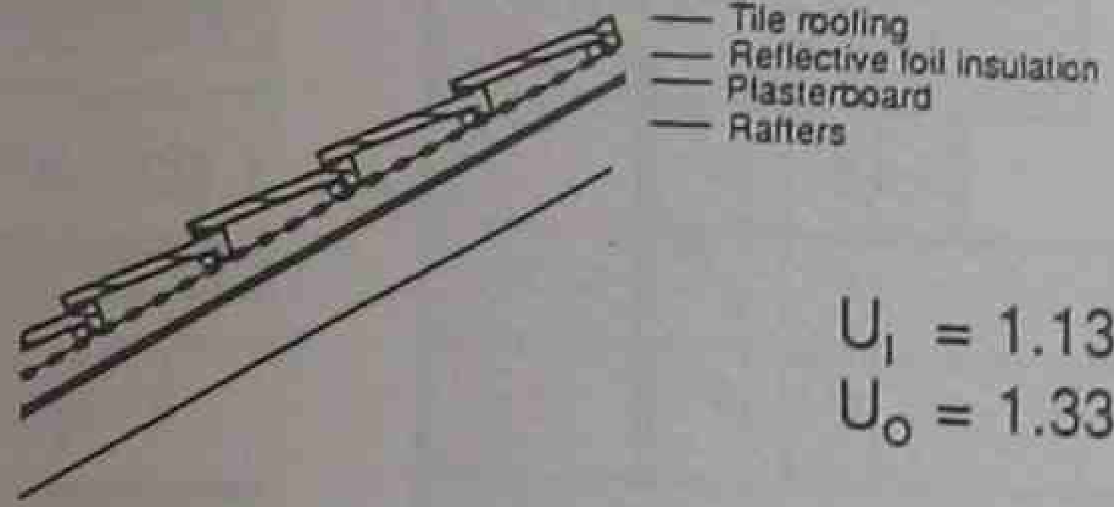
$U_I = 1.00$
$U_O = 1.13$

R 11 Metaldeck roof with reflective foil insulation and Raked ceiling with exposed rafters



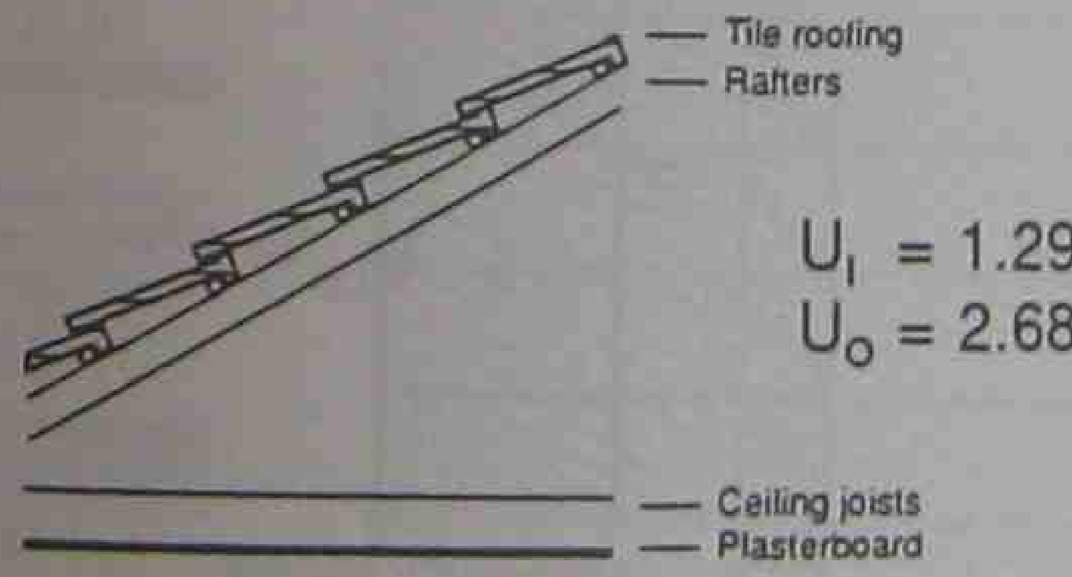
$U_I = 0.92$
$U_O = 1.26$

R 12 Tiled roof with reflective foil insulation under tiles and Raked ceiling with no insulation



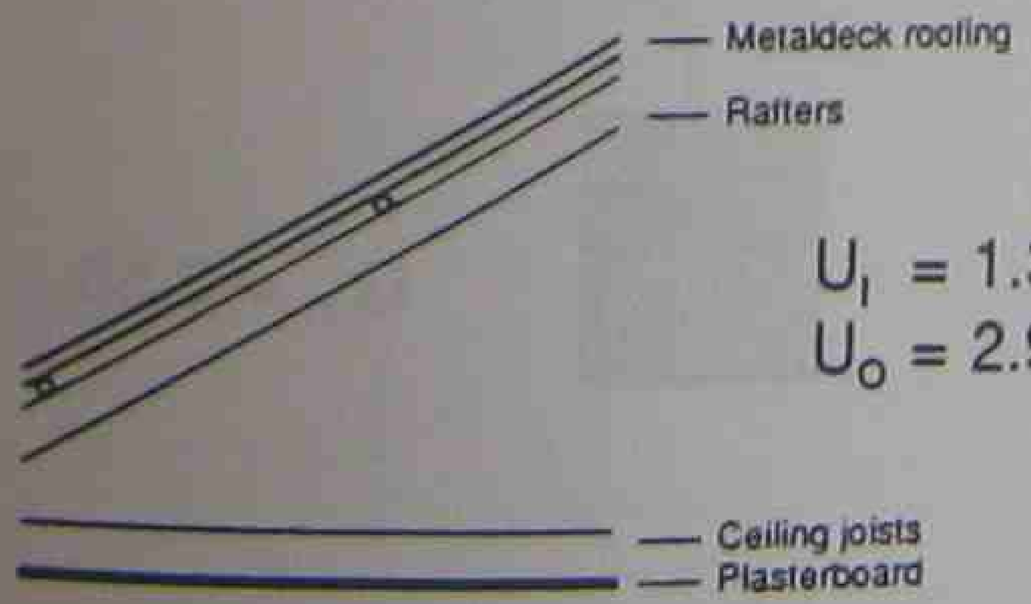
$U_I = 1.13$
$U_O = 1.33$

R 13 Tiled roof with reflective foil insulation under tiles and Raked ceiling withexposed rafters



$U_I = 1.29$
$U_O = 2.68$

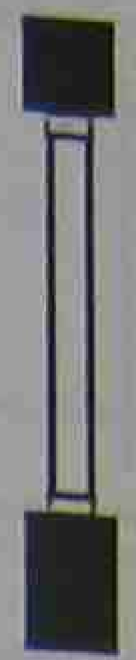
R 14 Tiled roof with no insulation



$U_I = 1.36$
$U_O = 2.97$

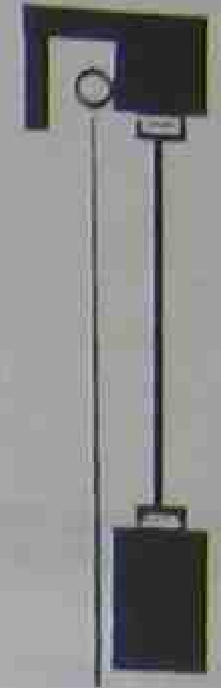
R 15 Metaldeck roof without insulation

GLAZING DETAILS



$U_{I,O} = 3.17$

G1 Double glazed

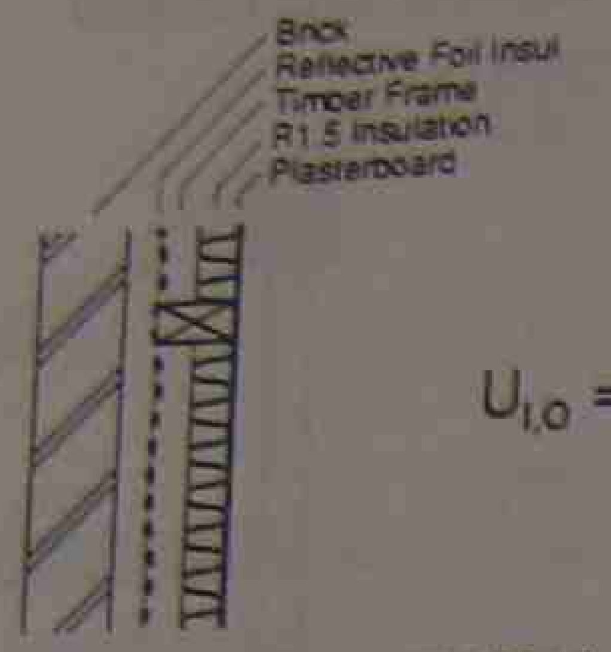


$U_{I,O} = 4.66$

G2 Single glazed plus thermal curtain & pelmet

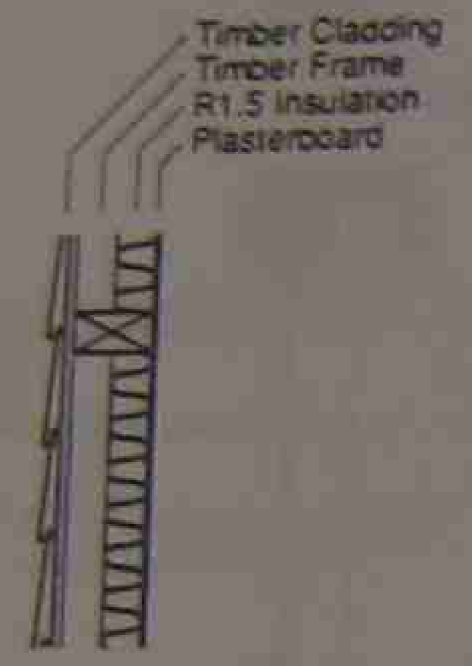
$U_{I,O} = 6.17$

G2 Single glazed



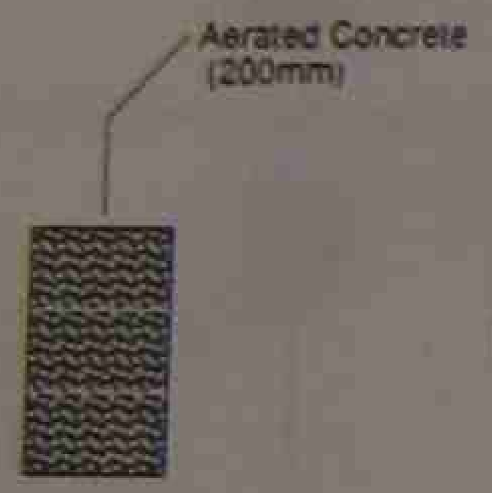
$U_{I,O} = 0.34$

W 1 Brick veneer with reflective foil and R1.5 insulation



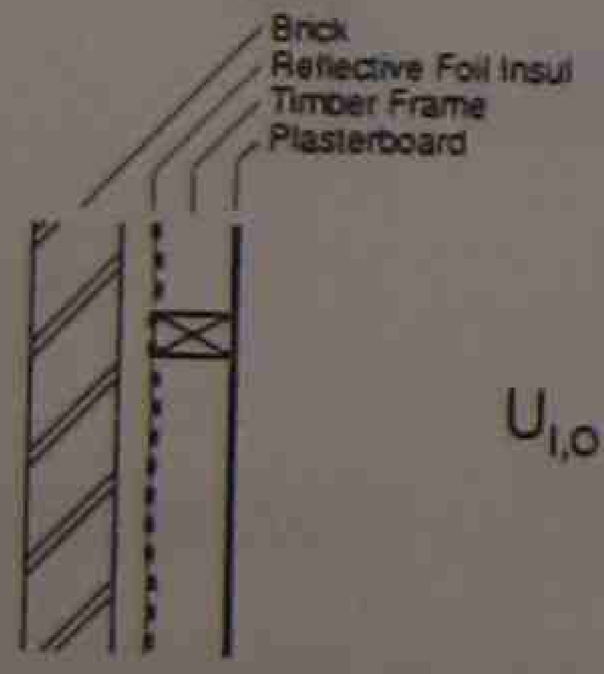
$U_{I,O} = 0.49$

W 2 Timber stud frame with R2.0 insulation



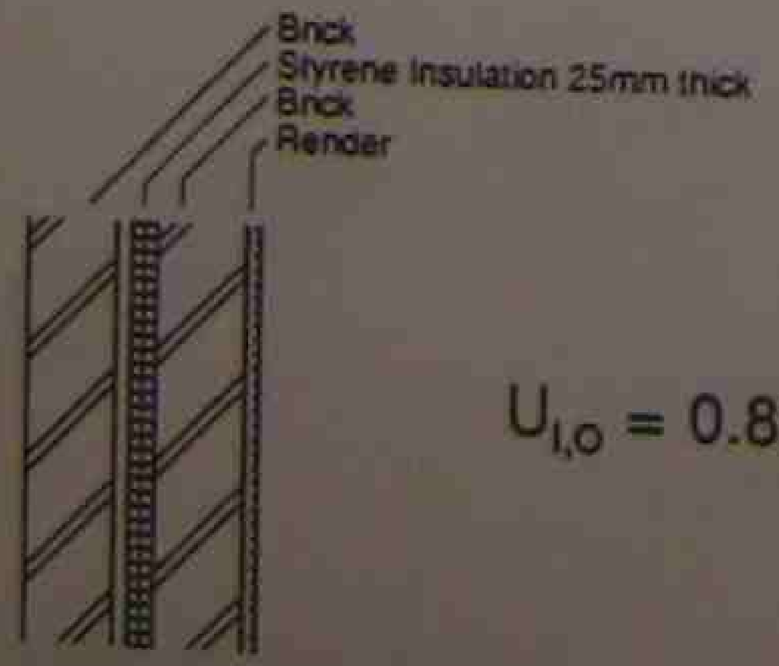
$U_{I,O} = 0.59$

W 3 Autoclaved Aerated Concrete rendered both sides



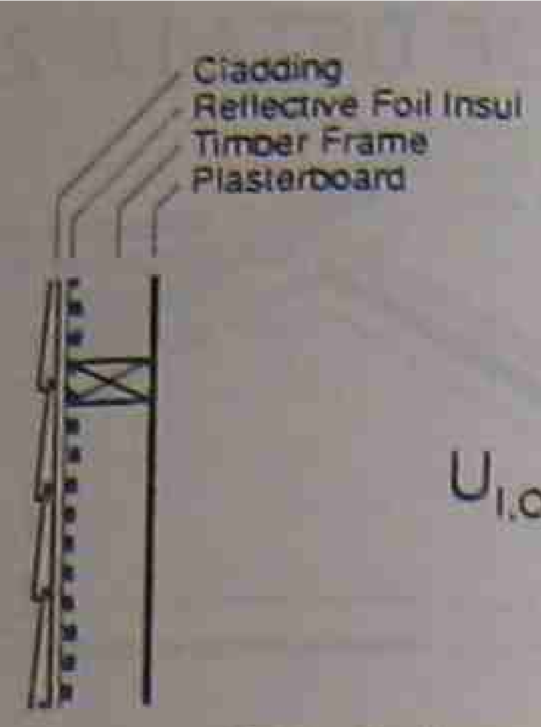
$U_{I,O} = 0.64$

W 4 Brick veneer with reflective foil insulation



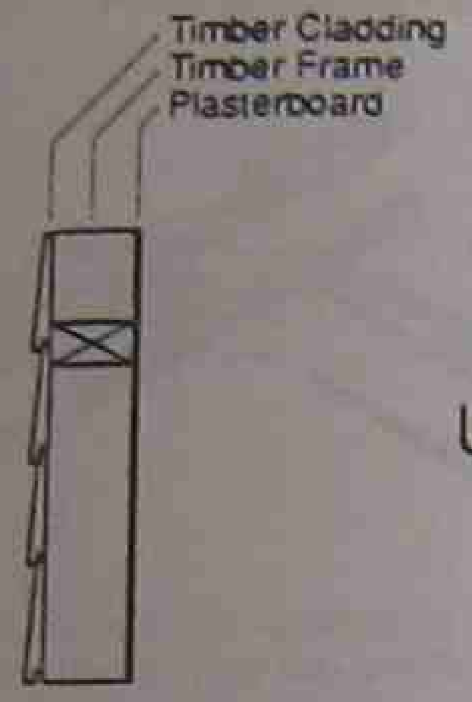
$U_{I,O} = 0.88$

W 5 Full brick rendered internally with styrene insulation



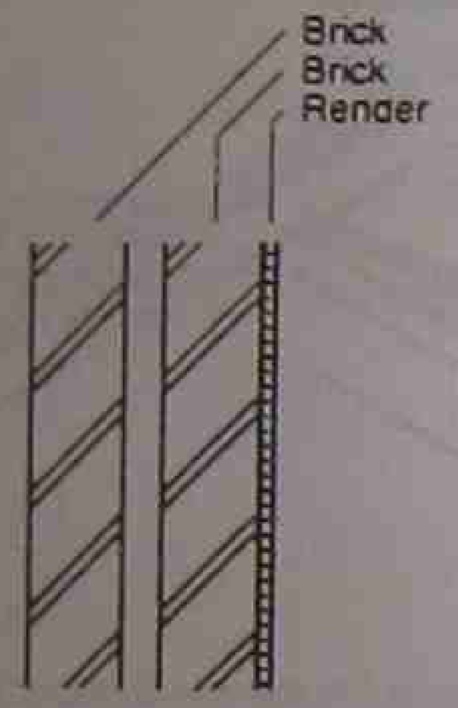
$U_{I,O} = 0.98$

W 6 Timber stud frame with reflective foil insulation



$U_{I,O} = 1.76$

W 7 Timber stud frame uninsulated

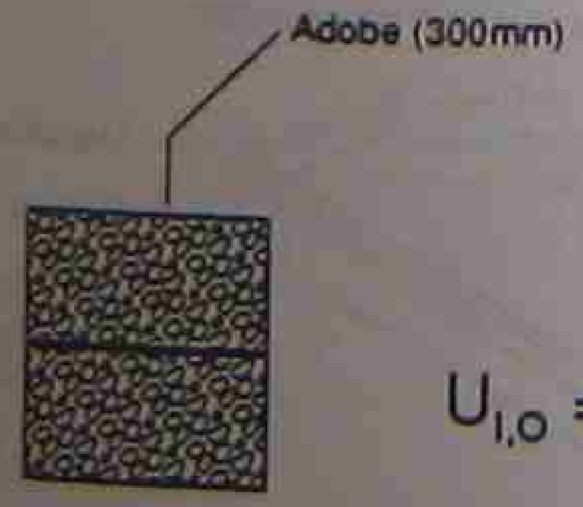


$U_{I,O} = 1.92$

W 8 Full Brick rendered internally

$U_{I,O} = 2.11$

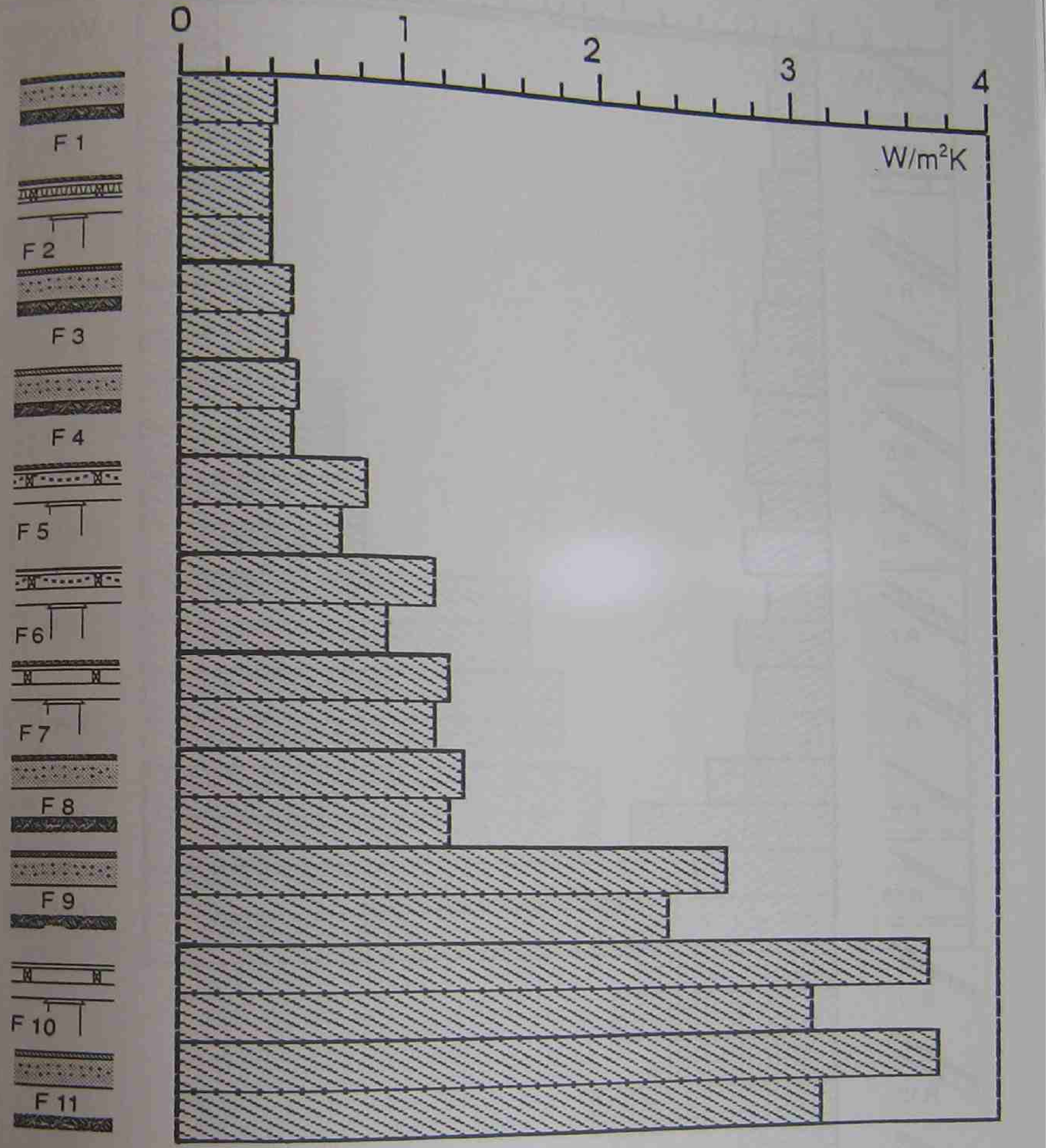
W 9 Brick veneer uninsulated

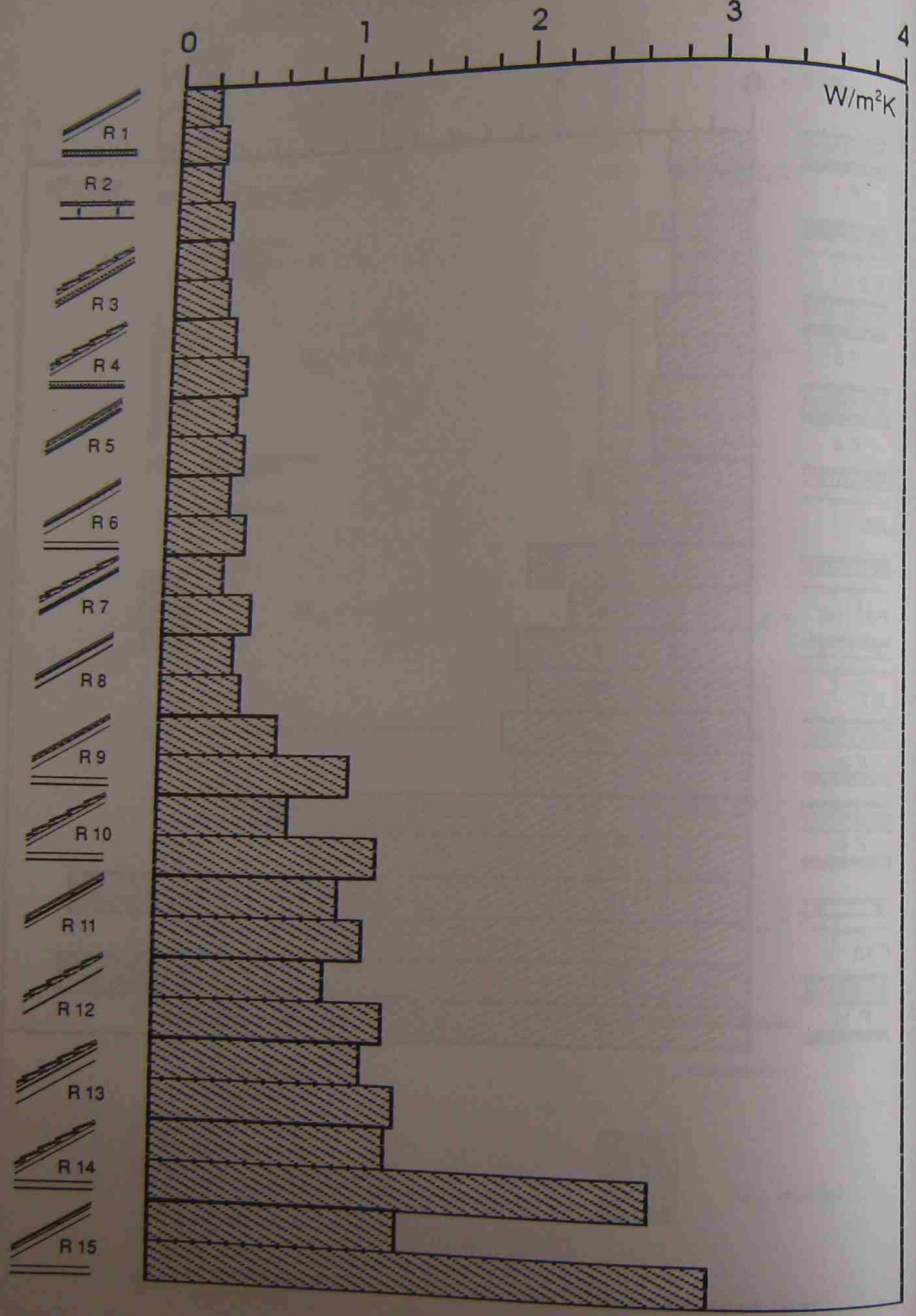


$U_{I,O} = 2.50$

W10 Adobe (mud brick - 300mm)

U-VALUES OF FLOORS




0
1
2
3
4
W/m²K
R 1
R 2
R 3
R 4
R 5
R 6
R 7
R 8
R 9
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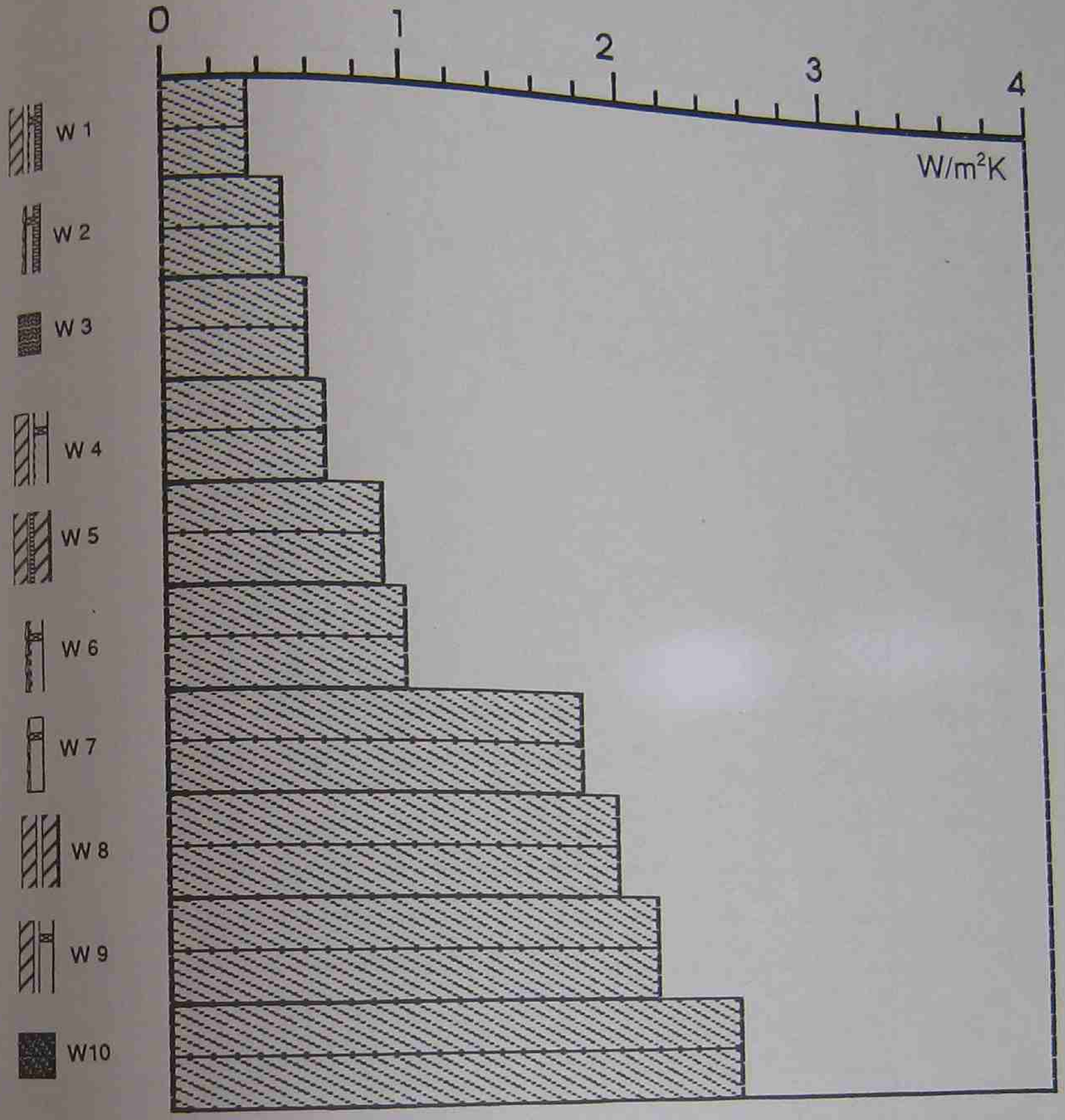
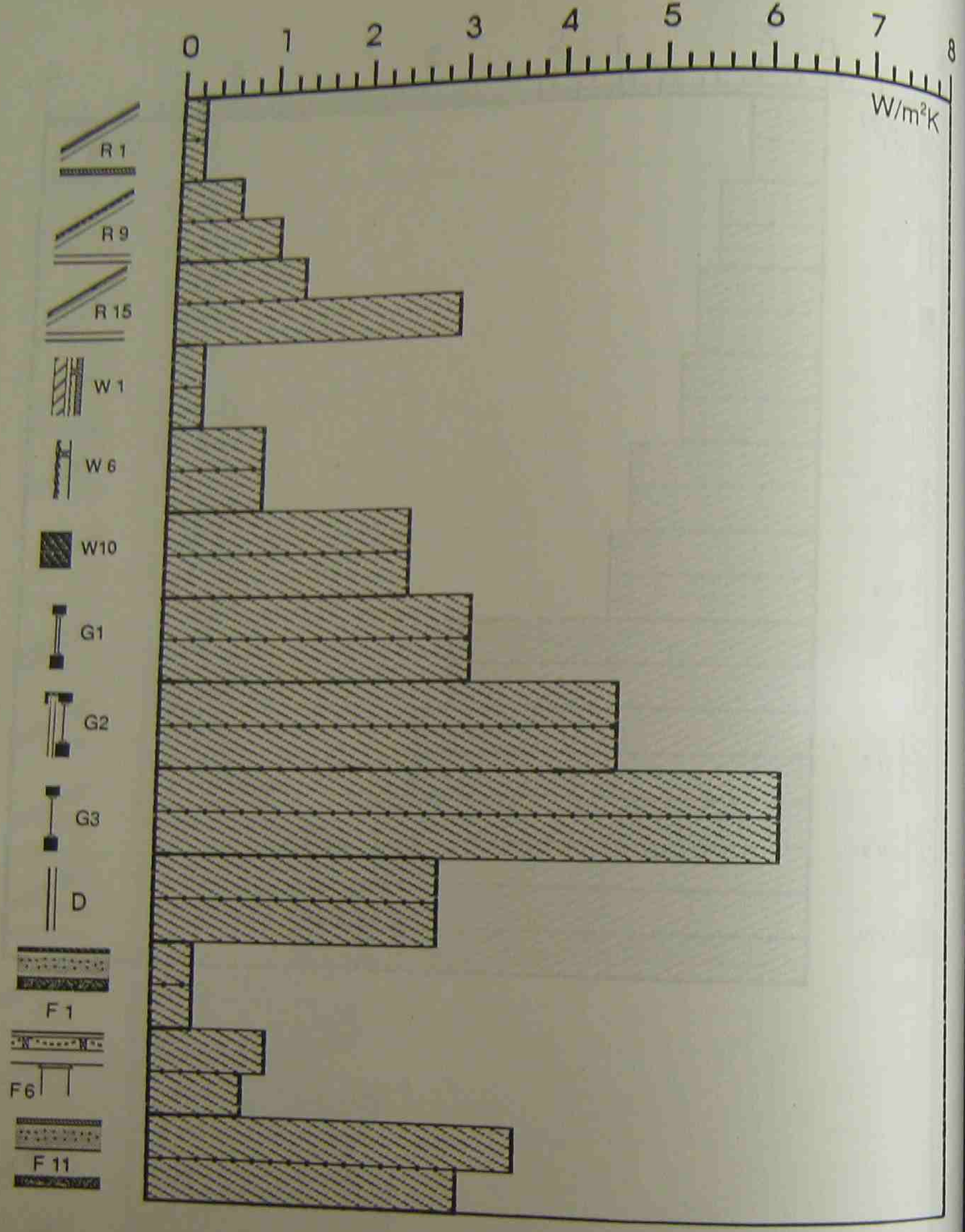
R 11
R 12
R 13
R 14
R 15


0
1
2
3
4
W/m²K
W 1
W 2
W 3
W 4
W 5
W 6
W 7
W 8
W 9
W10

U-VALUES OF



Unit 5

Windows and Shading

1 INTRODUCTION

Windows serve four main purposes in buildings. They allow the occupants to look out, they allow natural daylight to illuminate the inside, they allow sunlight to heat up the building and they enable natural ventilation to take place. However, great care must be taken that satisfying the first two purposes does not compromise thermal comfort.

A building will always be heated to some extent via direct solar gain through windows, and indirect gains through the walls and roof via solar energy absorption. This, in combination with the heat from the bodies of the occupants and the heating due to lights and other appliances will make the average temperature of the building greater than the average ambient temperature. While this is generally useful in winter, it can lead to gross overheating in summer and even to some uncomfortably high temperatures at certain times in winter.

A compromise must therefore be made so that the heat gain in summer is minimised. This can be achieved both directly and indirectly. Direct means of reducing summer gains include orientating the windows to reduce summer sun penetrations, decreasing the size of the windows, shading both windows and walls, and using light coloured walls and light coloured zinc or aluminium coated roofing material. Indirect means (which will be covered elsewhere) include night-time ventilation, direct venting of heat from appliances (eg. stove hoods) to the outside, summer venting of the ceiling cavity, good insulation of building elements, and the use of a concrete slab floor (which will lose heat to the ground which is at a lower temperature than the air in summer). Better insulation of internally installed hot water services and the use of more efficient appliances such as refrigerators, lights, TVs, microwave cookers, etc., will also reduce the internal heat gains.

2 WINDOW ORIENTATION

The graphs in Figure 1 show the daily solar radiation on walls of different orientations for Sydney radiation data. The north face of a building receives about twice as much sunlight in winter as the east and west sides and about five times as much as the south side. In summer, the north and south sides receive about the same as each other. The east and west sides receive about 50% more than the north and south sides (Figure 2). To optimise window placement in a building then, all the glass should be placed in the north wall. This is obviously not practical from a daylighting perspective so all non-north glazing should be kept to a minimum.

If a choice exists between a south or east/west window, then the choice should be south. A southern window will receive less winter sun but also less summer sun than an east or west facing window.

Although east and west facing windows receive about equal amounts of irradiation, it is better to have windows facing east rather than west. The sun enters the east windows in the morning when the house has cooled off during the night, whereas it enters the west windows in the afternoon when the building will be reaching its maximum temperature.

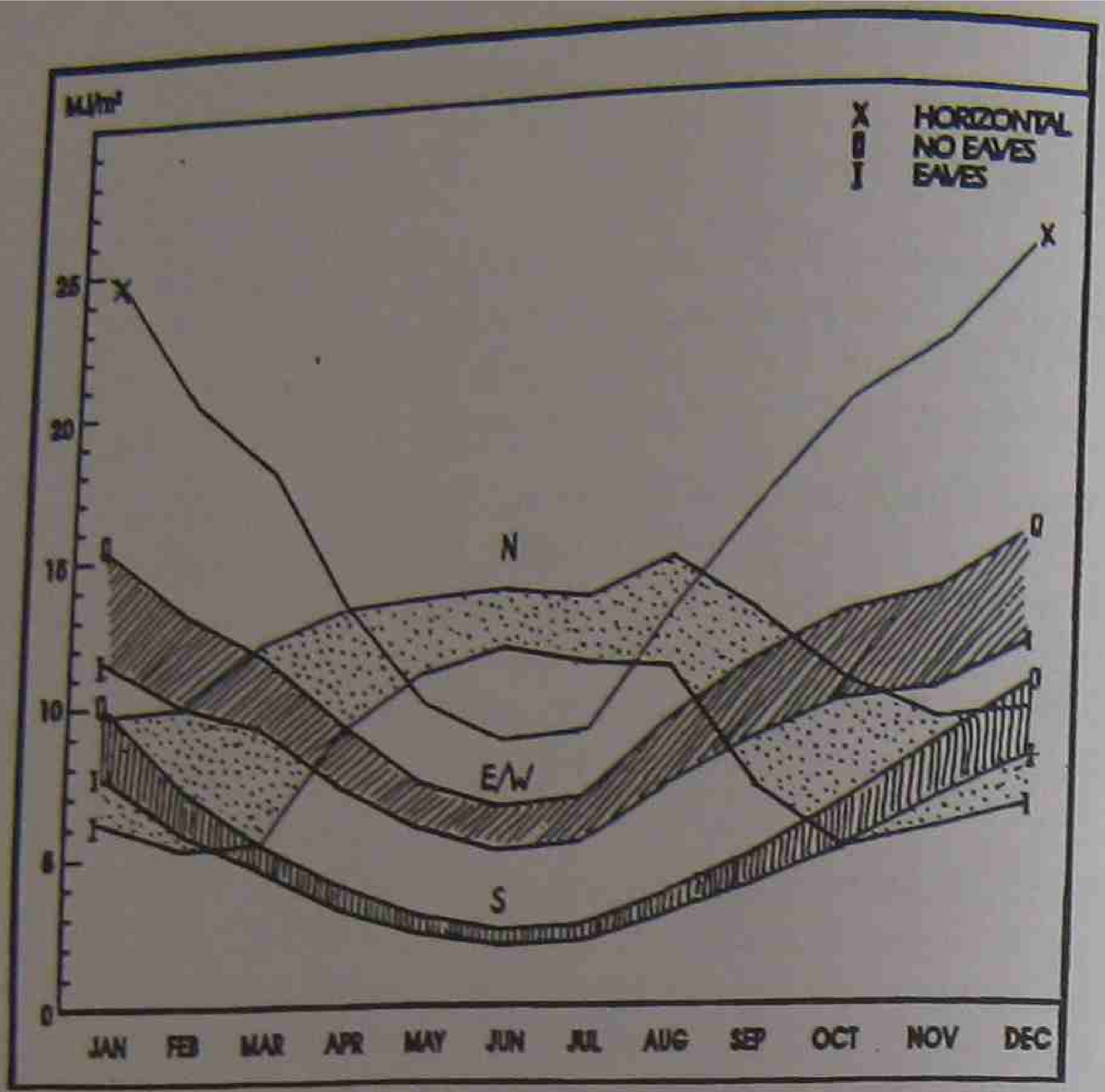


Figure 1 - Graphs of daily solar radiation received on walls of different orientation for Sydney radiation data. The lower line of each pair indicates solar gain received per square metre of 2.4m wall when shaded by 600mm eaves. The top line is for unshaded walls.

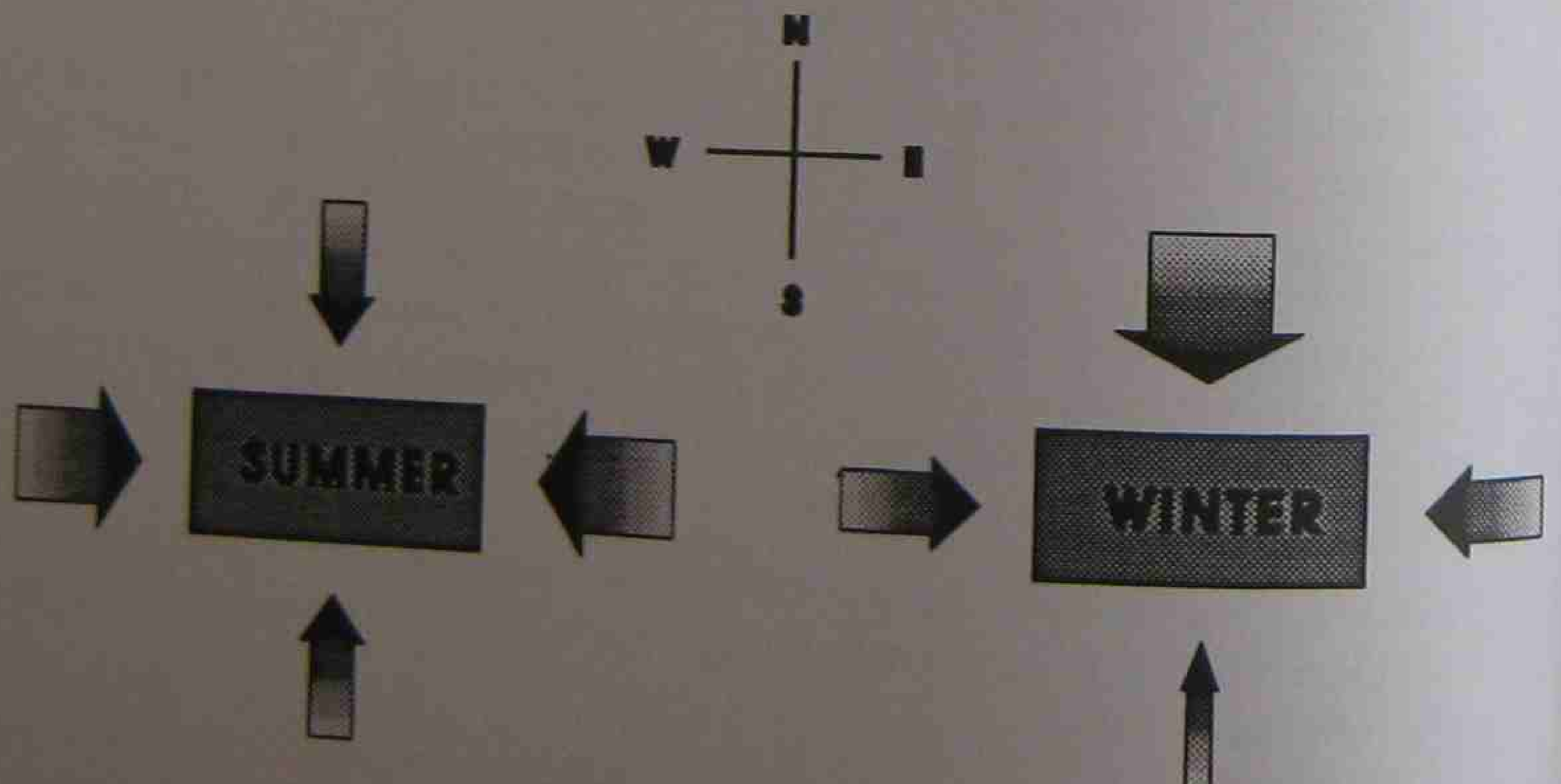


Figure 2 - Comparison of daily solar radiation received on walls of different orientation for summer and winter (Sydney). The width of the arrows indicate the relative amount of radiation received.

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3 TYPES OF GLAZING SYSTEMS

There are many different kinds of glazing systems although most are used only on commercial buildings. The most popular and cheapest is the single glazed window where glass is held in a wooden or aluminium frame. The frame is either fixed or can be opened to provide airflow. The problem with this kind of window is that the heat transfer through a single pane of glass is very high, ten times higher than a similar area of brick veneer wall fitted with reflective insulation. The insulation properties of this kind of window can be doubled by using a pelmet and curtain to provide an extra air space when the curtain is drawn at night.

Double glazing provides similar thermal properties, again by providing an extra air space. Fitting a pelmet and curtain will also increase the insulating value. Disadvantages include a decrease in sunlight penetration of about 15% over single glass and an extra cost of about 20 - 30% for Australian conditions. This type of glazing is usually supplied in hermetically sealed units.

Non-standard sizes or double glazed doors are usually supplied with a desiccant (such as silica gel) between the glass panels to stop internal condensation. Variations of double glazing include treble glazing and double glazing where the gap is filled with gases that are less conducting than air. Prototype double glazing where a gap of less than 0.1mm is provided by very small pillars which stop the two sheets from collapsing when the gap is evacuated have also been produced (Figure 3).

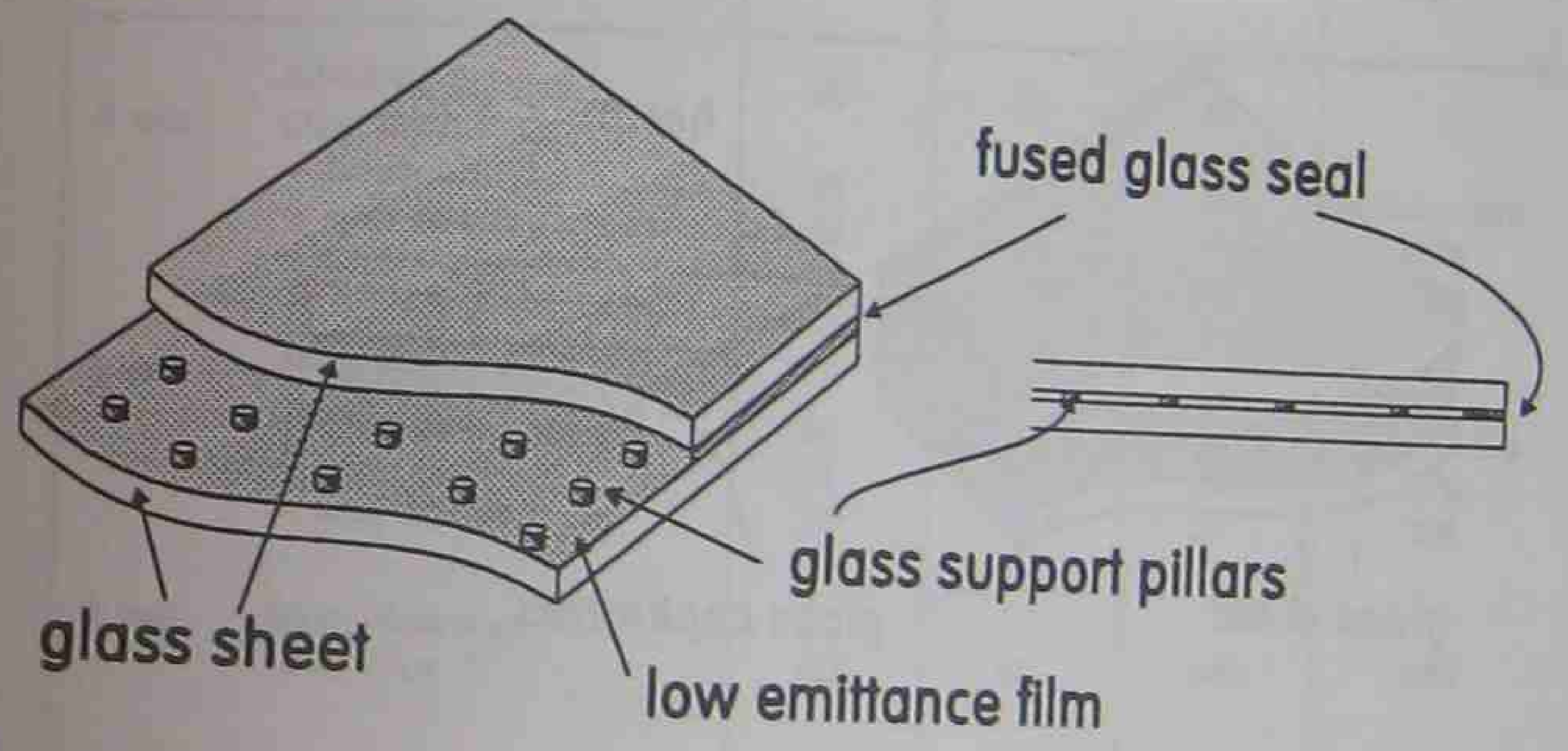


Figure 3 - Double glazing with a vacuum gap supported by pillars.

Glass has an emittance of about 0.9 which leads to a significant amount of heat being radiated across the gap in double glazed systems. Thin **low emittance films** have been successfully deposited on the internal surfaces of double glazing producing low conducting or "low E" windows (Figure 4). Commercially available dry gas filled double glazed windows with one low emittance transparent metallic coating have a claimed conductance of one quarter that of single glazing with a light transmittance of 79%.

Evacuated windows with low emittance coatings are expected to allow only one tenth the heat flow across a single pane of glass.

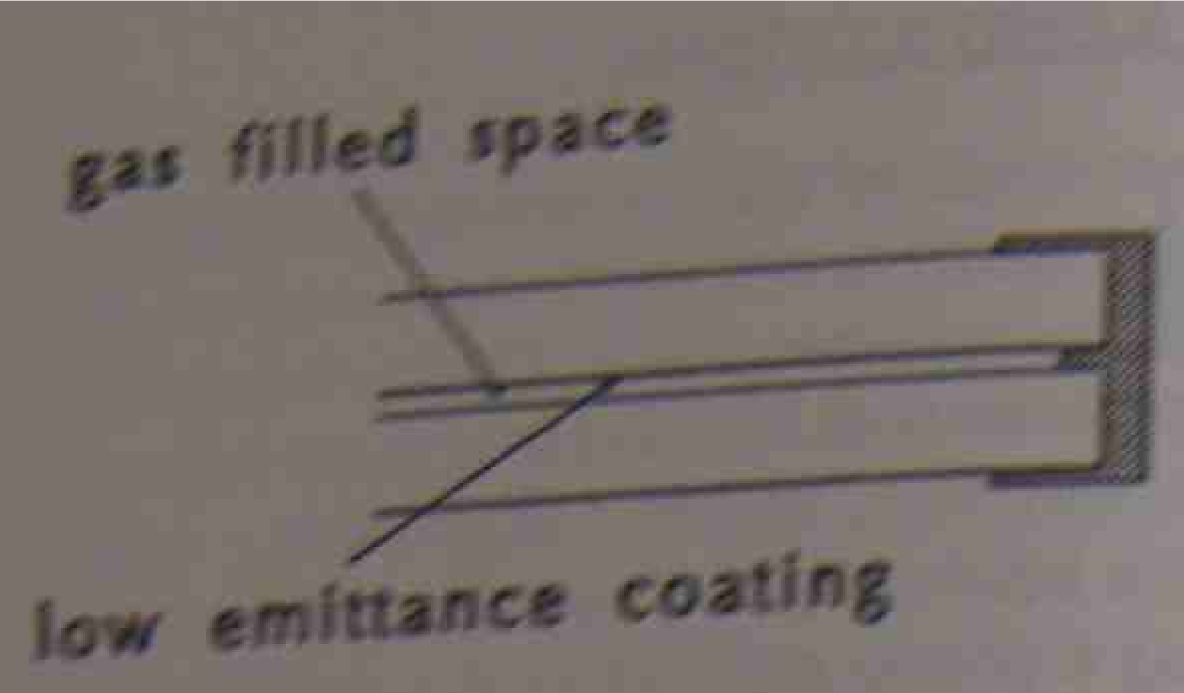


Figure 4 - Double glazing with a low emittance internal surface.

Translucent insulation is a term usually applied to insulating materials which allow light through but through which objects are not visible. Several basic kinds exist at present, most of which have insulating materials sandwiched between layers of glass or plastic. Some use honeycomb or capillary structures (Figure 5) which are perpendicular to the outside layers, others use foams, bubbles or fibres which scatter light and a third group use homogeneous materials such as aerogel (Figure 6). The best of these reduce heat conduction to about one sixth that of single glazing. Transmittance can vary between about 0.3 and 0.7. Low transmittance materials are used in roofs where solar overheating is a potential problem.

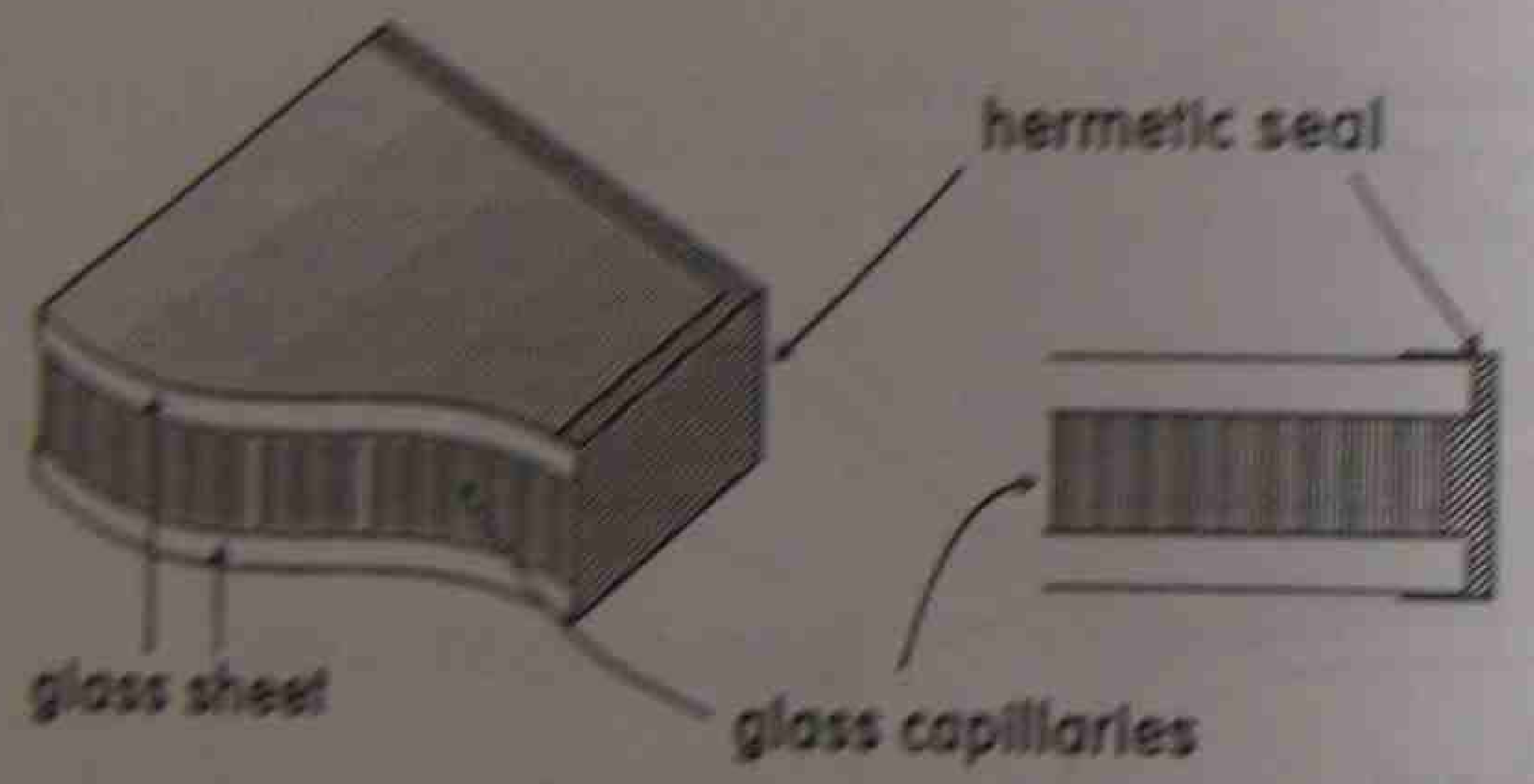


Figure 5 - Transparent insulation with glass capillaries between double glazing.

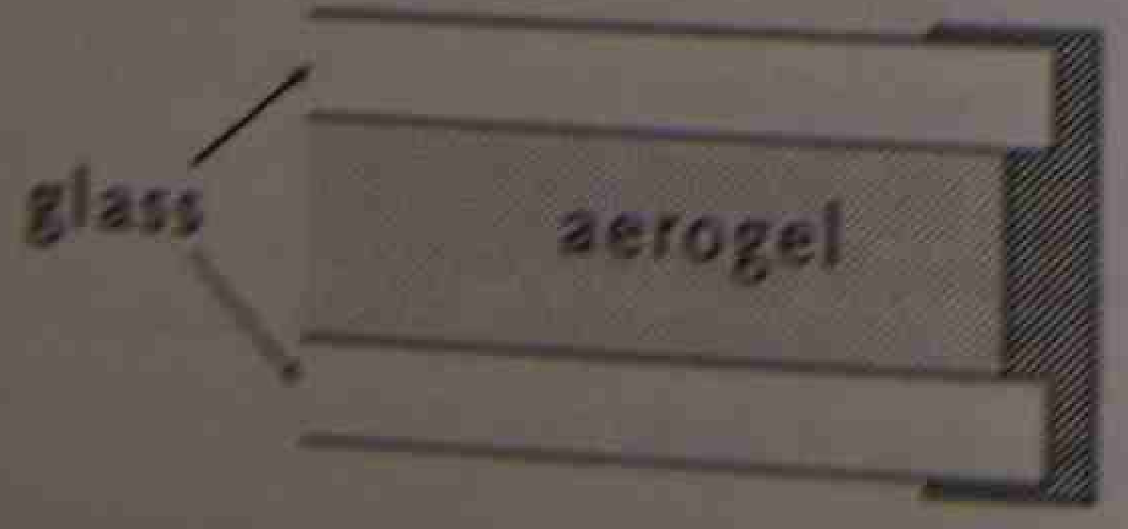


Figure 6 - Double glazing with aerogel filling.

A number of materials exist which reduce the amount of light penetrating the glazing without offering the reduced heat flow of translucent insulation. Perhaps the most common is light or **"heat" reflecting glass** which uses thin metal films such as aluminium or gold to reduce the transmittance by increasing the reflectance. Using reflecting films on windows will reduce solar gain to a greater extent than they reduce daylighting. The reason for this is that only about half of the solar spectrum is visible to the human eye, and even for this fraction the spectral response of the eye is non linear. Also, the eye's response to intensity is logarithmic rather than linear. This means that heating effects of sunlight and visual acuity are not directly proportional. Spectrally selective films have been developed which primarily reduce the transmittance of the sunlight which contributes to heating and not to seeing.

Heat absorbing glass converts a proportion of the sunlight to heat, some of which is lost to the outside. However, glass temperatures in excess of 20°C above outside temperatures are possible which can lead to thermal discomfort from radiation. Some heat absorbing windows have even cracked because of the expansion occurring during overheating. The solar optical properties for light at normal incidence of clear glass, heat reflecting glass and heat absorbing glass are given in Table 1.

Solar-Optical Properties Glass with Various Treatments		Solar-Optical Properties			Transmission of	
		Reflectance r	Absorptance a	Transmittance t	Visible Light	Ultra-Violet
3 mm	ASHRAE Standard Clear Sheet Glass	.08	.05	.87		
	– Untreated *	.09	.05	.86	approx. 90%	80%
	– with RSL20 *	.56	.30	.14	17%	25%
	– with RSL40 *	.38	.32	.30	27%	45%
6 mm	Clear Plate Glass *					
	– Untreated *	.08	.20	.72	approx. 80%	57%
	– with RSL20 *	.44	.44	.12	10%	10%
	– with RSL40 *	.29	.44	.27	38%	38%
6 mm	Heat Absorbing Grey Glass *	.055	.56	.385	39%	
6 mm	Heat Reflecting 15/23 Gold "Solarshield"	.48	.43	.09	15%	
6 mm	"Coldlite" Heat Absorbing Glass	.05	.65	.30	64%–70%	

Table 1 - Solar optical properties of clear, heat reflecting and heat absorbing glass. (Source: Hassell, 1977).

Thermochromic glass is coated with a transparent film which turns opaque white when heated. This reversible effect decreases transmittance from 90% at 24°C to below 20% at 30°C.

Reversible transmittance changes are also possible in **photochromic compounds** which go dark as the illumination increases. Photochromic sunglasses have been commercially available for some time.

Electrochromic compounds undergo reversible changes when small voltages are applied. The field is only applied when changes are required. This technology has an advantage over passive glazing systems such as thermochromic and photochromic windows in that much greater control over transmittance can be achieved.

Liquid crystals can be manufactured in the large area sizes suitable for windows but a constant electric field must be applied to reduce transmittance.

Holographic films have been produced which can act as selective filters which transmit visible wavelengths while reflecting infra red radiation.

Other thin film coatings have been produced which are angular selective. They will allow light to enter at certain angles (determined by the obliqueness of the sputtered metal coatings) while attenuating light from other directions. These films can be used on windows so that looking out and down is like looking through normal glass, but light coming in from high in the sky will be largely blocked (Figure 7).

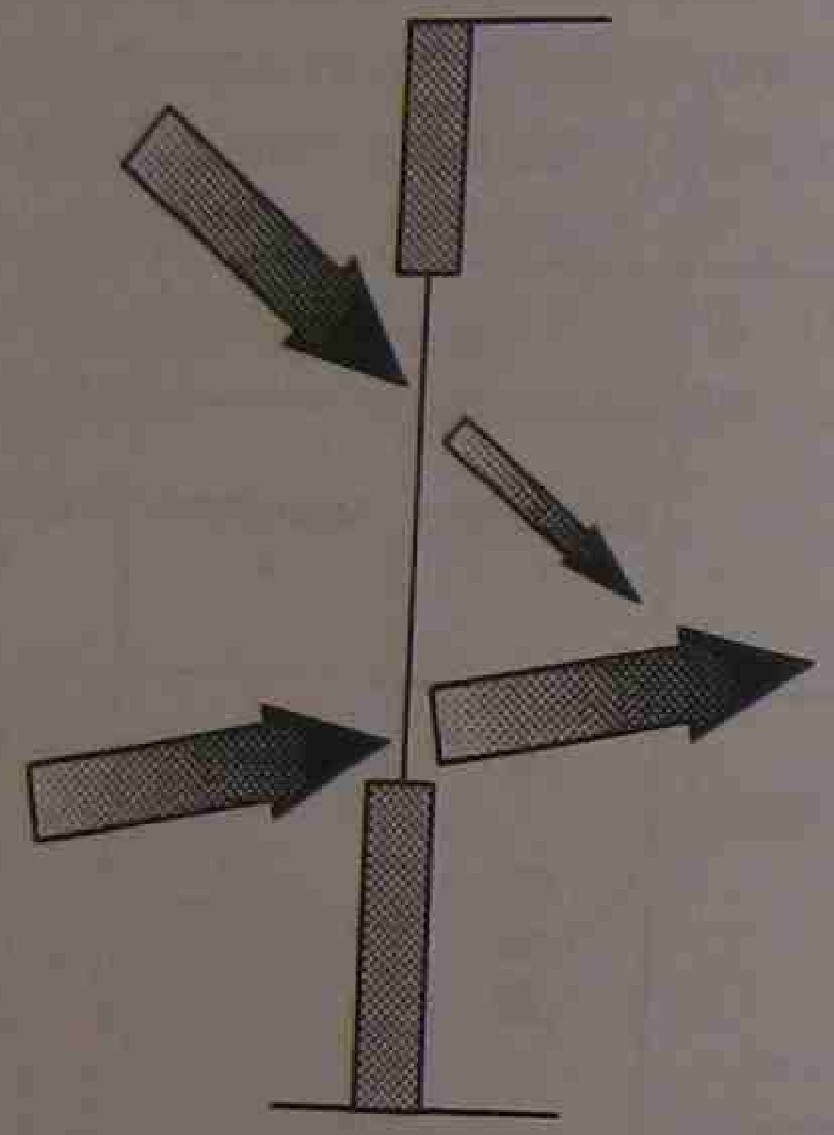


Figure 7 - Angular selective coatings reduce the intensity of sunlight coming from the sky.

Getting daylight to parts of a building where there are no outside walls which can be converted to windows has also been achieved in a number of ways. **Skylights** have been around for a long time but they present special problems. It is virtually impossible to shade oblique upward facing planes so summer overheating can be a problem. In winter, cooling can take place when the warm air of the building rises to the skylight where it is transferred and lost to the outside. Double glazing can reduce this effect somewhat. Often a reflective well is used to direct the sunlight downward. This can however produce a distracting glare (Figure 8).

A number of **daylight systems** have been devised to reflect sunlight coming through a window onto the ceiling. This produces more even lighting and reduces glare, while enabling light to penetrate further into the building (Figure 9). The reflection can be achieved with external louvres or small reflectors built into the space between double glazing. A novel recent development uses very thin cuts in a plastic film sandwiched between two layers of glass. This causes some of the light to totally internally reflect onto the ceiling from where it is diffused into the room. The disadvantage with these systems is that the view out of the window is obstructed by slats or strips or some other visible distortion.

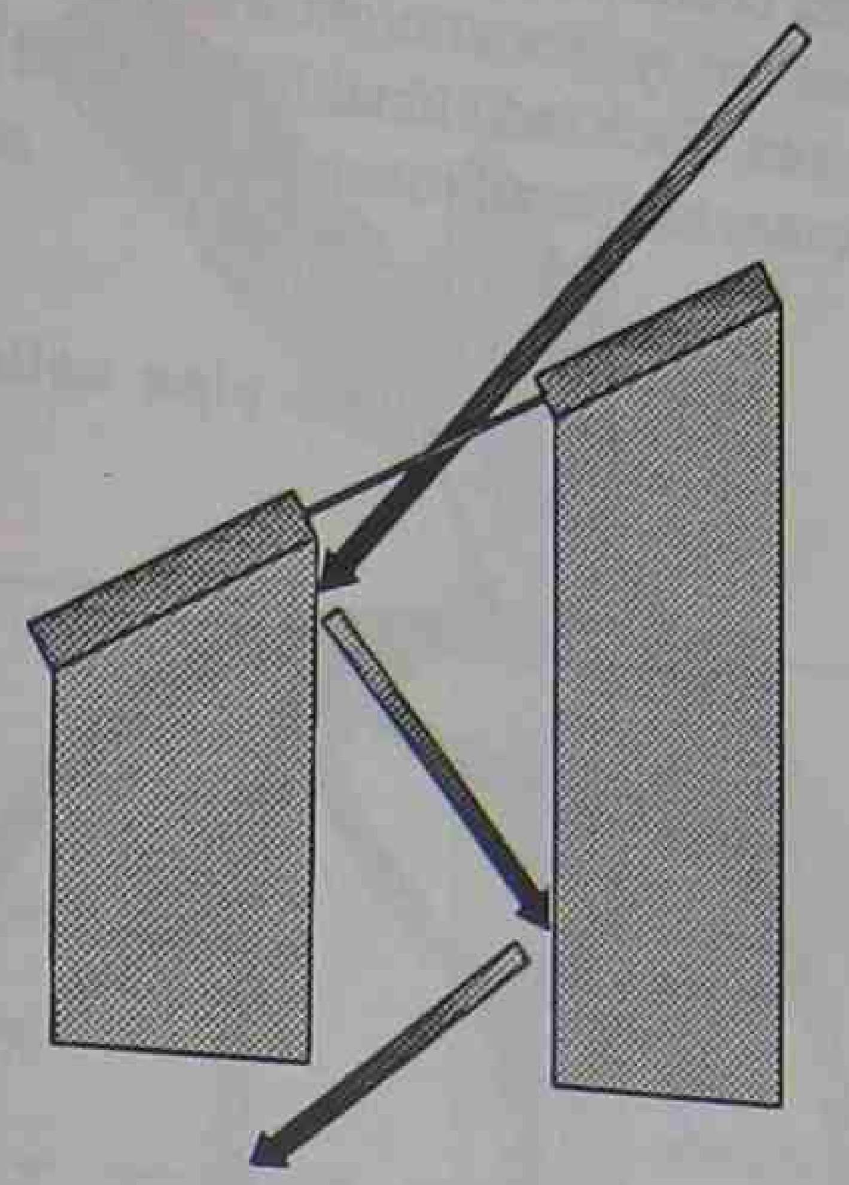


Figure 8 - Sunlight entering through a skylight is difficult to control and can produce glare.

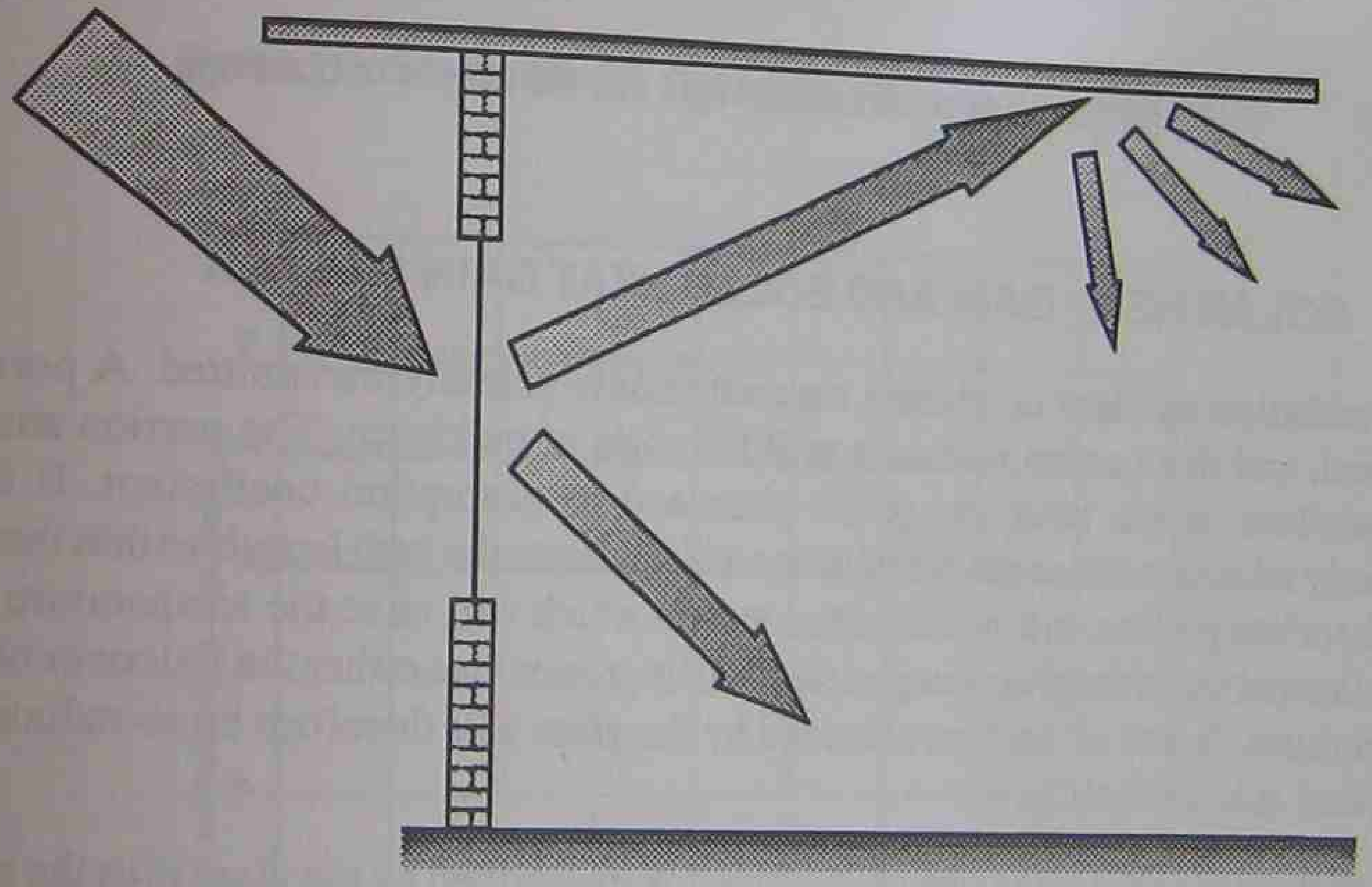


Figure 9 - Sunlight reflected onto the ceiling reduces glare and increases the depth of penetration of daylight.

Some interesting developments have taken place recently with **light pipes** which reflect light, in a similar way to an optic fibre, between 10 and 30m into a building. A collector outside of the building absorbs sunlight using a fluorescent dye which re-emits light over a wavelength range corresponding much more closely to the range over which we are able to see. In fact, more useable light is emitted at the end of the light pipe than is absorbed in the collector. This "cold" light is then totally internally reflected along the pipe. It is emitted at the end where the surface is roughened to overcome internal reflection. Several light pipes could be connected to a single collector (Figure 10). It would also be possible to use the system at night when a single efficient light source could be used instead of the sun. Each individual light would have to be provided with some sort of shutter arrangement to control intensity.

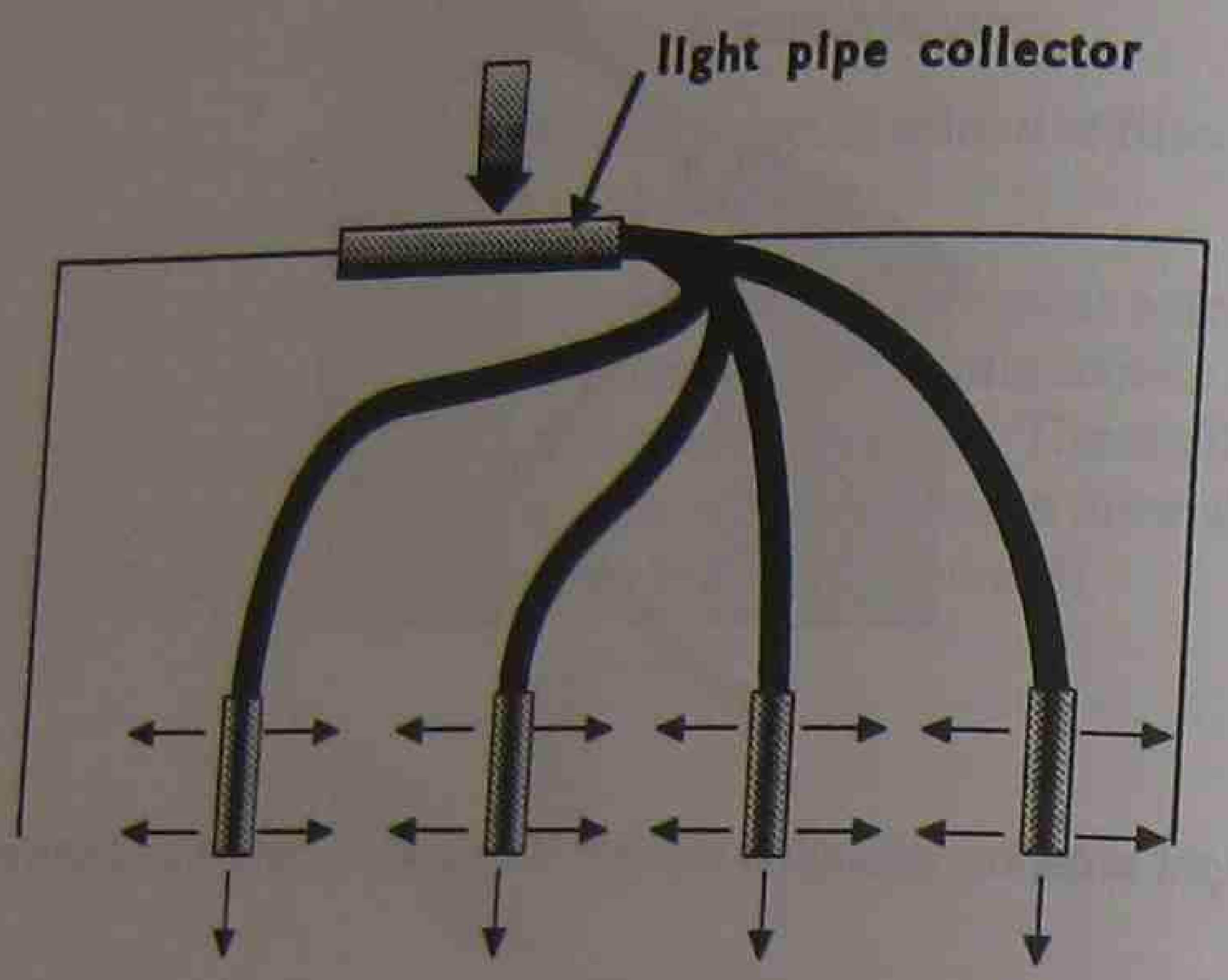


Figure 10 - Light pipes conduct light into the interior of buildings.

4 SOLAR HEAT GAIN AND SOLAR HEAT GAIN FACTOR

Solar radiation incident on glazing material is only partially transmitted. A portion is reflected, and this portion increases with the angle of incidence. The portion absorbed is dependent on the thickness of the glass and its absorption coefficient. It is also indirectly related to the angle of incidence which affects the path length within the glass. The absorbed portion will be converted to heat which will raise the temperature of the glass. In most cases the glass temperature will be greater than either the indoor or outdoor temperatures. Some of the heat absorbed by the glass will therefore be re-radiated and convected into the building.

Solar heat gain (SHG) is the sum of the solar flux transmitted by the glass plus the portion of the absorbed radiant flux that is radiated into the building.

The solar heat gain factor (SHGF) is the solar heat gain due to "standard" 3mm clear glass as defined by ASHRAE. For sunlight at normal incidence this is taken to be 0.88. The diagram in Figure 11 shows the energy flux breakup for "standard" 3mm window glass.

The energy flux breakup shown above is for sunlight at normal incidence. This is not usually the case so angle of incidence correction must be applied. The graph of Figure 12 shows the SHG as a function of angle of incidence for standard 3mm glass.

An average angle of incidence of 60° is used for the diffuse and reflected components of radiation. This value is very close to the theoretical value calculated for isotropic radiation.

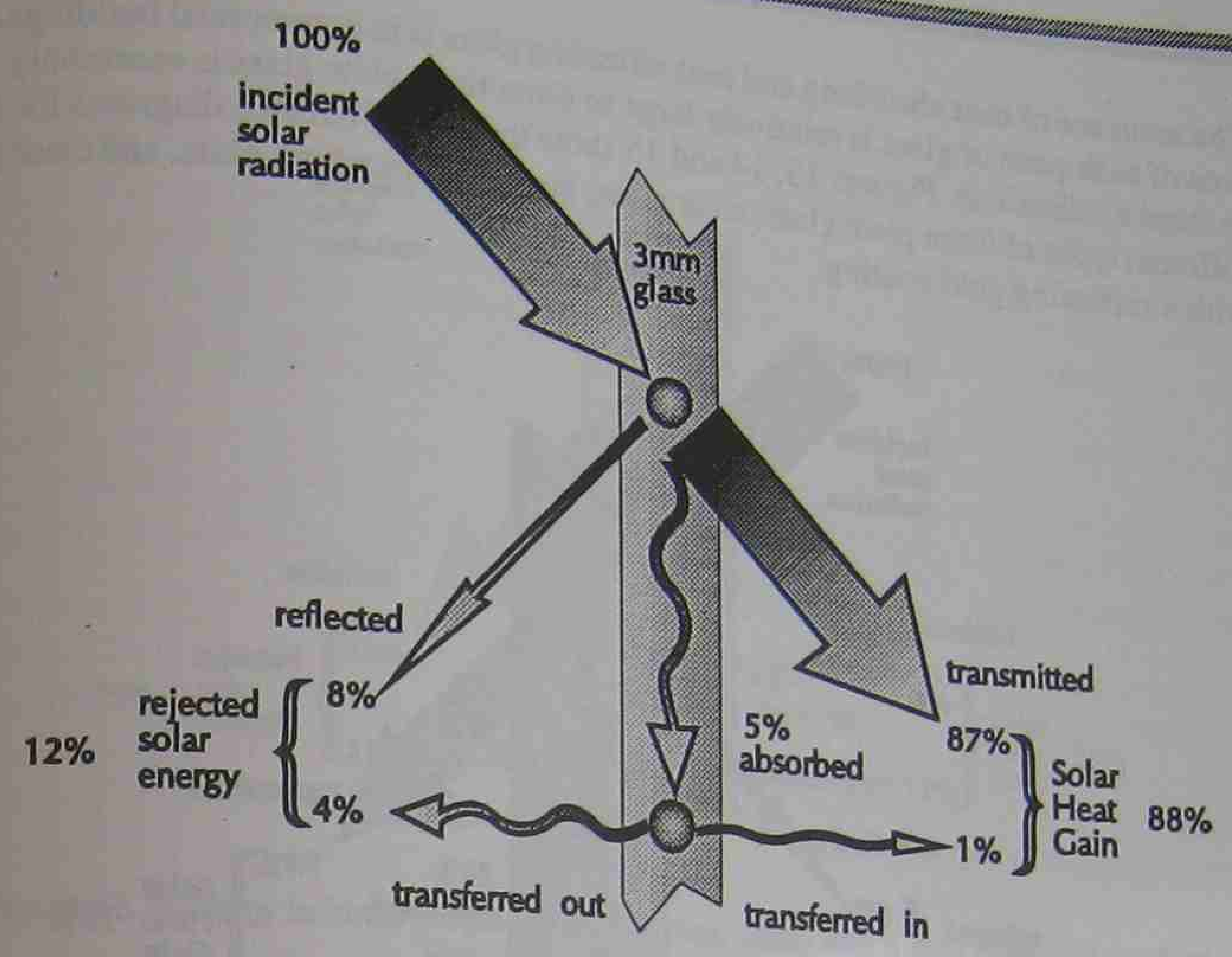


Figure 11 - Energy balance diagram for standard 3mm clear glass.

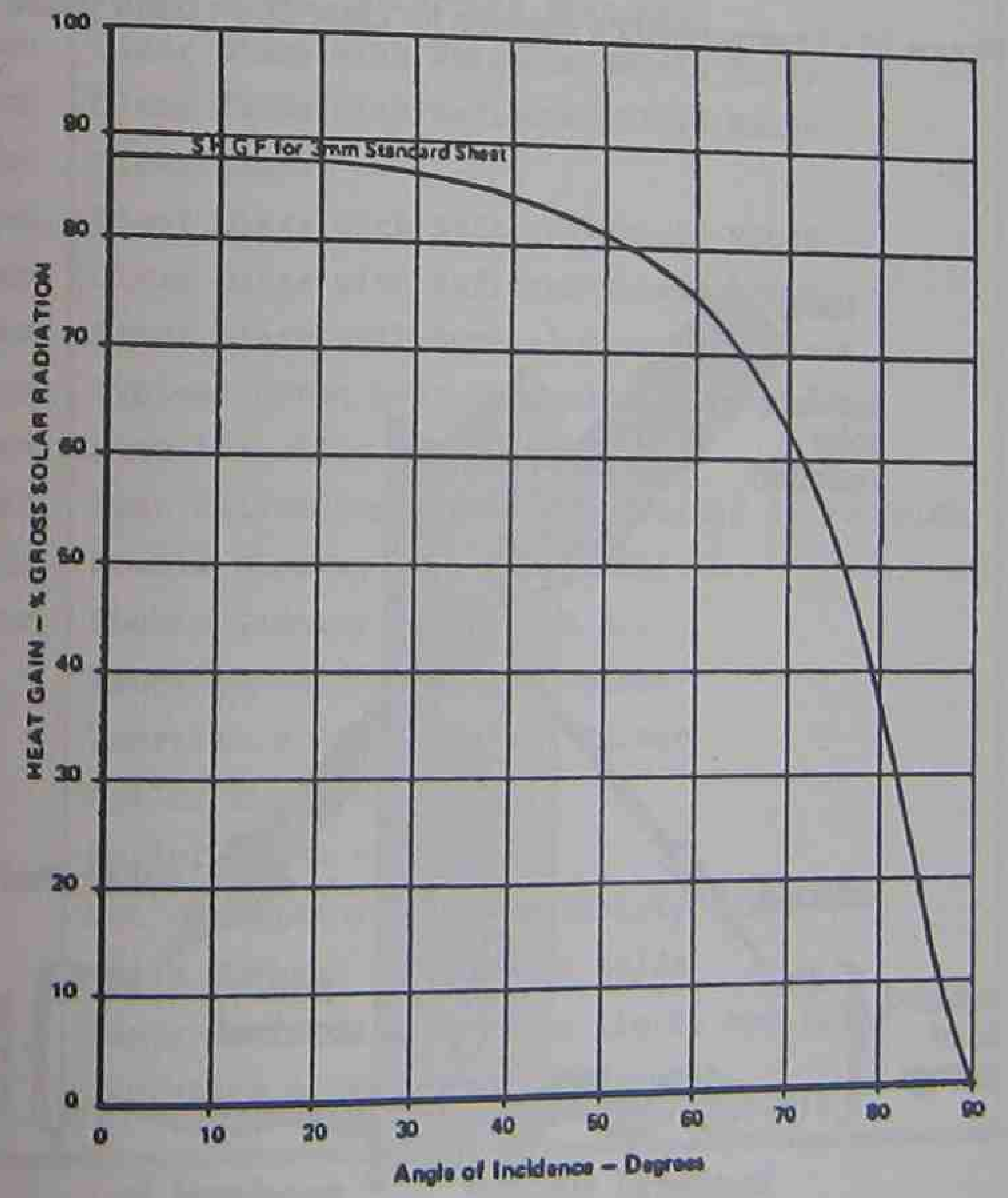


Figure 12 - Solar heat gain factor (SHGF) as a function of angle of incidence, (i.e., SHG for standard 3mm clear glass). (Source: Hassall, 1977).

The main use of heat absorbing and heat reflecting glass is in commercial buildings. The area of each pane of glass is relatively large so 6mm thick plate glass is commonly used in these applications. Figures 13, 14 and 15 show the energy balance diagrams for three different types of 6mm plate glass; clear glass, grey heat absorbing glass, and clear glass with a reflecting gold coating.

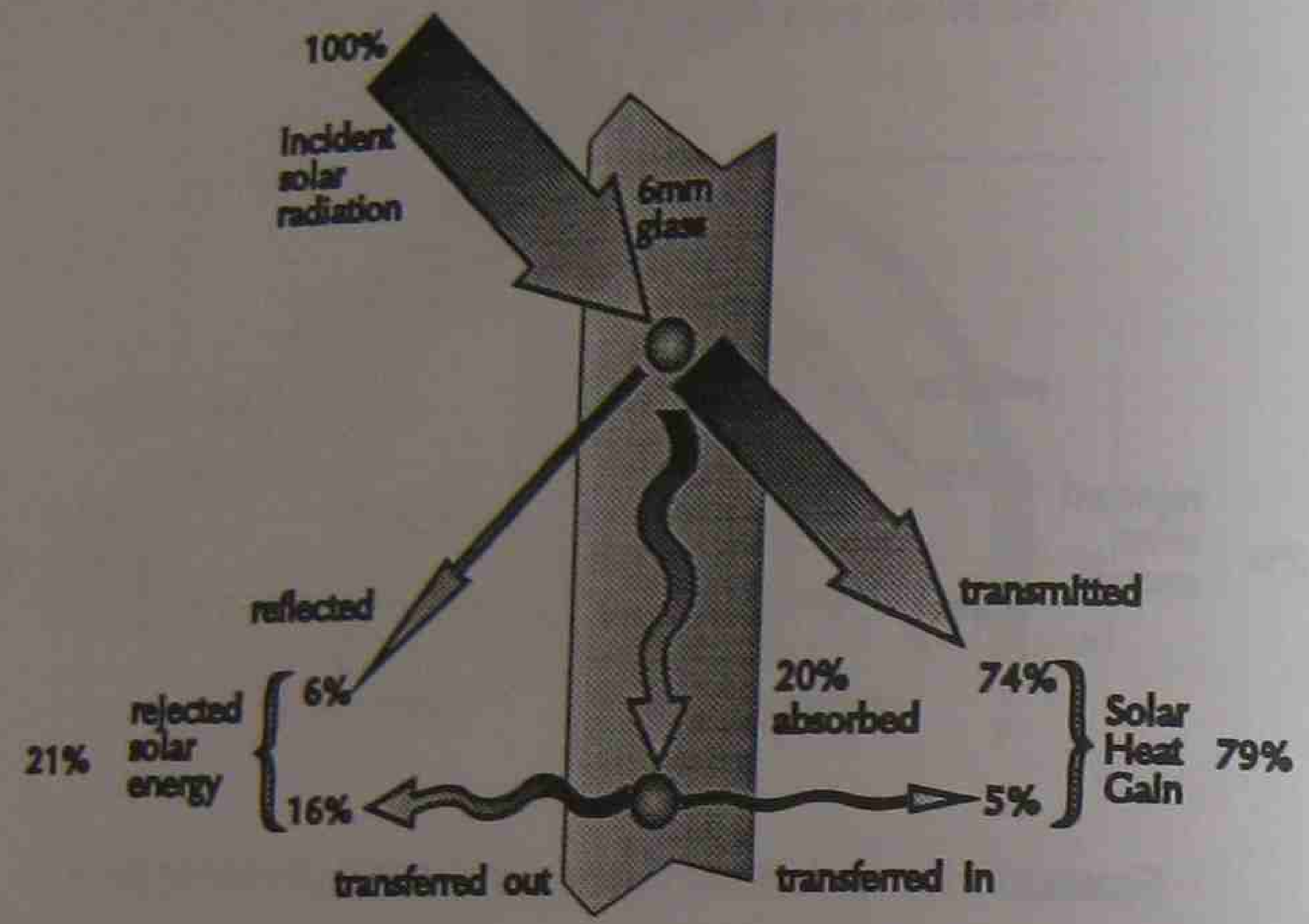


Figure 13 - Energy balance diagram for clear 6mm plate glass.

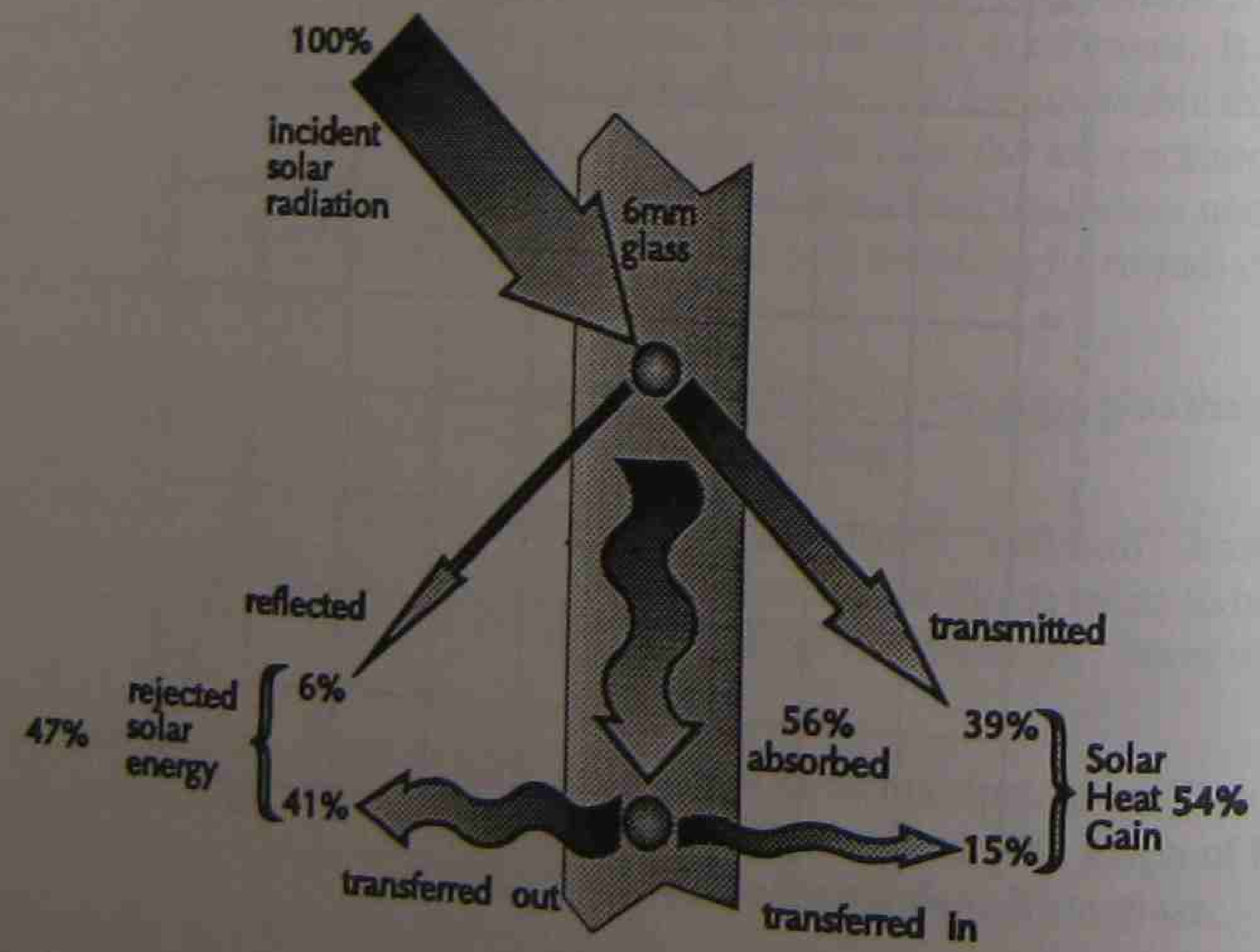


Figure 14 - Energy balance diagram for 6mm grey heat absorbing glass.

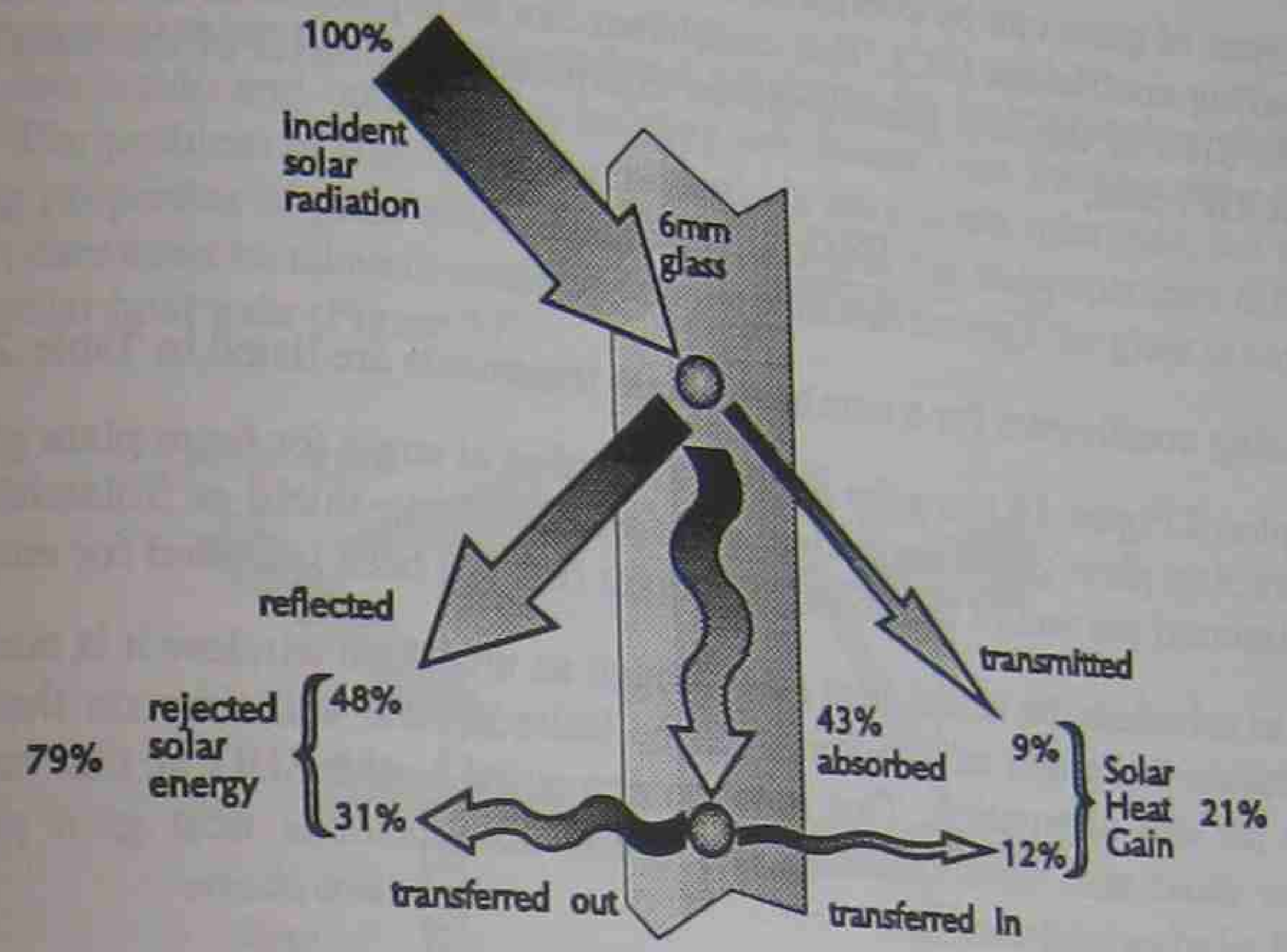


Figure 15 - Energy balance diagram for 6mm clear glass with a gold reflecting coating - Pilkington's Solarshield 15/32.

Thick	Material	SC
3 mm	Clear Glass (Reference Standard)	1.00
3 mm	Clear Glass with Reflecto-Shield RSL40	0.44
3 mm	Clear Glass with Reflecto-Shield RSL20	0.25
6 mm	Clear Glass	0.90
6 mm	Clear Glass with Reflecto-Shield RSL40	0.45
6 mm	Clear Glass with Reflecto-Shield RSL20	0.27
6 mm	Clear Glass with Typical Green Flow Coat	0.70
6 mm	Typical Green Heat Absorbing Glass	0.67
6 mm	Heat Absorbing Grey Glass	0.61
6 mm	Heat Reflecting Glass (Solarshield 15/23-Gold)	0.24
3+3mm	Double Glazing (Clear + Clear)	0.90
3+3mm	Double Glazing (Clear + H.A.)	0.56
	Venetian Blinds - Light Colour	0.55
	Venetian Blinds - Medium Colour	0.64
	Roller Shade - White	0.40
	Roller Shade - Medium	0.62
	Net Curtains with folds (fairly dark)	0.75
	White Curtain lining with folds	0.45
	Heavy Curtains with white lining and folds	0.35
	Miniature Louvres - dark 17/inch	0.49 -0.13

Table 2 - Shading coefficients for various window treatments. (Source: Hassall, 1977).

Other types of glass can be compared to the standard 3mm glass by using the concept of a shading coefficient (SC). This coefficient can be expressed as a ratio of the solar heat gain SHG of the new glazing system compared to the SHG of the standard 3mm glass (SHGF) thus,

$$SC = \frac{SHG}{SHGF}$$

The shading coefficients for a number of glass treatments are listed in Table 2.

The graphs of Figure 16 show the SHG as a function of angle for 6mm plate glass, grey heat absorbing plate glass, 6mm clear glass with Reflecto-shield or Solarshield. Note that the internal portion of the absorbed radiant flux has been included for each graph.

In order to calculate the actual heat gain through an unshaded window it is necessary to first calculate the angle of incidence for the latitude, date and time on the plane of arbitrary tilt and orientation. This must be converted to the SHG at that angle. The irradiance must also be calculated. The actual instantaneous heat gain per m^2 of unshaded window will then be:

$$P = G_{b\beta} \times SHG(\theta) + G_d \times SHG(60^o) + G_r \times SHG(60^o)$$

where $G_{b\beta}$ - beam irradiance on a plane of tilt β
G_d - diffuse irradiance on the plane
G_r - reflected irradiance on the plane
θ - angle of incidence of light on the plane

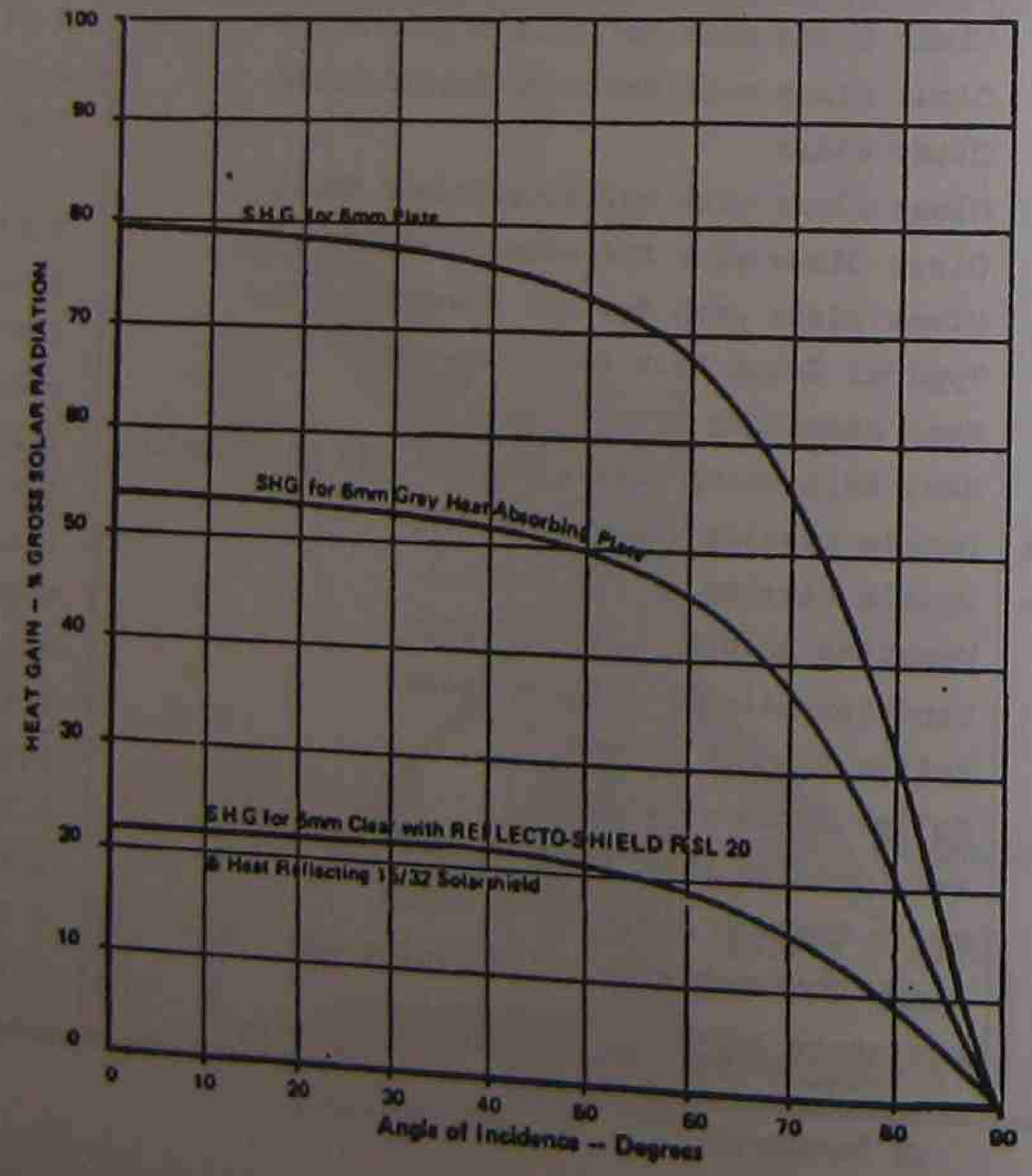


Figure 16 - Solar heat gain (SHG) as a function of angle of incidence for various glass treatments. (Source: Hassall, 1977).

5 WINDOW GAINS AND LOSSES

Heat losses and gains through conventional windows due to temperature differences between the inside and outside of a building are greater than for any other building element. The problem in summer is that not only is there direct solar gain, but the poor insulating properties of glass allow significant heat gain due to temperature difference. In winter, care must be taken to establish that the heat loss through the glass is not greater than the solar heat gain (Figure 17).

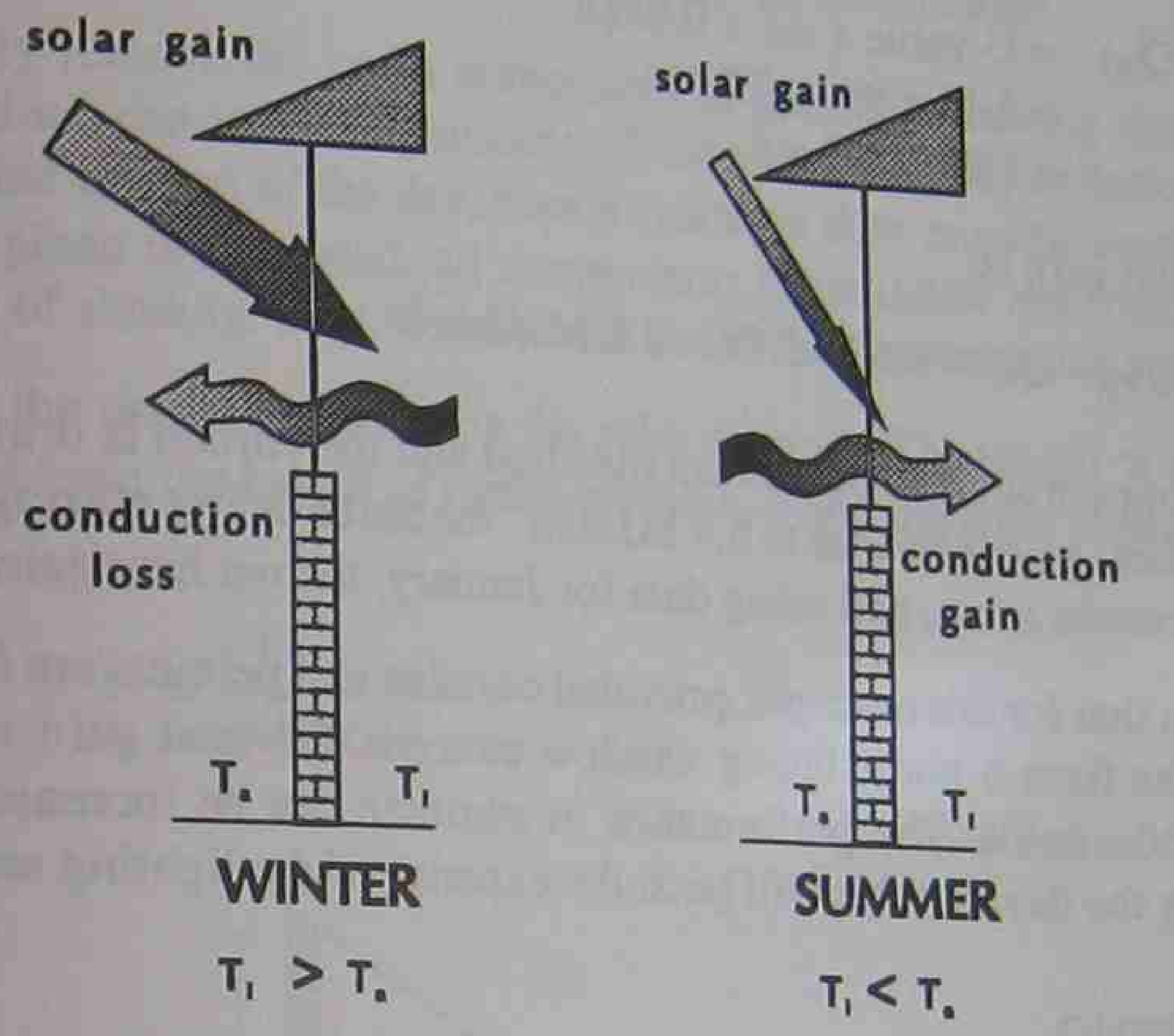


Figure 17 - Energy transfer through windows for summer and winter.

Example: Calculate the net gain or loss of heat through a north facing single glazed window for January and July in Sydney. The window is 0.9m high and 0.2m from the bottom of the eaves which are 0.6m wide. Assume for the window that 90% of it is glass, the transmittance is 0.76 and the U-value is 6.14.

Calculation for July: From computer program RAD, in July $H_o = 8.80$ MJ/d.m^2. On a vertical wall facing North $H_v = 12.87$ MJ/d.m^2 and if the wall is shaded $H_{vs} = 12.67$ MJ/d.m^2.

The daily gain for a window is:

$$\begin{aligned} Q_{wg} &= H_{vs} \times \% \text{ glass} \times \text{transmittance} \\ &= 12.67 \times 0.9 \times 0.76 \\ &= 8.67 \text{ MJ/d.m}^2 \end{aligned}$$

The average temperature for July is:

$$\begin{aligned} T_{av} &= \frac{T_{max} + T_{min}}{2} \\ &= \frac{16.8 + 6.5}{2} \\ &= 11.7^oC \end{aligned}$$

Using Auliciem's formula for the comfort temperature:

$$T_i = 17.6 + (0.31 \times T_{av}) = 21.2^oC$$

So,

$$\Delta T = T_i - T_{av} = 9.5^oC$$

Total heat loss from a window for a day is:

$$Q_{wl} = \text{U-value} \times \Delta T \times 0.0864 = 6.14 \times 9.5 \times 0.0864 = 5.04\ \text{MJ/d.m}^2$$

So the net heat gain is:

$$Q_{wg} - Q_{wl} = 8.67 - 5.04 = 3.6\ \text{MJ/d.m}^2$$

If a well fitting curtain and pelmet are installed and the curtain is drawn for half of the time the net heat gain increases to 6.3 MJ/d.m^2 for north facing glazing. Using the same pelmet and curtain setup, and using data for January, the net heat gain is 5.3 MJ/d.m^2.

It can be seen that for this example, provided curtains and pelmets are fitted, the net heat gain in winter from a north facing window exceeds the heat gain in summer, when heating is undesirable. The performance in summer can be increased if curtains are drawn during the day, but this will be at the expense of daylighting and views.

6 SHADING

An understanding of shading is fundamental to solar efficient building design. It is important to know what effects obstructions around a proposed building site will have on the solar site. It is also necessary to know the effects of eaves and shading devices on the solar gains of walls and through windows.

6.1 Shading and Solar Access

Shading can be caused by obstructions such as trees on the building site or by trees or buildings on adjacent sites. It is this second problem that is most difficult to address on small building lots.

It has been shown that high density housing provides cheaper servicing and better energy efficiency as far as transportation and services reticulation is concerned. However, unless a street runs near east-west solar access will be restricted in this situation.

Solar heating of buildings through windows in winter and controlled shading of walls and windows in summer can be achieved easily if most of the glazing is orientated to within 20° degrees east or west of north. Minimum allotment sizes of 600m^2 restrict this solar access when the need for privacy is considered, unless streets are orientated near east-west. Even if the dimensions of the block are such that a house on a north-south running street can be made to face north, there will still be insufficient space to provide shrubs or trees for privacy to the north of the house without severely shading the building during the heating months.

Subdivisions must make allowances for views, slopes, creeks, railways, interconnectivity of streets, etc., so it is not always possible to run streets east-west. However, for new subdivisions the minimum size of the block should be governed by its solar access as determined by block shape and the orientation of the street.

Even with sensible town planning for solar access the situation can still arise where a tree or building on an adjacent site can significantly block sunlight.

6.2 Calculation of Shadow Length and Sun Penetration

Shading will only remove the beam component of radiation, leaving the diffuse and reflected parts which can still be significant. To calculate the daily radiation on a plane that will be shaded for part of the day, hourly radiation data must be used. During the hours when the plane is unshaded, all components of radiation are considered while during the hours of shading, only the reflected and diffuse components are used.

The direction of the shadow is given by the solar azimuth. The length of the shadow, l can be calculated from the height of the obstruction, h and the solar altitude, α (Figure 18).

$$l = \frac{h}{\tan \alpha}$$

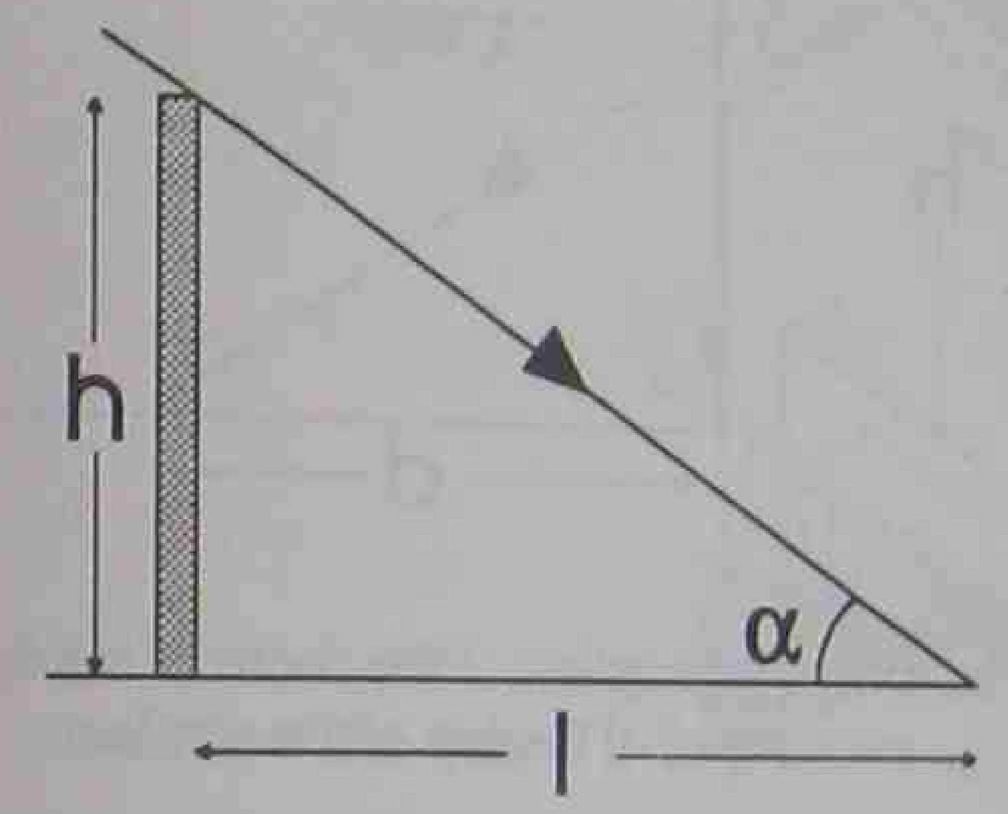


Figure 18 - Diagram used for the calculation of the length of a shadow.

The azimuth and the altitude can therefore be used to calculate the times and dates when a site will be shaded. Shadows will be larger in winter than in summer so obstructions on the north side will cut down the winter sun without necessarily casting a shadow in summer when this would be useful. Sun shadow angles can be found using a shadow angle protractor such as the one in the book by Phillips (1983).

6.3 Sunlight Penetration into a Room

It is useful to know the depth of sunlight penetration through a window into a room. This distance d, is measured along the normal to the wall containing the window of height h (Figure 19):

$$d = \frac{h \cos(\gamma + \psi)}{\tan \alpha}$$

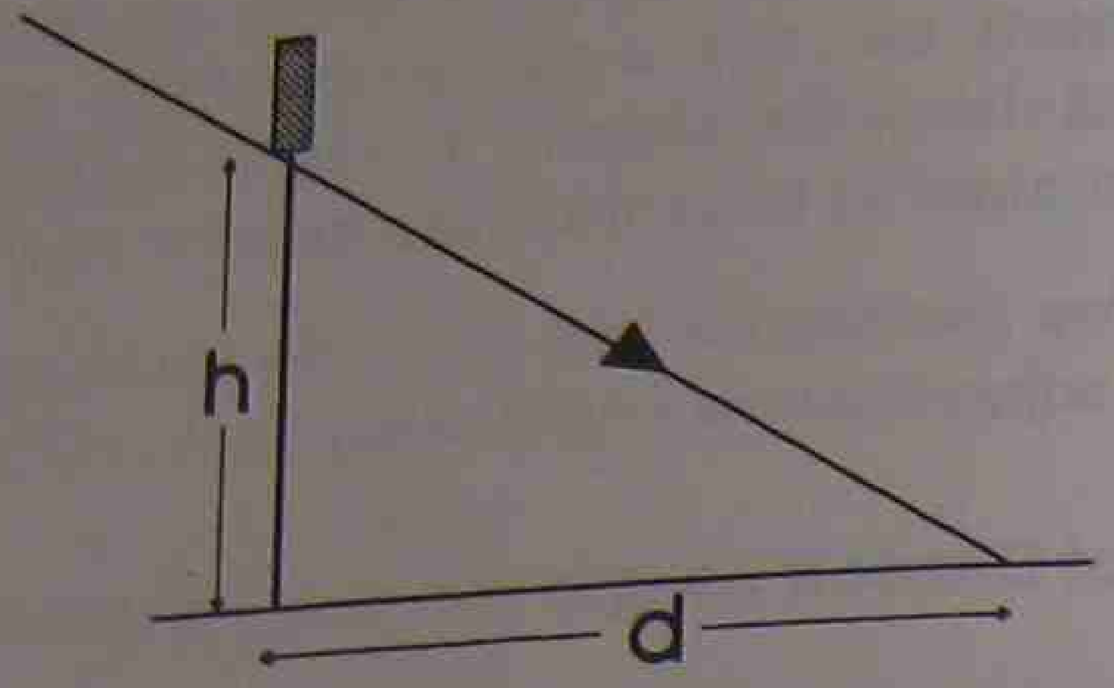


Figure 19 - Diagram used for the calculation of the depth of sunlight penetration through a window into a room.

For eaves of width w, which start at the top of the window, this distance will be (Figure 20):

$$d = \frac{h \cos(\gamma + \psi)}{\tan \alpha} - w$$

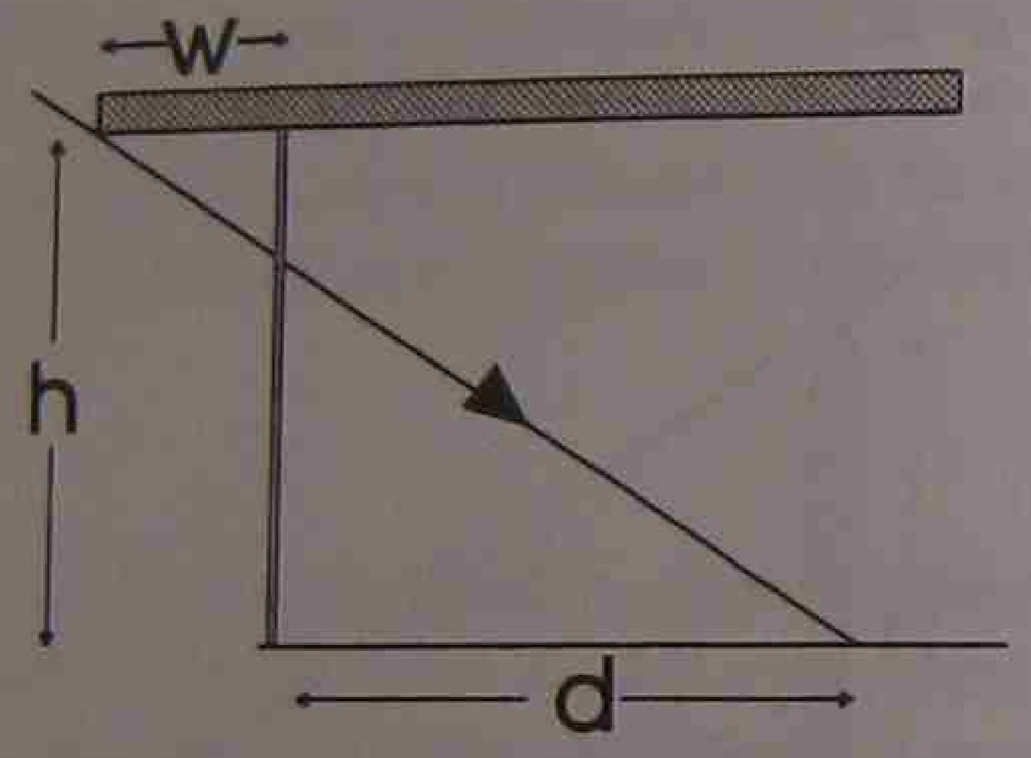


Figure 20 - Diagram used for the calculation of the depth of sunlight penetration where the eaves start at the top of the window.

The calculations are usually more complicated than this since most windows do not start at the floor or continue to eaves height. The equivalent eaves width (w) must be calculated and the sunlight floor patch will not start at the wall (Figure 21).

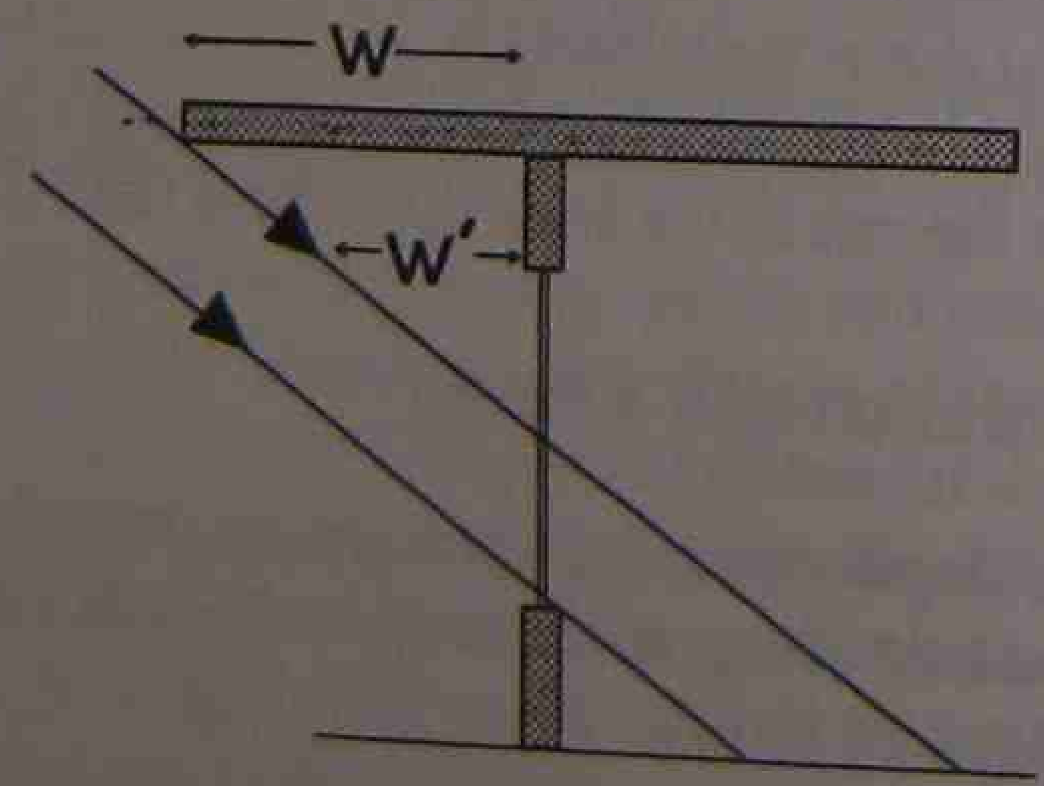


Figure 21 - Most windows do not occupy all the space between the floor and the eaves. The calculation of sunlight penetration for real windows is more complex.

Although the amount of solar energy coming through a window cannot be calculated from the sunlight penetration depth, this distance can be important when considering the type of surface to use on a high thermal mass floor such as a concrete slab. If the sunlit floor is dark then most of the energy will be absorbed by the surface and stored in the floor. If the sunlit floor is a light colour then most of the sunlight will be reflected, to be more or less evenly distributed to the walls, floor and ceiling. This may not be such a desirable situation, because the ceiling will have no thermal mass. The walls will only have good thermal mass if they are masonry. However, most homes with a concrete slab floor will have carpet in the living area, which will be on the north side (if the house is zoned optimally) and be sunlit in winter. In this case it would be worth considering using slate or dark floor tiles for the sunlit strip near the wall and using carpet elsewhere.

6.4 Vertical and Horizontal Sun Angles

Vertical (VSA) and horizontal (HSA) sun angles are used to calculate the shape of shadows on walls caused by horizontal or vertical sunbreak devices (Figure 22).

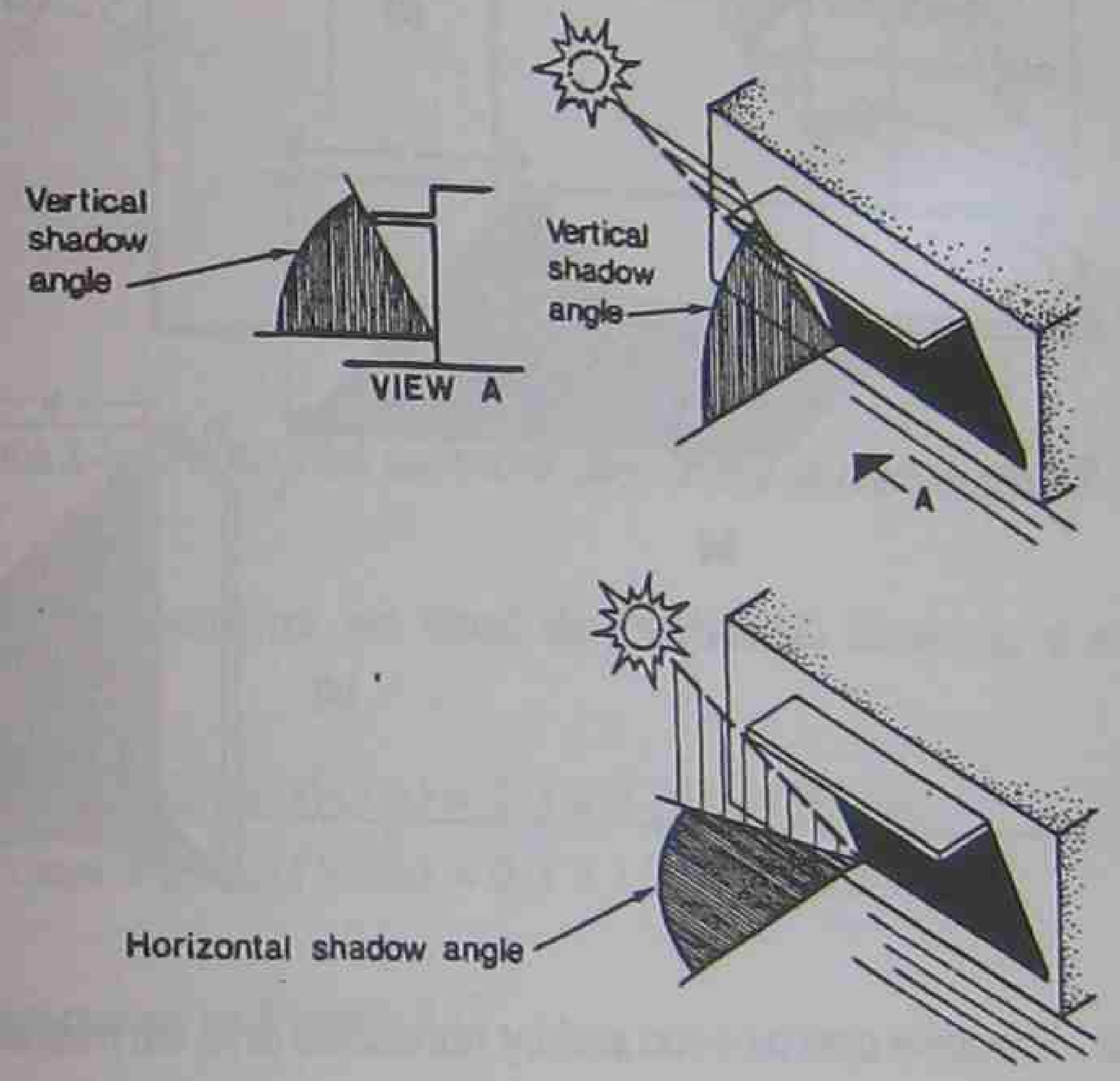


Figure 22 - Vertical and horizontal sun angles. (Source: Phillips, 1983).

Consider a point of distance one unit from a wall length, tan (VSA) is the vertical distance and tan (HSA) the horizontal distance of the shadows from the normal projection of the point on the wall. It can be seen from the diagram (Figure 23(a)) that the end of a shadow of a rod of length l will be displaced a horizontal distance u and a vertical distance v, where:

$$u = l \tan(\mathrm{HSA})$$

$$v = l \tan(\mathrm{VSA})$$

For long horizontal sunbreaks such as eaves, it is VSA which determines the length of the shadow down the wall (Figure 23(c)). The length of horizontal shadows cast by long vertical shading devices is determined by the HSA (Figure 23(d)).

The HSA can be found from the difference between orientation (γ) and the azimuth (ψ) thus:

$$HSA = \gamma + \psi \quad \text{(The positive value of } \gamma + \psi\text{).}$$

The VSA is related to the HSA and the altitude (α). Trigonometry can be used to show that:

$$\tan VSA = \frac{\tan \alpha}{\cos HSA}$$

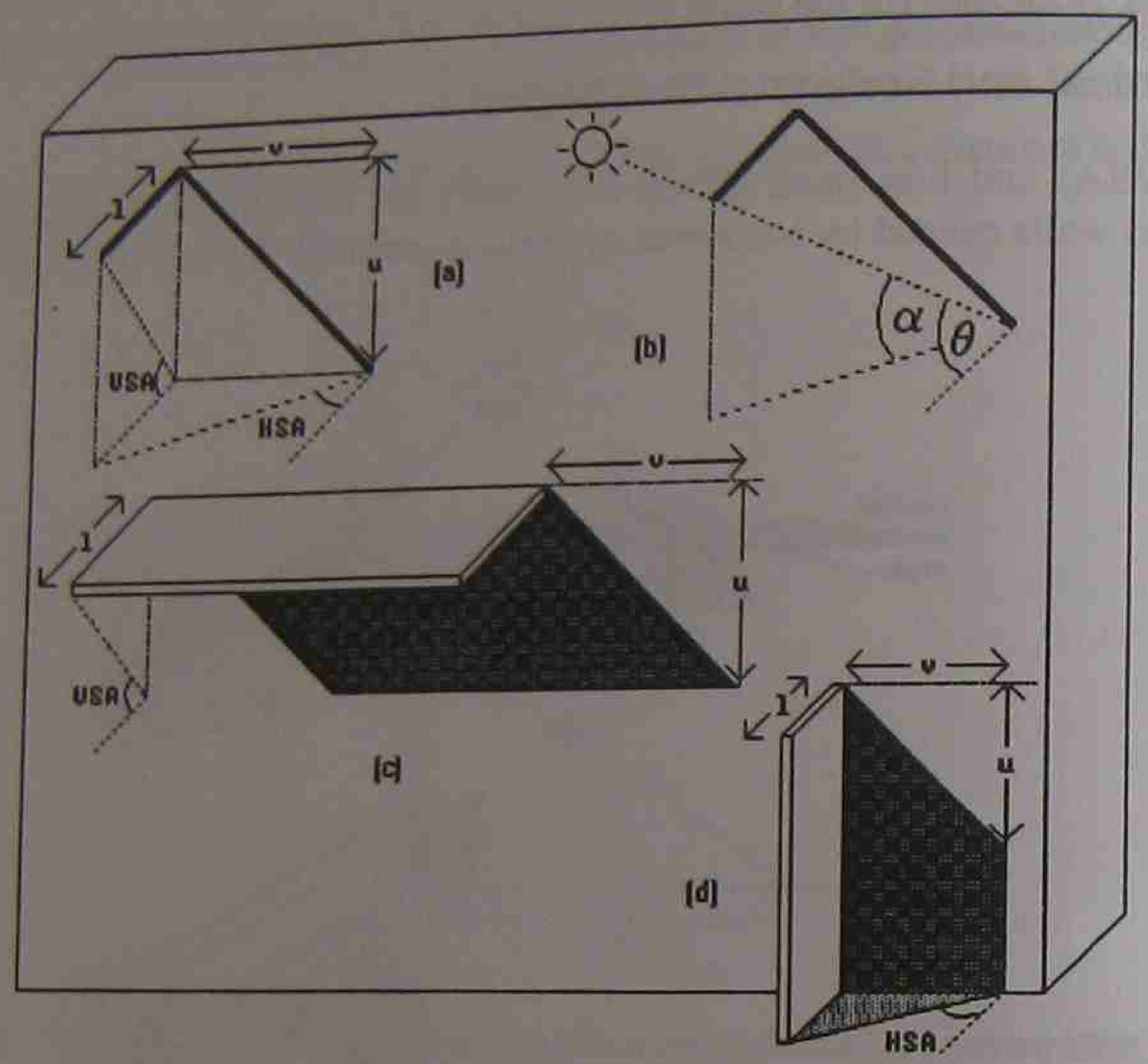


Figure 23 - Shadows cast by a rod and by horizontal and vertical shading devices.

Example: Calculate the shape of the shadow formed on a 1m x 1m western window in Brisbane at 3pm solar time on November 1, if shaded by a horizontal sunbreak of width 300mm attached 200mm above the window (Figure 24). The latitude of Brisbane is 27.5° South.

Solution: To find the azimuth and altitude the following methods can be used:

- ☐ hand calculations (described in Unit 2).
- ☐ solar charts (if one is available for that location)
- ☐ computer programs such as SOLPOS.
- ☐ Spencer's Solar Tables.

Using SOLPOS:

$$\alpha = 46.39 \text{ and } \psi = 82.49$$

Now

$$HSA = |\gamma + \psi| = -90 + 82.49 = 7.51$$

$$\tan VSA = \frac{\tan a}{\cos HSA} = \frac{\tan 46.39}{\cos 7.51} = 1.059$$

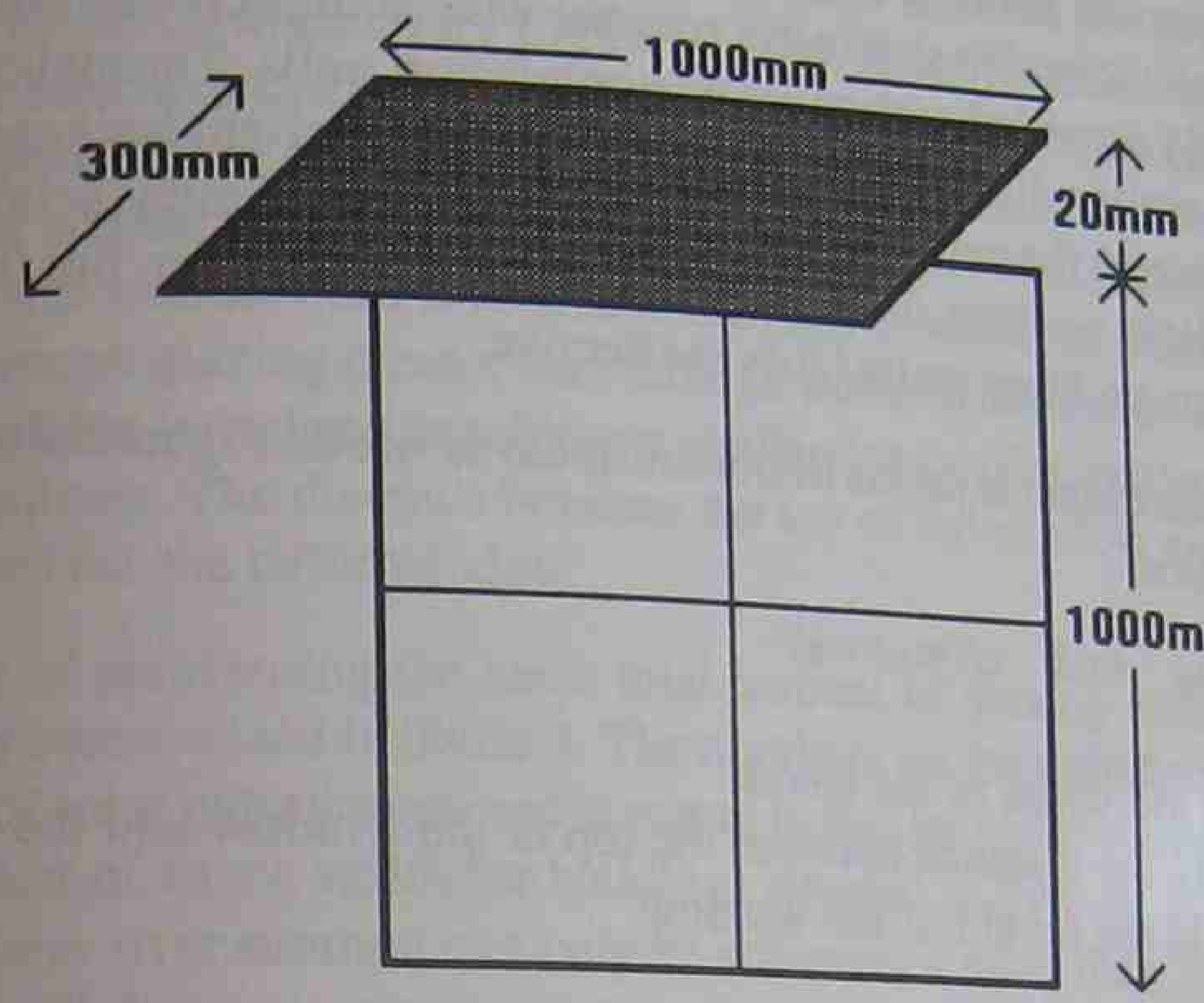


Figure 24 - Horizontal sunbreak used in the worked example.

To find the shadow dimensions we need the horizontal distance, u and the vertical distance, v:

$$u = L \tan (HSA) = 0.3 \times 0.1318 = 0.04\text{m}$$

$$v = L \tan (VSA) = 0.3 \times 1.059 = 0.32\text{m}$$

The shadow will appear as in Figure 25.

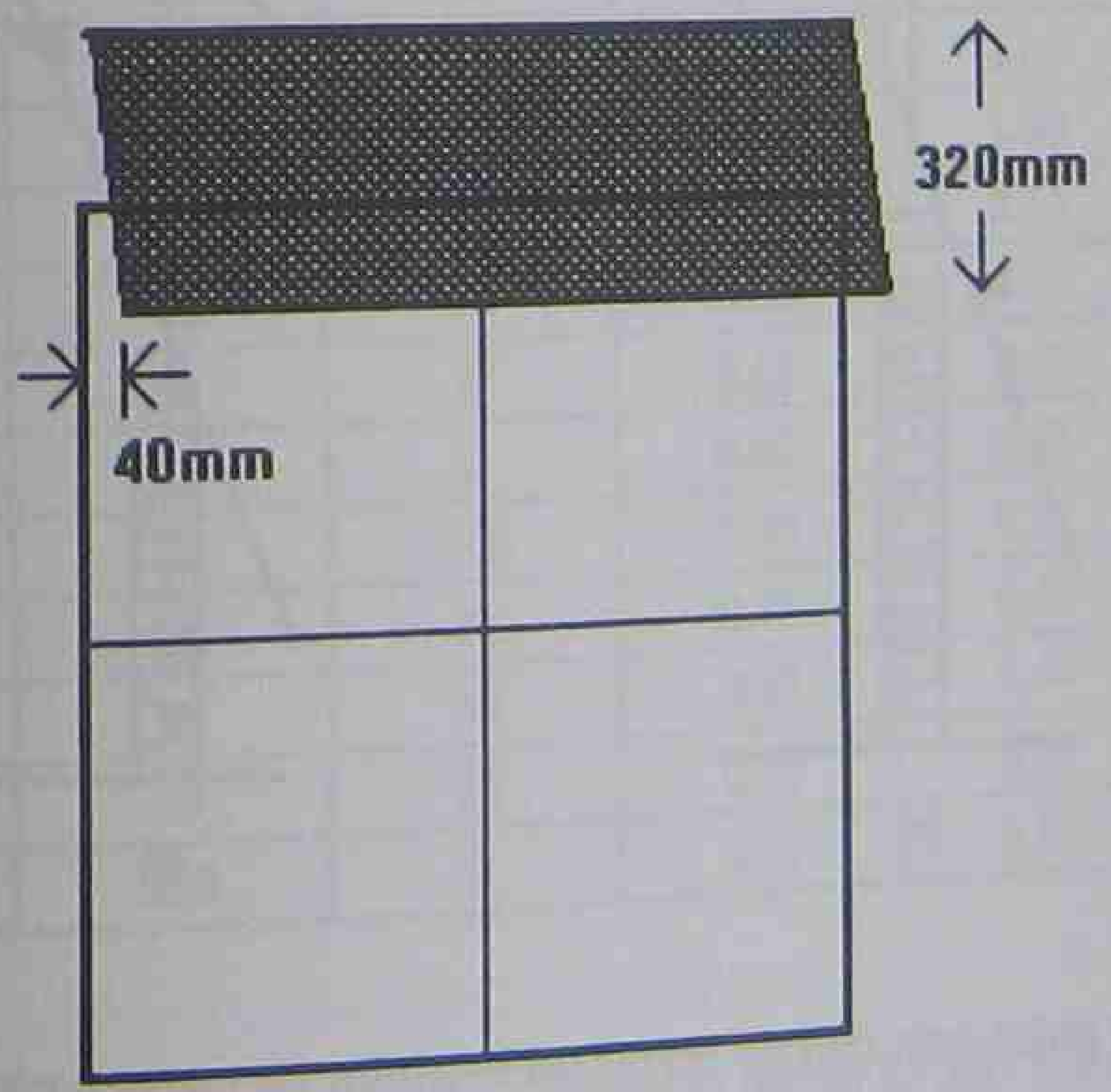


Figure 25 - Shadow produced for the example above.

7 EFFECT OF SHADING ON HEAT GAINS

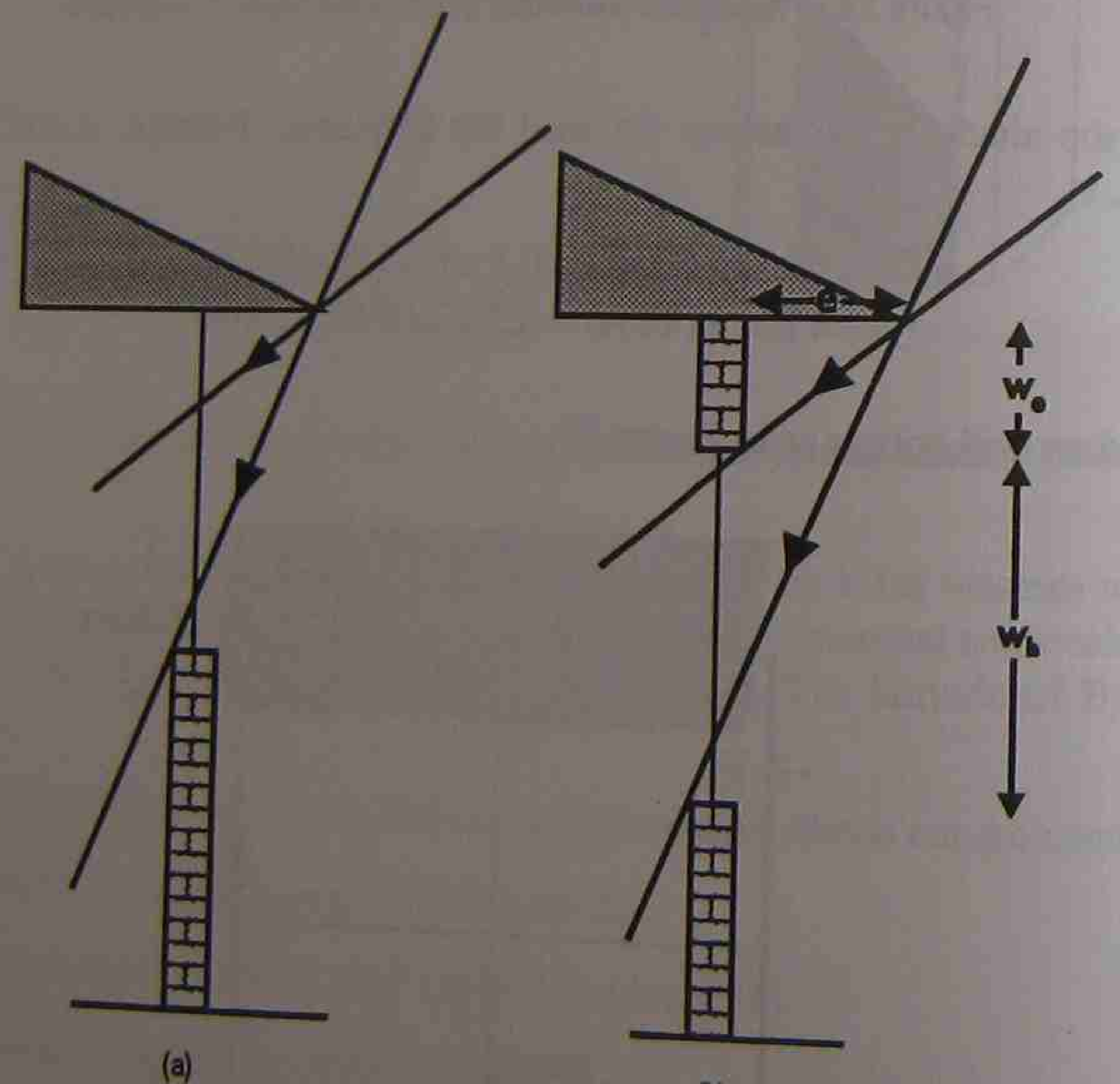
Shading devices external to the glazing system can be designed to exclude the direct or beam component of solar radiation. However, the diffuse and reflected components of sunlight can still contribute a significant amount of energy. Even the beam components may not be completely excluded for certain times of the day.

Perhaps the most common shading device is the eaves, formed when the roof extends past the top of the wall. Selective shading in summer with sunlight penetration in winter can only be effectively provided with eaves on north facing walls. Throughout the year, east and west facing walls will be largely exposed to direct sunlight because of the low altitude angle of the sun in the early morning and late afternoon. South facing walls will only have direct sunlight on them during the summer half of the year, but the very low sun angles make eaves on these walls fairly ineffective.

Window height and placement is just as important as eaves width. Figure 26(b) illustrates the two important ratios;

$$e/w_e \quad \text{and} \quad e/(w_e+w_h)$$

where
- e is the width of the eaves
- w_e is the distance between the top of the window and the eaves
- w_h is the height of the window



(a) (b)

Figure 26 - Greater solar gain can be achieved in winter by careful placement of the window with respect to the eaves.

These two ratios determine when the sun is excluded and when it is admitted into a window. It can be seen from Figure 26(a) that if the window is too close to the eaves then the winter sun will be excluded to some extent as well as the summer sun. A better solution is shown in Figure 26(b) where by lowering the window and increasing the eaves width, the same summer sun exclusion occurs with full winter sun penetration.

The graphs of Figure 27 show the daily irradiation on 0.9m and 1.8m windows on north walls in Sydney. Each case has a distance of 0.2m between the eaves and the top of the window. The eaves widths vary from 0 to 1.2m. It can be seen from both sets of curves that winter selective shading works only over a limited range of eaves width. Once the eaves are greater than about 0.6m, the attenuation in winter becomes significant and the net effect is similar to having smaller windows to start with. The disadvantage of larger windows over smaller ones is related to the high U-values of windows, making the heat transfer through glazing greater than through walls. Wider eaves widths are required for the longer (1.8m) windows to achieve a similar degree of selective shading to the shorter (0.9m) windows. The distance between the top of the window and the eaves must also be increased for the taller window.

The effect of distributing the same total amount of glazing around the perimeter of a building is summarised in Table 3. The numbers on the right hand side of the table are the ratios of solar radiation gained in winter to that gained in summer. They are tabulated as a function of eaves width for buildings situated in Sydney. It can be seen that a net gain in winter over summer can only be achieved if more than 70% of the glazing is in the north wall. For poor glazing distributions, where only one quarter or less of the total glazing is in the north wall, it is actually an advantage to place the bulk of the remaining glazing in the east wall rather than the south wall.

Glazing Distributions (%)			North Eaves Width (M)		
N	S	E&W	0 - 0.3	0.3 - 0.6	0.6 - 0.9
100	0	0	1.43	1.90	1.66
75	25	0	1.16	1.45	1.29
75	0	25	1.12	1.37	1.24
50	50	0	0.88	1.05	0.94
50	25	25	0.88	1.04	0.94
50	0	50	0.87	1.00	0.94
25	0	75	0.67	0.73	0.72
25	25	50	0.65	0.71	0.69
25	50	25	0.63	0.69	0.67
25	75	0	0.60	0.67	0.63
0	0	100	0.50	0.52	0.54
0	25	75	0.47	0.49	0.51
0	50	50	0.43	0.44	0.46
0	75	25	0.38	0.39	0.40
0	100	0	0.31	0.32	0.34

Table 3 - Ratio of solar radiation gained in winter to that gained in summer in Sydney for various glazing distributions around a building.

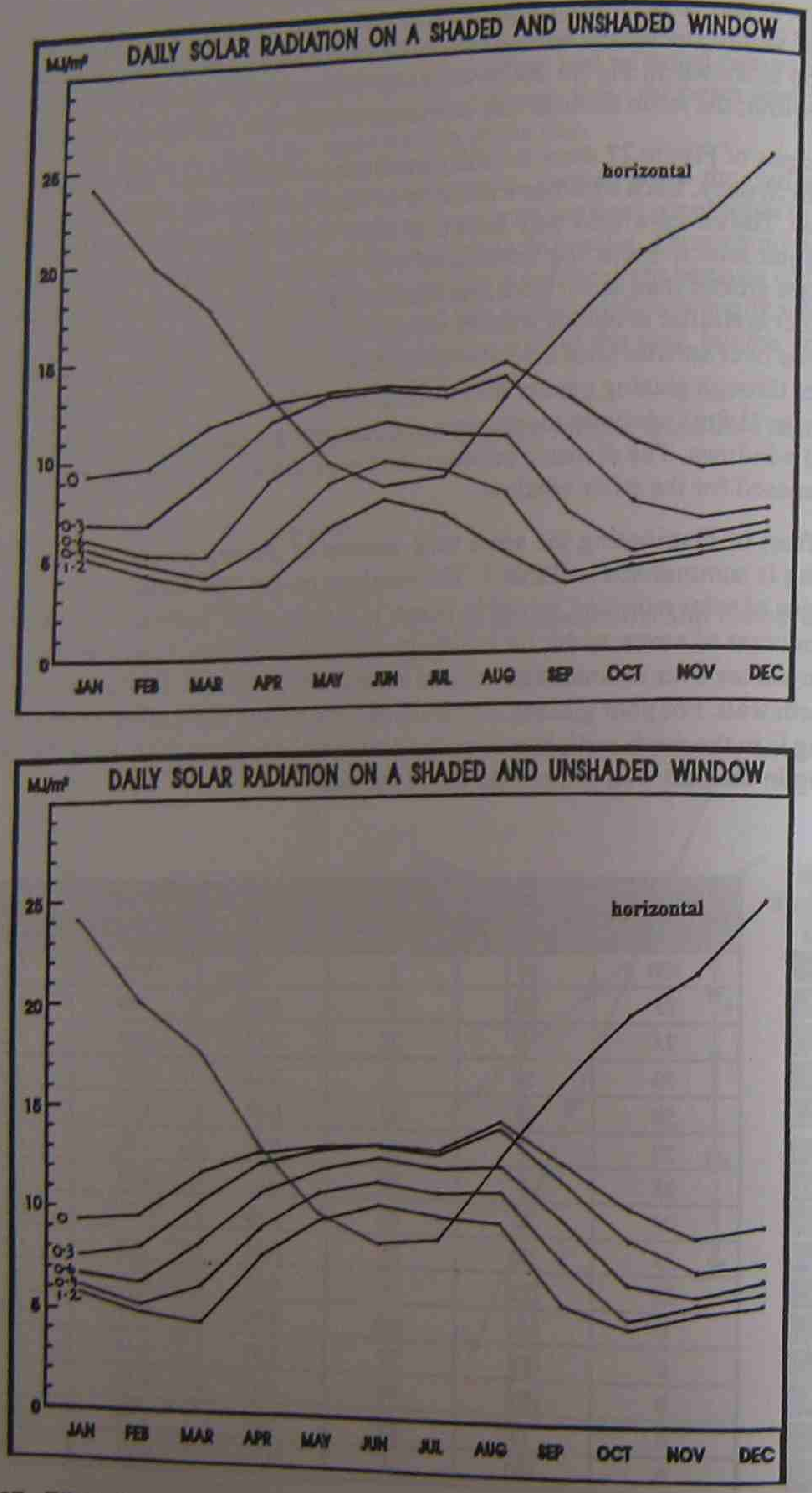


Figure 27 - Effect of eaves width on daily irradiation received on north walls in Sydney for (a) 0.9m and (b) 1.8m windows. (Eaves width varies from 0 to 1.2m but window to eaves distance remains a constant 0.2m.)

8 TYPES OF SHADING DEVICES

There are many different kinds of shading devices for windows and walls. The most common are fixed eaves outside and blinds or curtains inside. In order for shading to be effective it must block the sun outside of the building. Once sunlight enters a building through a window, any sort of reflecting device will not be able to fully return all of the sunlight, the difference being converted to heat within the building. External shading devices are installed so that solar energy absorbed by the device is not transferred as heat into the building. They may also shade some of the ground in front of the window which can reduce the amount of ground reflected radiation entering the building.

Horizontal shading devices refer to devices that are fixed in a horizontal plane (Figure 28). These are most effective for the shading of north windows. **Vertical devices** are fixed in a vertical plane, although the individual shading fins may be fixed or allowed to rotate about either horizontal or vertical axes (Figure 29). Combination vertical and horizontal devices may also be used for non north facing windows (Figure 30).

Fixed shading louvres or slats on a north face will exclude the sun to an ever increasing extent as the vertical sun angle (VSA) increases. Only during the equinox will the VSA remain constant for the whole day,

i.e. VSA = 90 - lat (equinox)

Using Melbourne as an example, in January VSA varies from 72° to 83° while in July it varies from 9° to 31°. A slat of 28° would ensure good sunlight penetration in July for most of the day while excluding the summer sun. It is important to have the louvres thin compared with their width so that they produce a minimum of shading when fully open. Glare from the tops of louvres into the room can be a problem if they are painted a reflective colour.

Adjustable devices offer definite advantages over fixed systems if they are adjusted correctly. Adjustable slats allow the sun to be included or excluded at will. As well as more precise control as the earth's declination changes they also allow heating during a cold day in summer, or exclusion of direct sunlight during a hot day in winter.

Perforated and expanded steel sheet which allows only light of a certain VSA to penetrate is commercially available. This is illustrated in Figure 28(f). Care must be taken to ensure that angles produced by the perforations are suitable for the location.

Adjustable louvres are more expensive than fixed louvres, which in turn are dearer than perforated and expanded sheet or fixed eaves. A cheap and very effective sunshading vegetation can be grown on trellises made from fencing wire stretched between horizontal poles (Figure 30(c)). Deciduous vines such as ornamental grapes grow very quickly and will lose their leaves in winter when full sun penetration is required.

Non-north facing windows are the most difficult to shade. Adjustable louvres as shown in Figures 28 and 29 work well but are expensive and obscure the view. Fixed vertical fins on the north side of the window are a cheaper alternative (Figure 29(c)). "Egg crate" shading devices seem to work on east and west walls but exclude winter sun on north walls (Figure 30(a)). The mini louvre system shown in Figure 29(d) can be used on windows of any orientation but it is expensive and obscures the view to some extent. Triangular shading fins on the north side of a window and above it provide a rectangular shadow pattern on the window without obscuring too much of the view, (Figure 30(b)).

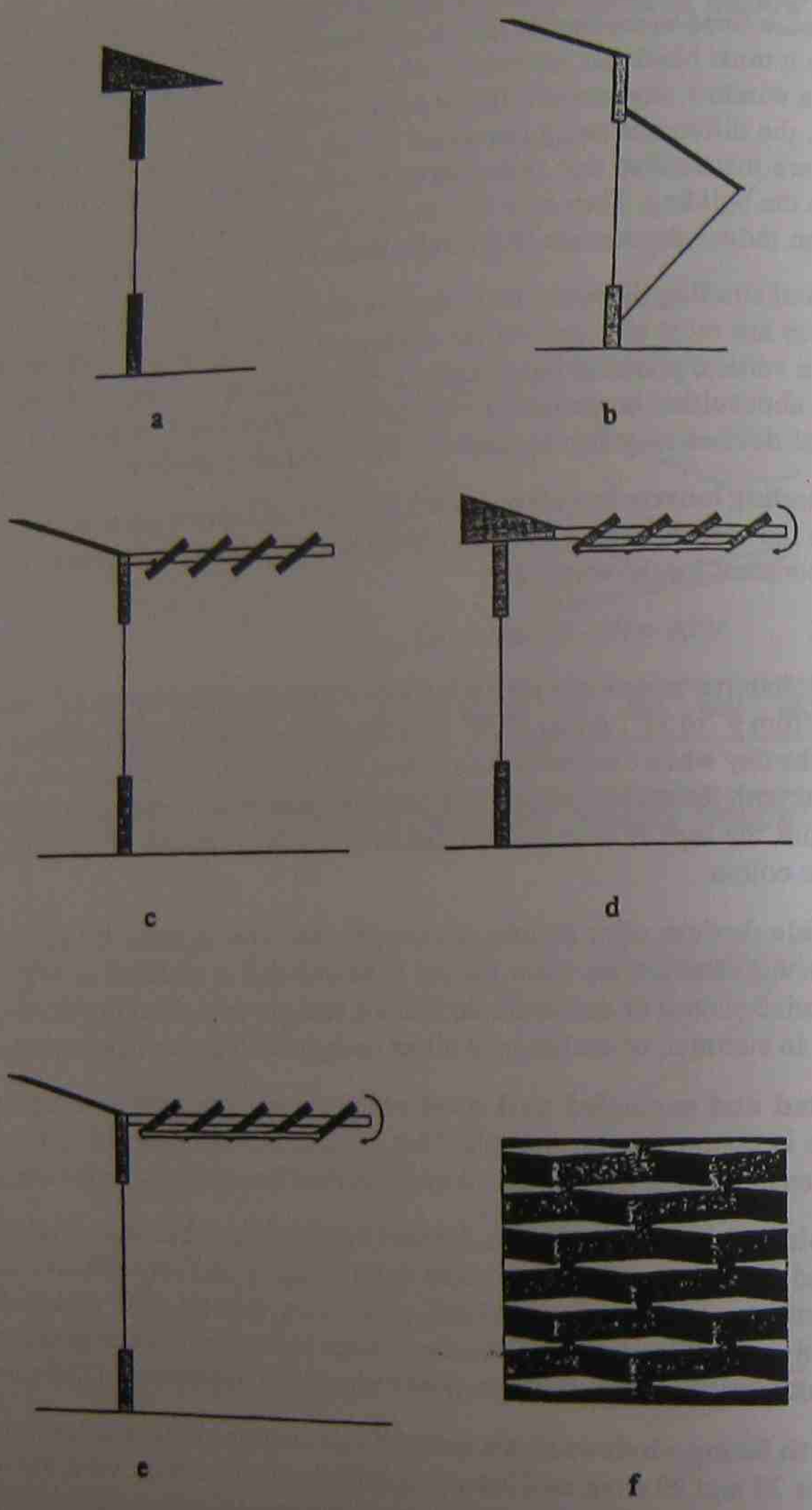


Figure 28 - External horizontal shading devices. (a) fixed eaves, (b) adjustable awning, (c) fixed slats, (d) adjustable louvres with fixed eaves, (e) adjustable louvres, (f) perforated and expanded mesh.

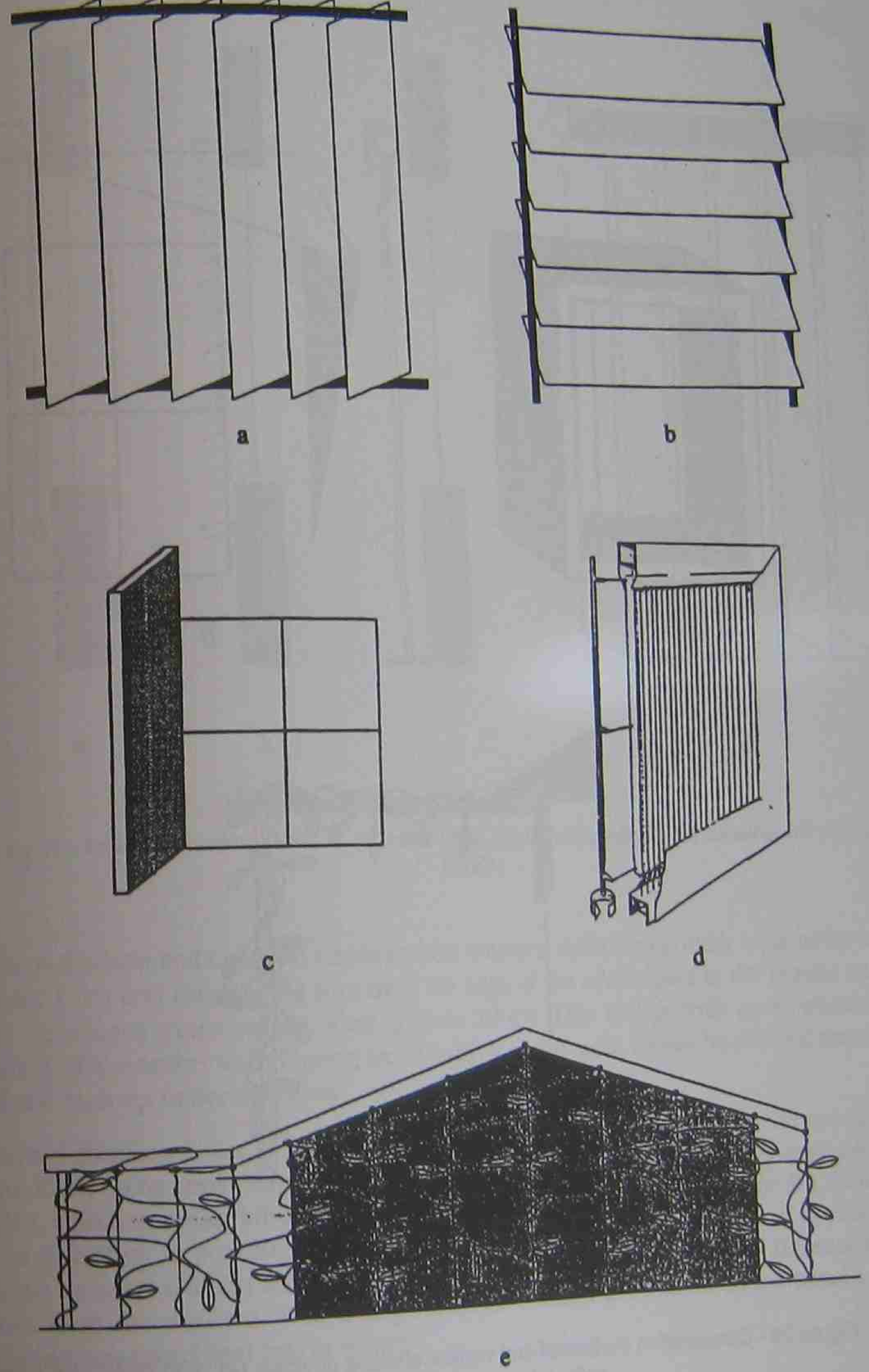


Figure 29 - External vertical shading devices. (a) vertical fixed slats or adjustable louvres, (b) horizontal fixed slats or adjustable louvres, (c) vertical fins, (d) vertical mini louvre shading system, (e) climbing plants or vines.

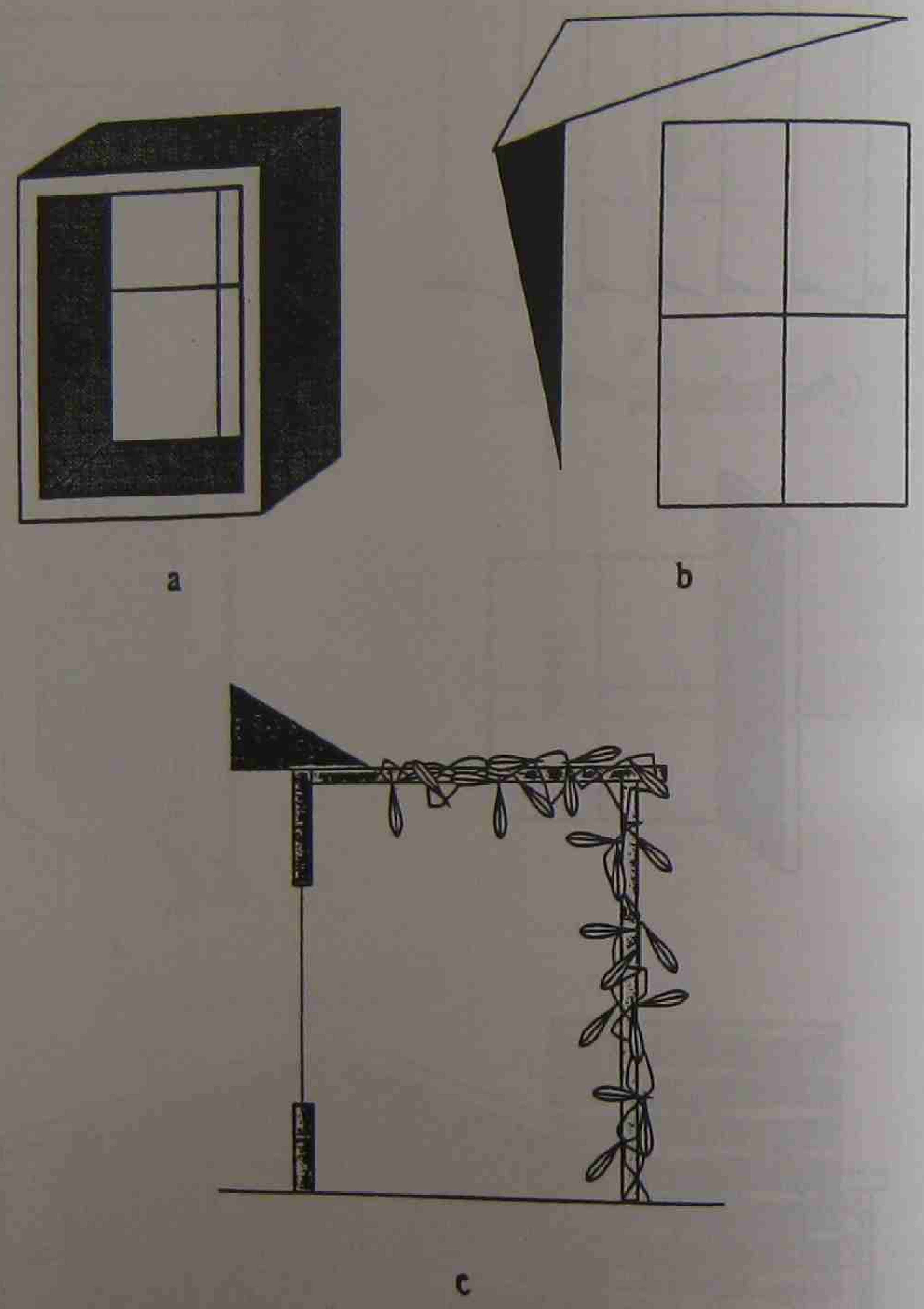


Figure 30 - Combination horizontal and vertical shading devices. (a) “egg crate”, (b) triangular sails, (c) vegetation grown on a trellis.

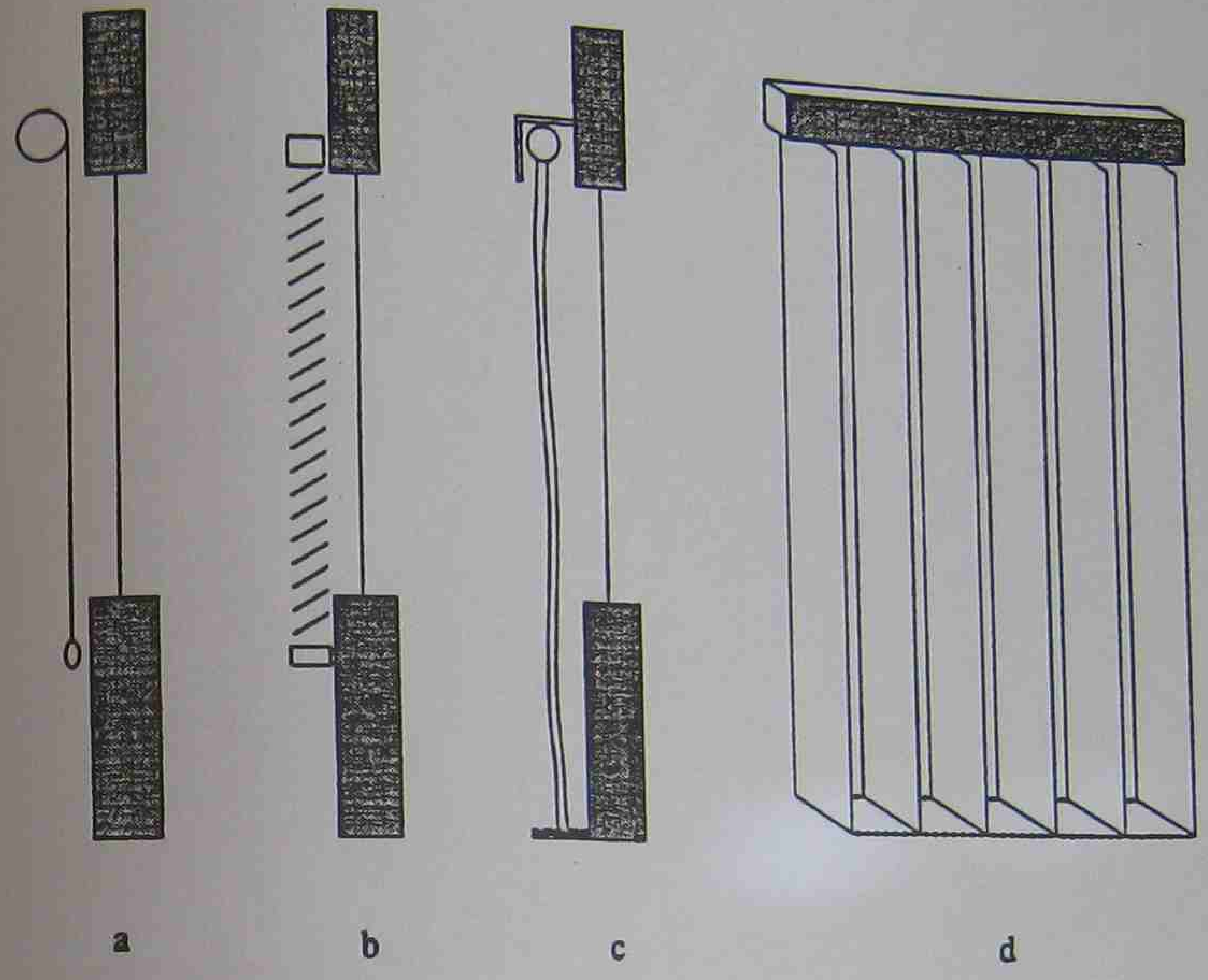


Figure 31 - Internal shading devices. (a) roller blind, (b) venetian blinds, (c) curtains, (d) vertical slat blinds.

Perhaps the best and cheapest alternative for **western walls** is to provide wide eaves of at least 1.0m and run fencing wire from the edge of the eaves down to the ground and train deciduous vines up the wires (Figure 29(e)). This will provide good westerly shading of the entire wall. Placing any windows in this wall, should be avoided except perhaps high up under the eaves.

Internal shading is not as effective as external shading. However, internal devices are more likely to be used than adjustable external shading devices because they are easy to adjust. Curtains, roller blinds, venetian blinds, or vertical slat blinds (Figure 31) should be as reflective as possible on the window side otherwise the light levels in the room will be reduced without making a great difference to the heating effect of the sunlight penetrating the window. Well fitting blinds or curtains provide an added benefit in reducing unwanted heat loss in winter.

Unit 6

Insulation

1 INTRODUCTION

Insulation products may act as sound-proofing or fire retardants, but are primarily used to reduce heat flow. Insulation reduces heat loss in winter and reduces heat gain in summer. It therefore reduces heating and cooling energy requirements and improves thermal comfort.

This unit discusses different types of insulation, selection of insulation and installation in the building fabric. It begins with a general discussion of heat transfer in buildings, which builds on material presented in Unit 4.

2 HEAT TRANSFER IN BUILDINGS

The heat loss characteristics for a typical brick veneer dwelling in temperate climates is shown in Figure 1(a). The actual amount of heat lost varies according to house design and the severity of the climate. As a general rule, however, most heat is lost through the ceiling and roof structure. Indicative relative building heat gains in summer are presented in Figure 1(b). As shown, windows (exposed to sunshine) and the roof/ceiling provide areas for significant heat gain. Other main paths of heat loss and gain are through the walls, windows and ventilation. The actual amount of heat lost through solid elements (walls, roof, floors and windows) depends on the U-value of the particular element, its area and the difference between inside and outside temperatures. Basic strategies for controlling heat gains and losses include creating still air cavities, coupling the floor and providing insulation.

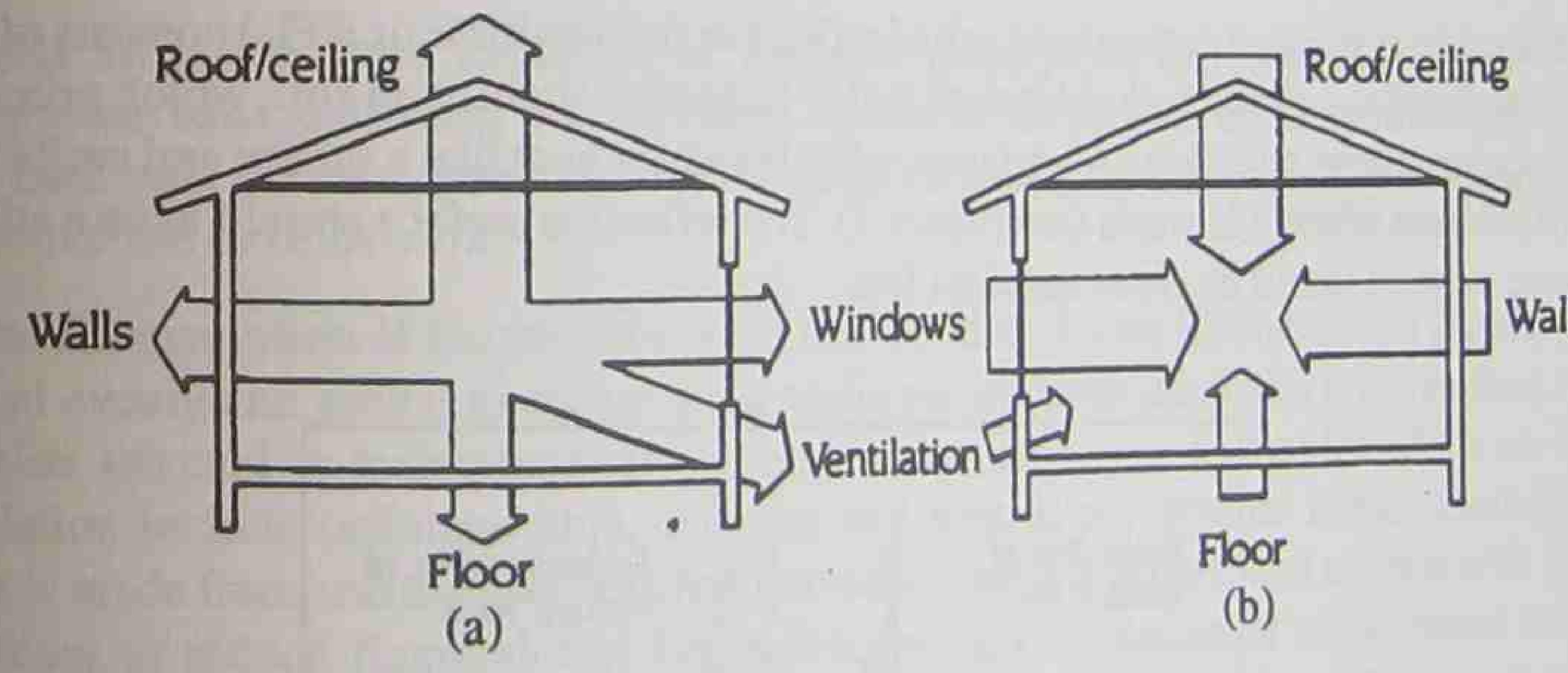


Figure 1 - (a) Indicative relative heat loss in winter from a brick veneer dwelling with timber floor. (b) Indicative relative heat gain in summer for the same dwelling. (Source: Energy Victoria, 1991).

A practical understanding of heat transfer (in the form of radiation, convection and conduction) may be gained by examining the case of a common plasterboard ceiling. **Radiation** occurs when warm plasterboard radiates heat to the cooler tiles (see Figure 2a). **Convection** occurs when air (heated by the warmed plasterboard) rises and comes into contact with the cold tiles, where it cools down by losing some of its heat to the tiles (see Figure 2b).

Conduction takes place within the plasterboard itself, and involves the transfer of heat from one layer of material to the next.

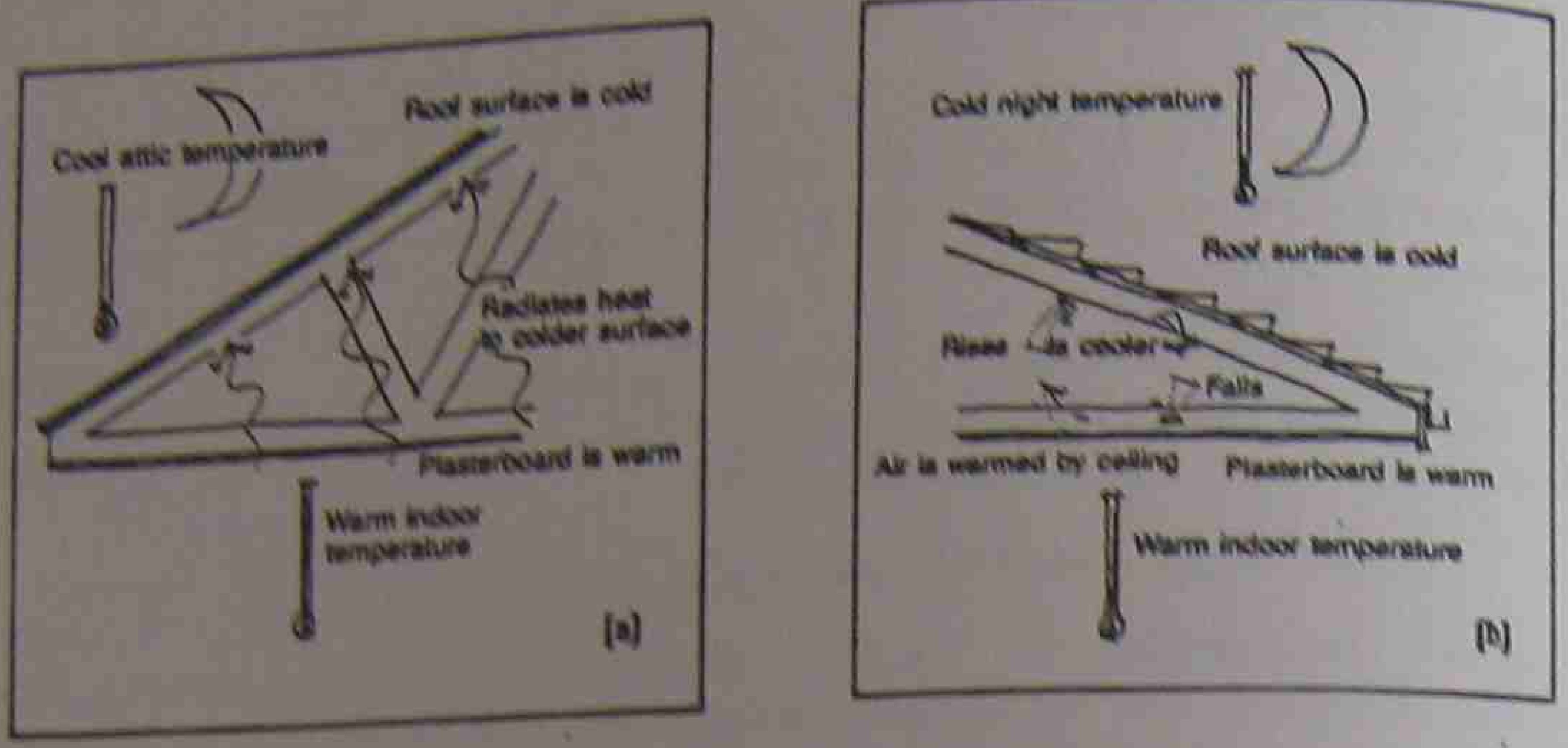


Figure 2 - (a) Radiation in a plasterboard ceiling. (b) Convection in a plasterboard ceiling. (Source: Gregory and Darby).

3 TYPES OF INSULATION

There are two basic types of insulation - reflective and bulk - although these two types are sometimes combined into a composite material.

3.1 Reflective Insulation

Reflective insulation (sometimes called reflective foil laminate or RFL) consists of thin sheets faced on one or both sides with highly reflective aluminium foil, which primarily reduces **radiant** heat flow. Aluminium reflects radiant heat like a mirror and emits little radiant heat when it is warm (see Figure 3). The reflective surface should have a still air space next to it and be clean and dust free.

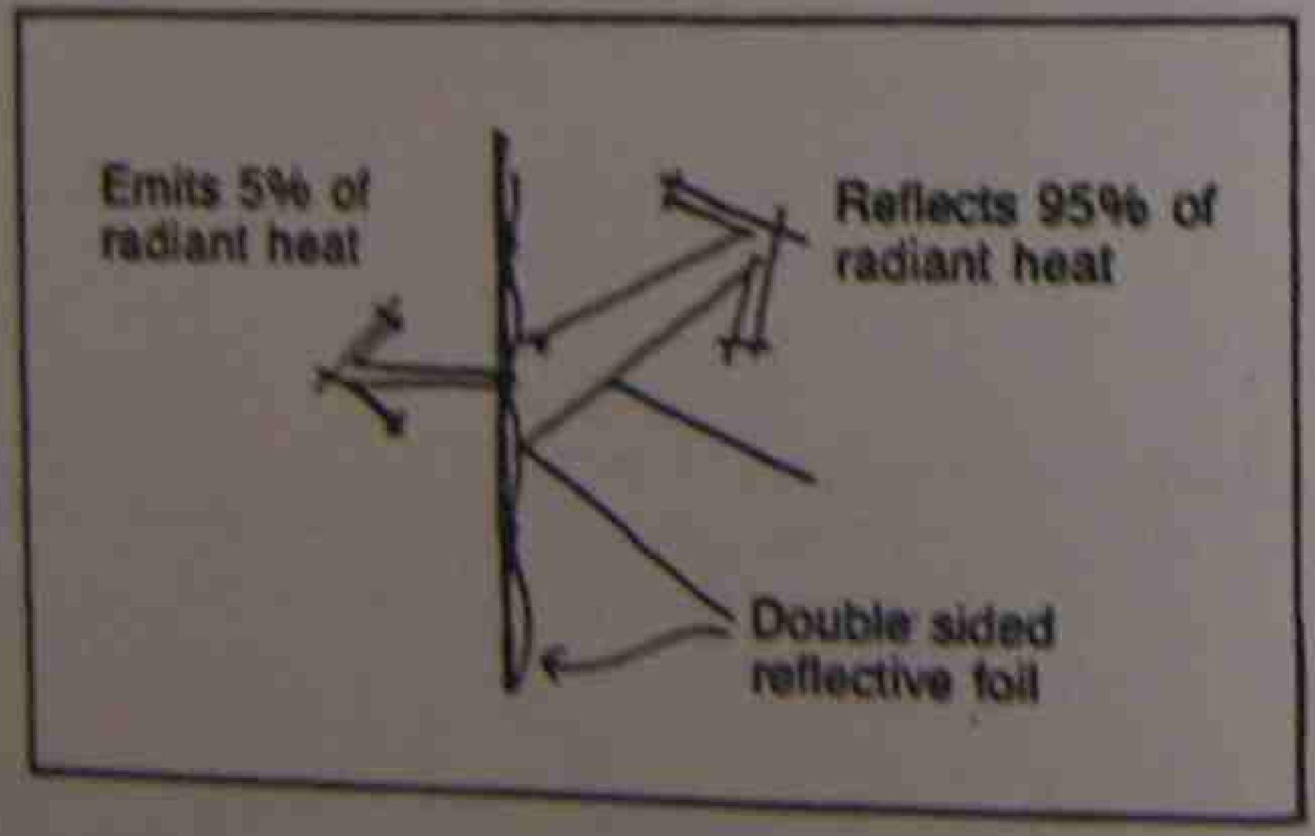


Figure 3 - Radiant properties of double-sided reflective foil (Source: Gregory and Darby).

In practice, dust deposits on upward facing foil make downward applications preferable. Single-sided reflective foil, with blue-coloured backing is often used under roofing material (as sarking). The blue surface faces up in roofs or outwards in walls and reduces glare during installation.

Foil batts combine two, three or four layers of reflective foil laminate, separated by spacers, to create air gaps between layers. Foil batts utilise the insulating effect of reflective surfaces and the air-trapping qualities of bulk insulation.

3.2 Bulk Insulation

Bulk insulation reduces **conducted and convected** heat flow. Trapped air, in many layers or cells, provide resistance to heat being convected. The greater the number of air pockets, the greater the insulation value. So, the resistance of this type of insulation depends on its thickness or bulk. Bulk insulation comes in five different forms - batts, blankets, boards, loose-fill, and foamed in-situ insulation. Bulk insulation needs to be kept dry to maintain thermal performance and stop moisture from saturating the batt, and adjacent wall lining.

Batts are lightweight, flexible and resilient. They consist of long, fine fibres and are usually bonded with a thermosetting resin. The fibres are spun from glass or rock and so are called mineral wool or specifically fibreglass batts and rockwool batts. The thickness of batts typically ranges from 50mm to 100mm.

Blankets, like batts, are spun mineral wool. The main difference is the product size. Batts are in smaller sizes while blankets come in long, wide rolls. So a fibreglass blanket will have the same R-value as fibreglass batts of the same thickness and characteristics. This is also true of rock wool blankets and batts. However if blankets are compressed against structural timber (for example) then thermal resistance is reduced. Batts, which fit snugly between structural timber do not have this disadvantage.

Boards are made from expanded or extruded polystyrene and urethane foam. All polystyrene batts and sheets contain flame retardants. As they are combustible, they are best used only between non-combustible surfaces such as plasterboards, fire retardant reflective foil or brickwork.

Loose fill insulation is blown or pumped into position. Loose fill insulation should be spread evenly and sealed to ensure good performance. Even thickness ensures that the R-value selected is maintained throughout the insulated area. Examples of loose fill insulation include cellulose fibre, eelgrass, and foamed polystyrene beads. Cellulose fibre is made from waste paper which is pulverised into a fine fluff, and treated with fire retardant to reduce flammability. Eelgrass loose bulk insulation is made from dried eelgrass that is treated with fire retardant. Foamed polystyrene beads and are normally blown or pumped into areas, as is cellulose insulation.

Foamed in-situ bulk insulation includes Urea Formaldehyde (UF Foam) and Polyurethane Foam. UF foam insulation is produced at the job site by the combination of an aqueous solution of urea formaldehyde resin, and aqueous solution foaming agent which includes an acid catalyst, and air. It is essential that the ingredients of the insulation mix are mixed properly and accurately for optimum performance, and to avoid the insulation disintegrating after placement. Apart from problems of deterioration and shrinkage, UF foam may give off toxic formaldehyde gas during and after placement. It has therefore been banned in the USA and Canada as building insulation and is no longer generally used.

The conductivity of a range of bulk insulation materials are summarised in Table 1.

Insulating Material	Conductivity (W/mK)
cellulose	0.039
fibreglass	0.043
polystyrene	0.039
polyurethane	0.025
rockwool	0.035

Table 1 - Conductivity of selected insulation materials.

3.3 Composite Insulation

Composite insulation products are made from foils that are bonded to mineral wool batts or blankets or foam batts. Composite insulation combines the qualities of reflective foil and blankets or batts.

4 INSTALLATION OF INSULATION

Successful installation of thermal insulation depends on an understanding of placement details for specific applications and an understanding of basic principles which need to be followed.

4.1 Basic Principles

Where possible, **insulation should be placed during construction to avoid retrofitting.** If cost considerations will not allow all parts of the building to be insulated, reflective foil sarking should at least be installed in the roof during construction. In cold areas, where underslab edge insulation is required for a slab-on-ground, installation will be impossible once the house is built. Similarly, it may be difficult or impossible to insulate walls after construction.

It is, of course, important to **choose the appropriate R-value** for insulation to be used at any given location. Minimum recommended R-values for roof and ceiling insulation, for major Australian cities, are specified in Table 2. For locations not listed it is suggested that AS 2627 - Part 1, 1983, which provides a more comprehensive list, be consulted directly.

Cold bridges should be avoided when installing insulation. A cold (thermal) bridge is a poorly insulated part of an otherwise effectively insulated structure. It may be a gap between pieces of insulation or an area where insulation is tightly compressed. Alternatively, uninsulated structural timbers (with a typical R-value of only 0.6) may create a cold bridge.

A clearance around appliances which dissipate heat, of at least 50mm is recommended. All electric wiring encased in insulation must conform to the "SAA wiring rules" (see AS 3000 - Electrical Installations - Buildings, Structures and Premises). Specifically, wires which increase in temperature due to the installation of insulation also increase in resistance; thicker wires may therefore be needed to avoid increased fire risk.

As air cools, its ability to hold water vapour decreases. Surface condensation occurs when air saturated with water vapour contacts a colder surface and forms water droplets, as shown in Figure 4a. Interstitial condensation occurs inside permeable structures, when moist air condenses as the permeable structure becomes cold (see Figure 4b).

NEW SOUTH WALES		QUEENSLAND		SOUTH AUSTRALIA		VICTORIA	
Albury	2.5	Atherton	2.0	Adelaide	2.0	Ararat	2.5
Armidale	3.5	Ayr	2.0	Loxton	2.5	Bairnsdale	2.5
Bathurst	3.5	Beenleigh	2.0	Mount Barker	3.0	Ballarat	3.0
Bega	3.5	Bowen	2.0	Mount Gambier	3.5	Bendigo	2.5
Broken Hill	2.5	Brisbane	2.0	Murray Bridge	2.5	Bright	3.5
Canberra	3.5	Bundaberg	2.0	Naracoorte	3.0	Colac	3.0
Cessnock	2.0	Cairns	2.0	Port Augusta	2.0	Geelong	2.5
Dubbo	3.0	Caloundra	2.0	Port Lincoln	2.0	Hamilton	2.5
Goulburn	3.5	Charters Towers	2.0	Port Pirie	2.0	Horsham	2.5
Griffith	3.0	Dalby	2.0	Renmark	2.0	Lakes Entrance	2.5
Inverell	3.0	Gladstone	2.0	Stirling	3.5	Melbourne	2.5
Lithgow	3.5	Gold Coast	2.0	Victor Harbour	2.0	Mildura	2.0
Maitland	2.0	Gympie	2.0	Whyalla	2.0	Sale	2.5
Narrabri	2.0	Hervey Bay	2.0			Seymour	2.5
Newcastle	2.0	Innisfail	2.0	**WESTERN AUSTRALIA**		Shepparton	2.5
Orange	3.5	Mackay	2.0	Albany	2.0	Swan Hill	2.5
Port Macquarie	2.0	Maroochydore/ Mooloolaba	2.0	Bunbury	2.0	Wangaratta	2.5
Richmond	2.0	Maryborough	2.0	Busselton	2.0	Warragul	2.5
Singleton	2.0	Mount Isa	2.0	Collie	2.5	Warrnambool	2.5
Sydney	2.0	Nambour	2.0	Esperance	2.0	Wodonga	2.5
Tamworth	3.0	Rockhampton	2.0	Kalamunda	2.5	Wonthaggi	3.5
Taree	2.0	Roma	2.0	Kalgoorlie	2.0		
Wagga Wagga	3.5	Stanthorpe	3.5	Katanning	2.5	**TASMANIA**	
Wollongong	2.0	Tewantin-Noosa	2.0	Mandurah	2.0	Burnie	3.5
		Toowoomba	2.5	Manjimup	2.5	Devonport	3.5
		Townsville	2.0	Northam	2.0	Hobart	3.5
		Warwick	2.5	Perth	2.0	Launceston	3.5
		Yeppoon	2.0	Upper Swan	2.0	Queenstown	3.5
						Ulverstone	3.5
						Wynyard	3.5
						Zeehan	3.5

Table 2 - Minimum recommended R-values for ceilings/roofs for Australian cities. (Source: Drawn from AS 2627 - Part 1, 1983).

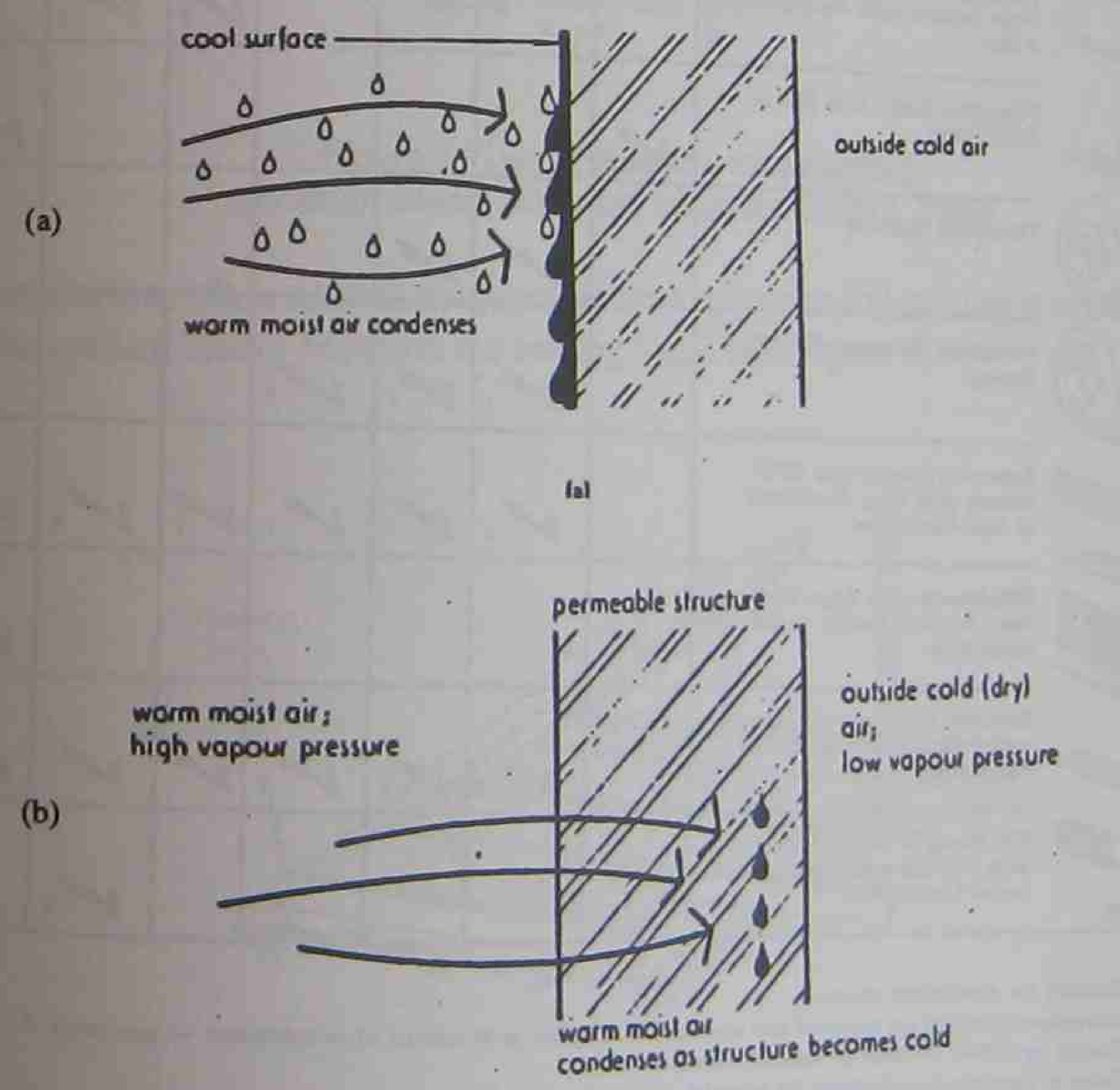


Figure 4 - (a) Surface condensation as warm air meets a cold surface (b) Interstitial condensation as warm moist air is cooled to dewpoint temperature inside the structure.

Vapour barriers on the warm side of insulation and ventilation to moisture generating areas are often needed to stop condensation. Vapour barriers include well-maintained painted surfaces, wall/ceiling linings which have been factory laminated with aluminium foil, polythene film, and polythene film on laminated aluminium foil.

Local **building codes should be consulted** to ensure compliance. In Victoria, for example, specified insulation levels are compulsory in all new homes.

Protective clothing should be worn when installing fibreglass insulation, to avoid inhalation of fibres and skin irritation.

TYPES OF INSULATION	APPLICATION						
	Ceilings - Pitched Roofs	Cathedral Ceilings & Metal Deck Roofs	Timber Floors	Suspended Slabs	Slab Edges	Full Masonry Walls	Framed Walls
Reflective Foil Laminate (RFL) – Rolls	✓1	✓1	✓1				✓1
Fibreglass Batts – Low Density	✓1	✓1	✓1				✓1
Fibreglass Batts – Medium or High Density with Hydrophobic Agent					✓3	✓2	
Fibreglass Batts with RFL or Foil Facing	✓3						✓2
Fibreglass Blankets		✓1	✓1				
Fibreglass Blankets with RFL Facing		✓1	✓1	✓3			
Expanded Polystyrene (EPS) Boards with Edge Treatment to Suit Application		✓1	✓1	✓1	✓1	✓2	✓1
EPS Boards with Edge Treatment and RFL Facing to Suit Application	✓3						✓3
Extruded Polystyrene Boards with Edge Treatment to Suit Application		✓3	✓3	✓1	✓1	✓1	✓3
EPS Beads or Mineral Wool with Hydrophobic Agent – Injected Cavity Fill						✓2	

✓ Suitable for application shown
1 Australian Standard for material and application available or in course of preparation –. see page 3
2 Tested by CSIRO Division of Building Research
3 Refer to product manufacturer for material and application data

Table 3 - Insulation types for given applications
(Source: Glass, Mass and Insulation Council, 1985).

4.2 Installation Details

Table 3 shows the suitability of different insulation types for different applications. Subsequent sections discuss and illustrate the most common applications for roofs/ceilings, walls and floors.

4.2.1 Roofs and Ceilings

Reflective foil is commonly installed directly under roofing, as shown in Figure 5. Note the folding of foil into the gutter and turning under. Also note the 150mm overlap and the gap of 100mm at the ridge board (rafter).

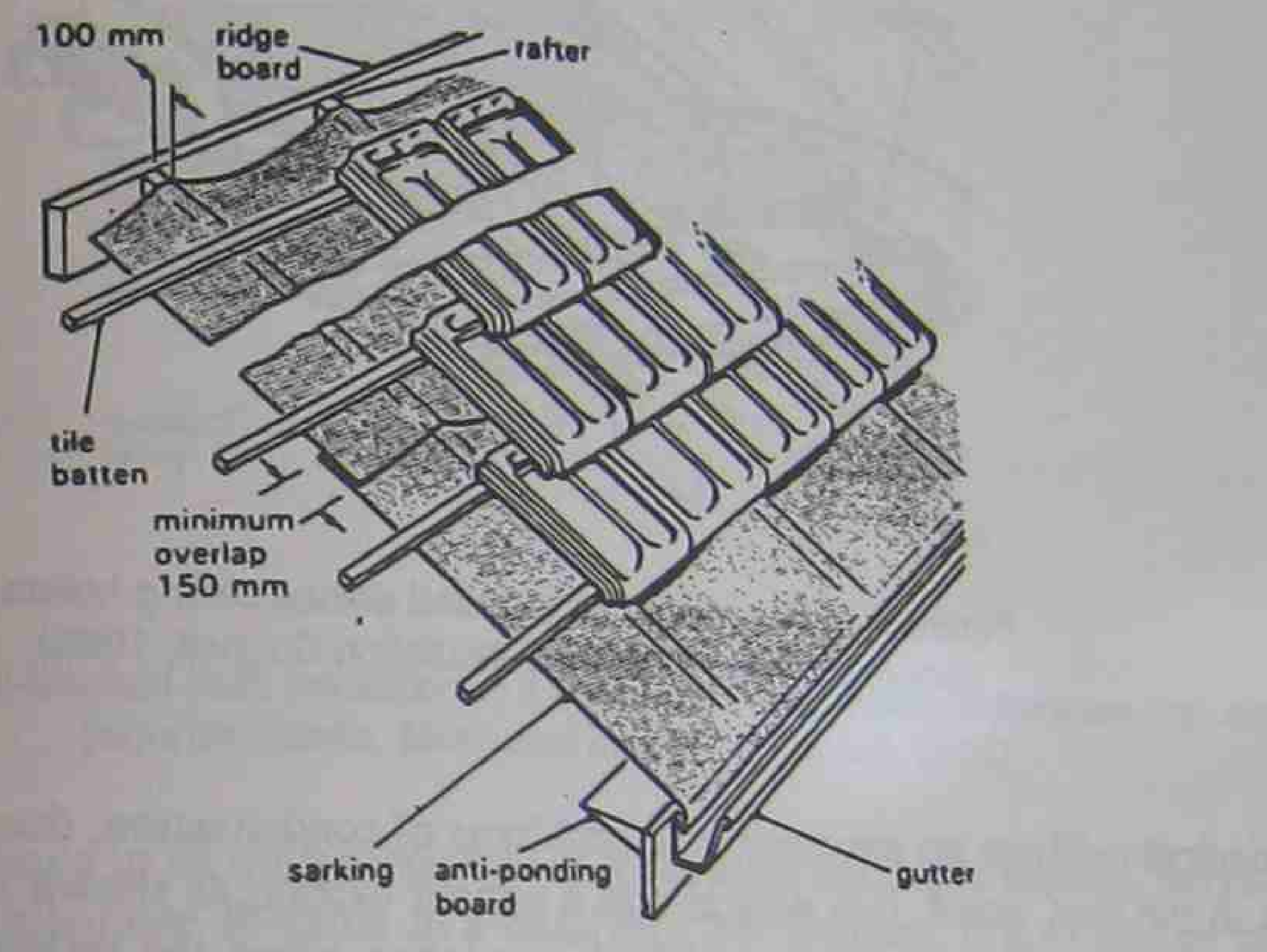


Figure 5 - Use of reflective foil as sarking.
(Source: Glass, Mass and Insulation Council, 1985).

Bulk insulation, often used in conjunction with reflective foil sarking is installed directly onto the ceiling lining between the ceiling joists (see Figure 6).

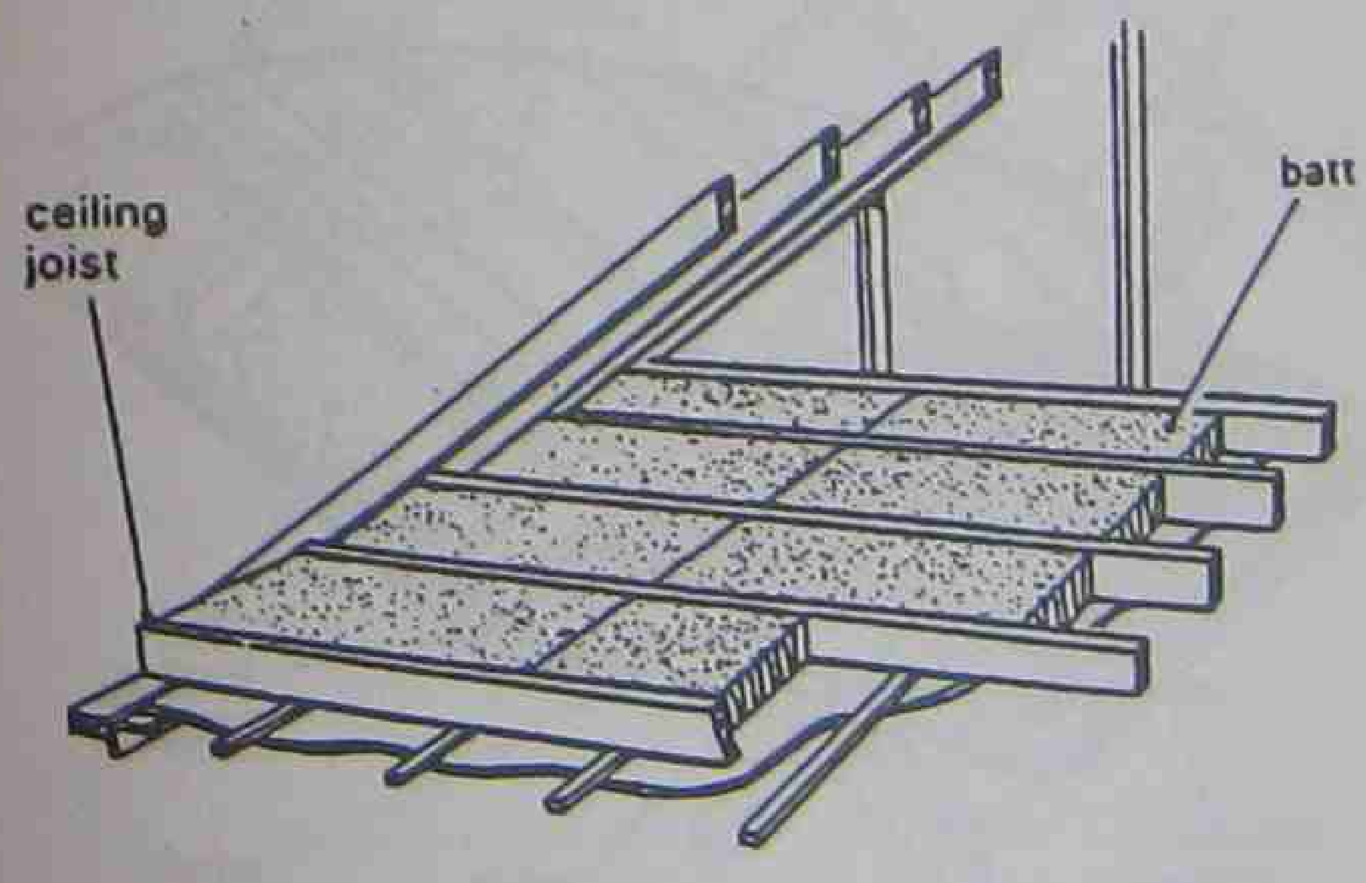


Figure 6 - Batts installed between ceiling joists
(Source: Glass, Mass and Insulation Council, 1985).

Figure 7 shows the installation of bulk insulation across ceiling joists. Bulk insulation suitable for this purpose includes expanded polystyrene boards, low density fibreglass batts and fibreglass batts with foil facing. In this last case, the down-facing foil provides both insulation and a vapour barrier.

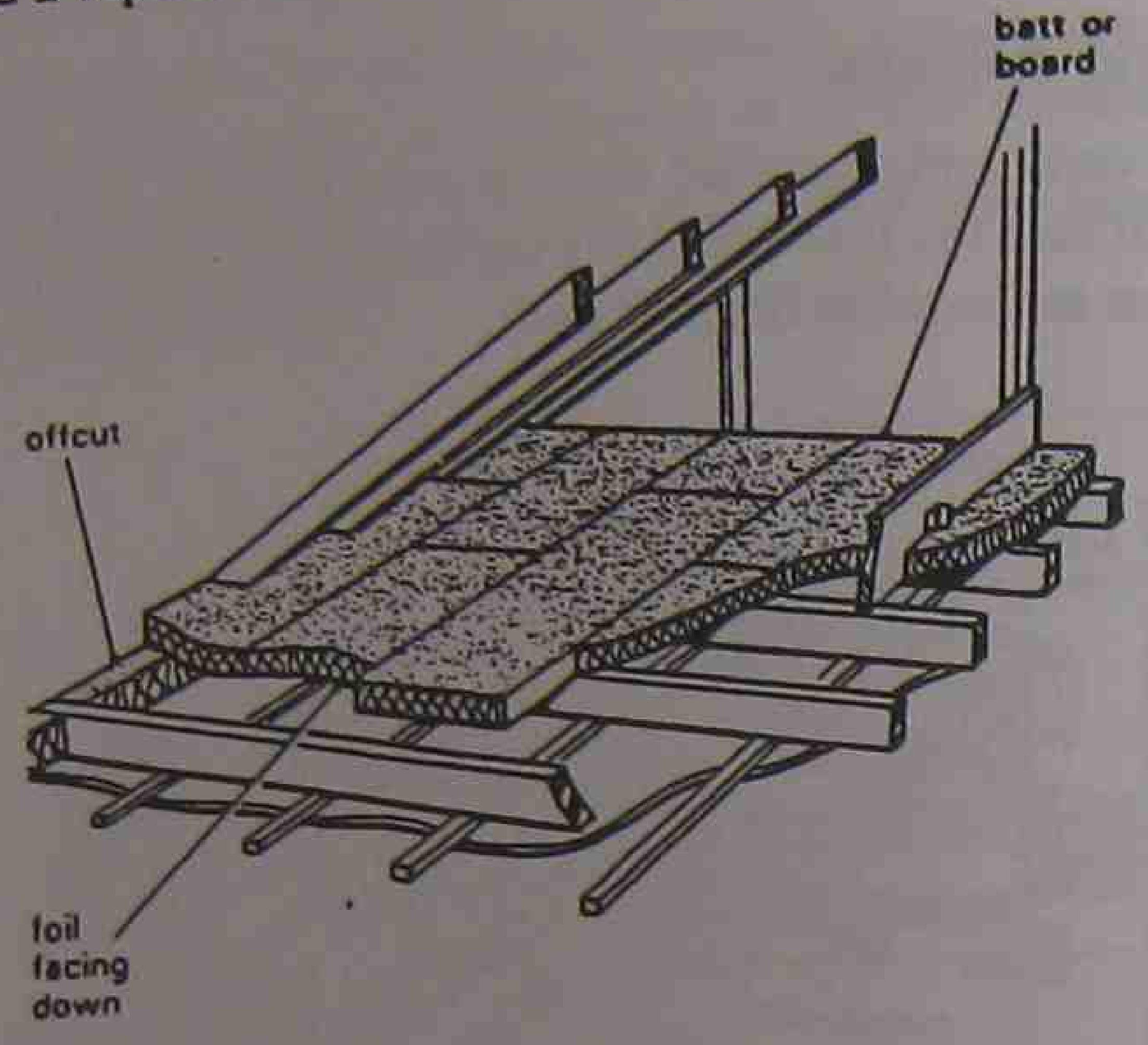


Figure 7 - Batts or boards installed across ceiling hoists.
(Source: Glass, Mass and Insulation Council, 1985).

Cathedral ceilings are susceptible to problems of condensation, due to low ventilation rates in the roof space. It is wise to add a vapour barrier, as shown in Figures 8 and 9. As Figure 8 shows, installation of bulk insulation when the rafters are concealed is relatively straightforward.

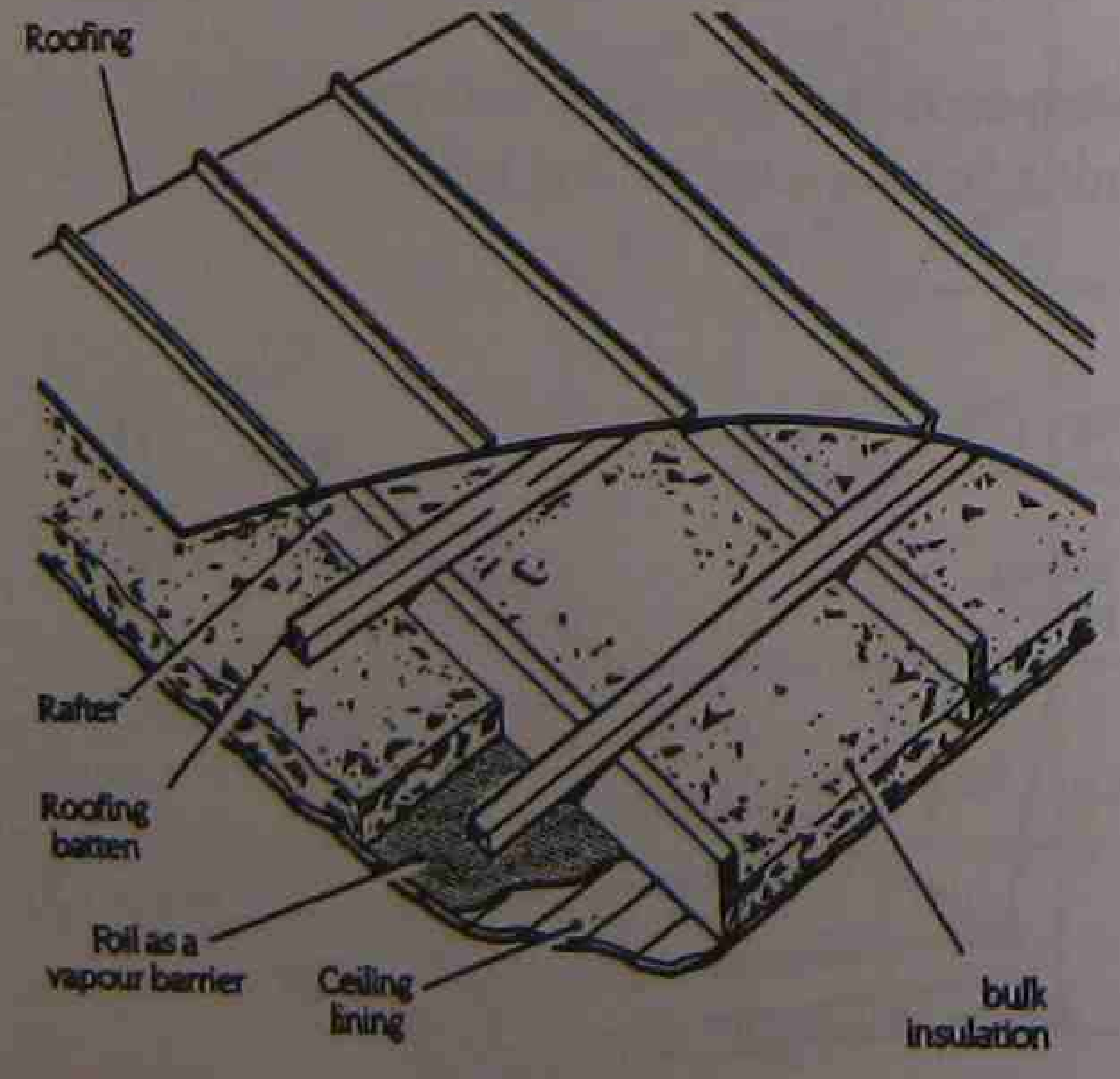


Figure 8 - Bulk insulation in a cathedral ceiling when rafters are concealed.
(Source: Energy Victoria, 1991).

The installation of foil-faced blanket in cathedral ceilings where the rafters are exposed is shown in Figure 9. The foil is installed facing down to act as a vapour barrier. In this example, the deck is clipped to the purlin to limit the compression of the blanket to not less than 10mm.

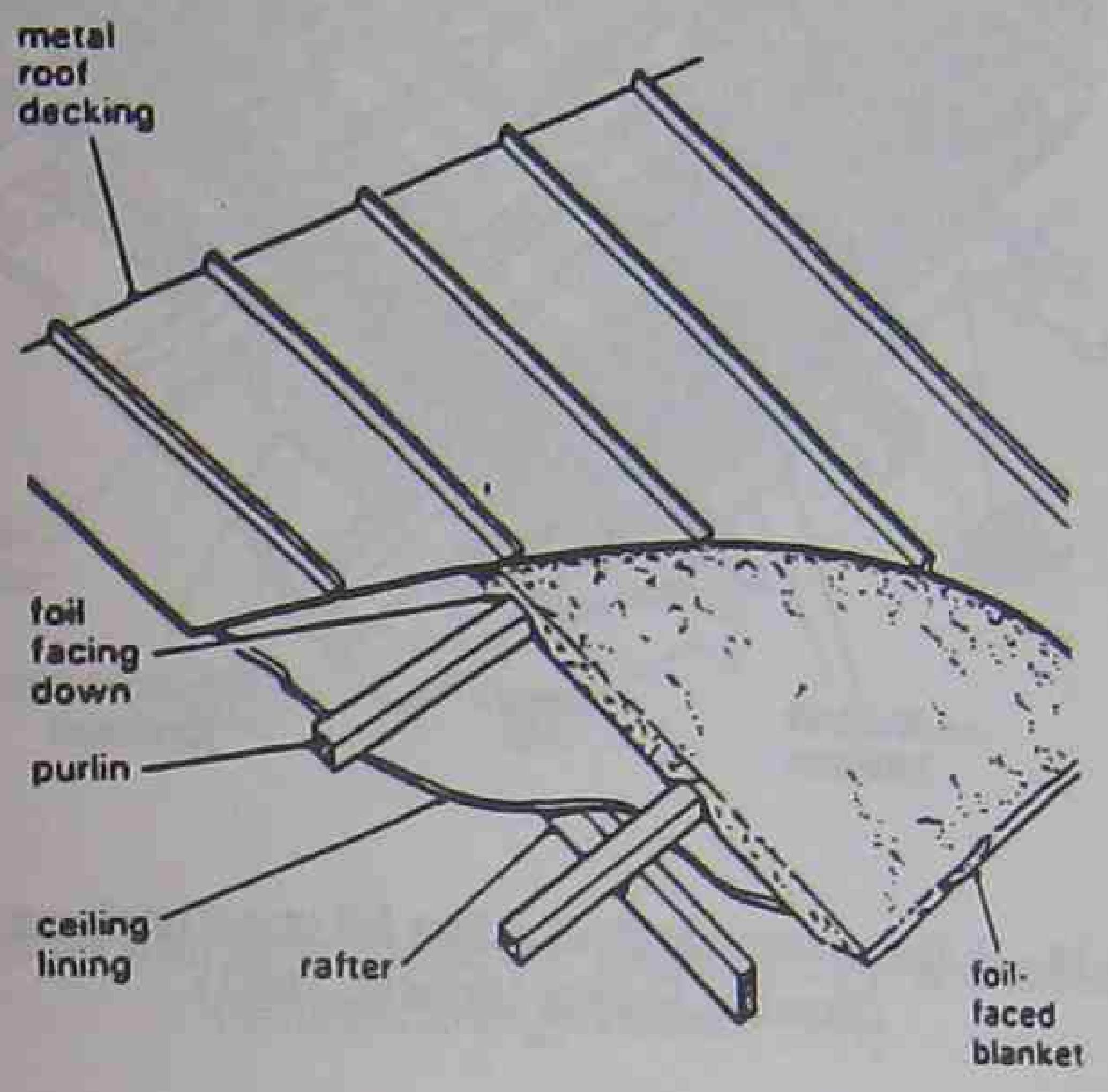


Figure 9 - Foil-backed bulk insulation in a cathedral ceiling where rafters are exposed.
(Source: Glass, Mass and Insulation Council, 1985).

In cases where space to fit bulk insulation in a cathedral ceiling is limited, polystyrene may provide an adequate R-value in a relatively thin product. It also acts as its own vapour barrier, so foil underneath is unnecessary. However reflective foil above the polystyrene may provide additional insulation if it does not become ineffective through dust deposition. Figure 10 shows a typical installation.

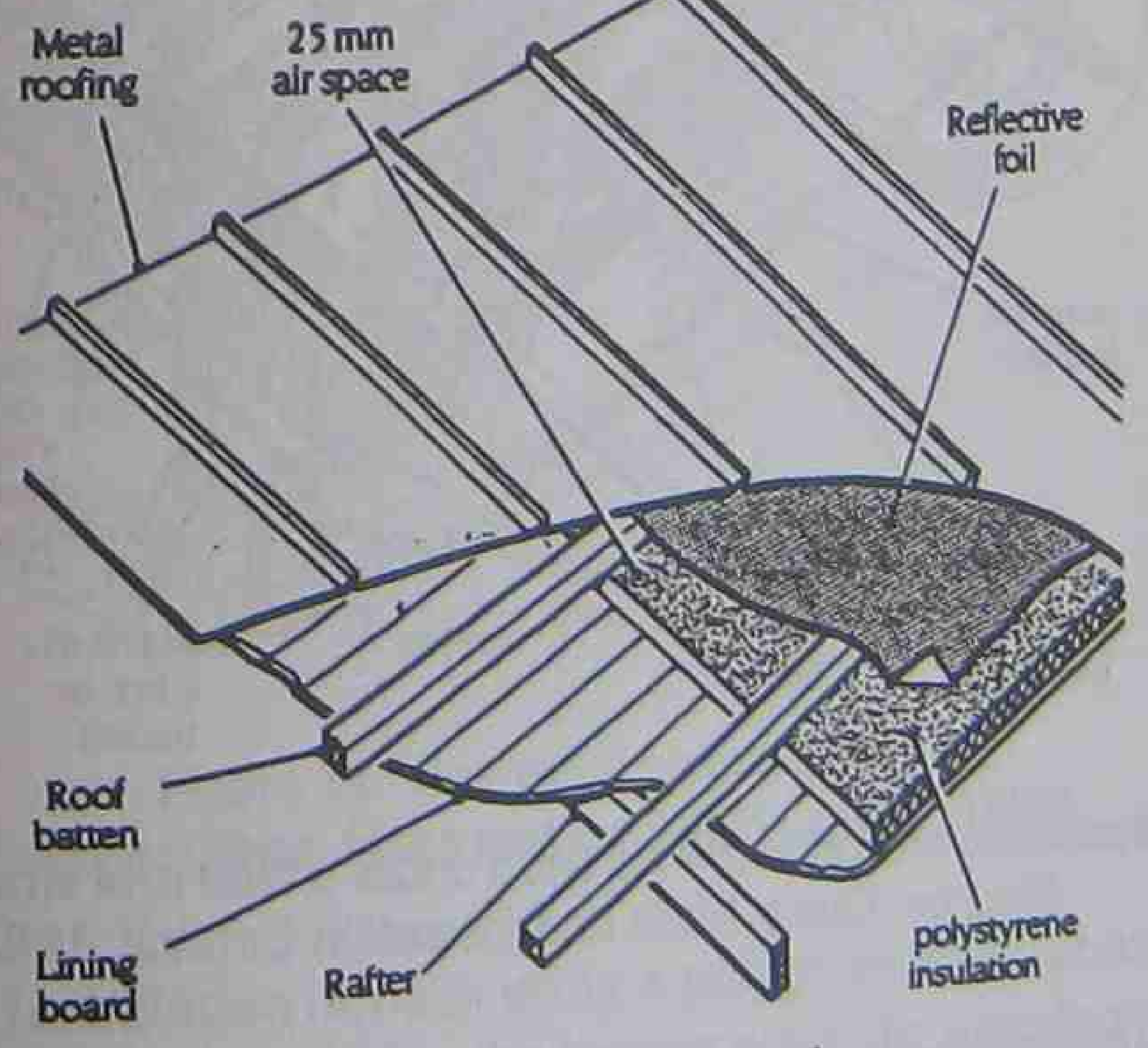


Figure 10 - Installation of polystyrene in a cathedral ceiling, where rafters are exposed.
(Source: Energy Victoria, 1991).

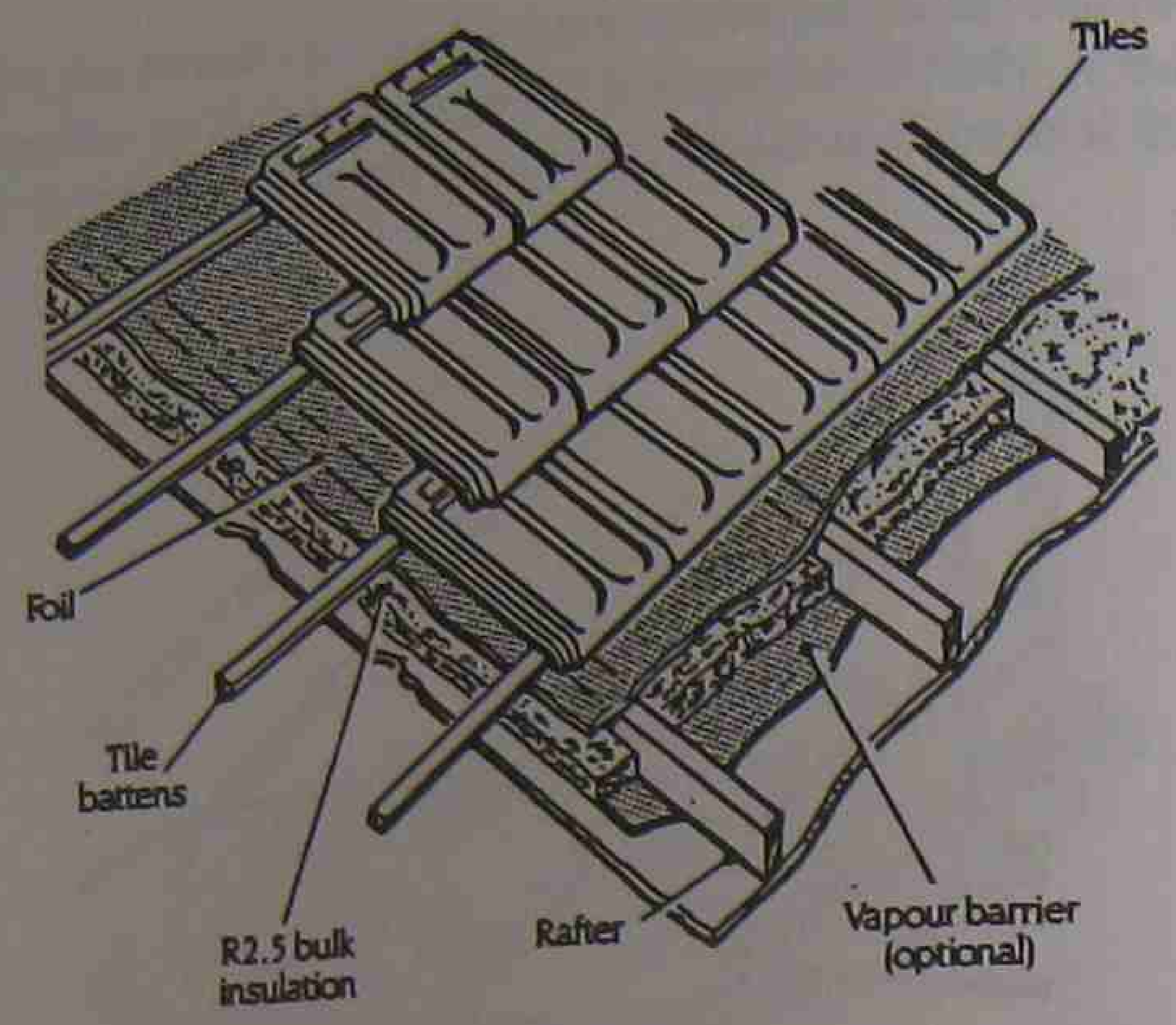


Figure 11 - Bulk insulation and reflective foil used under a tiled roof.
(Source: Energy Victoria, 1991).

Figure 11 shows bulk insulation and reflective foil installed under a **tiled roof**, where rafters are concealed. Figure 12 illustrates the case where the rafters are exposed. In both cases, the foil, correctly installed, should prevent the penetration of moisture into the batt.

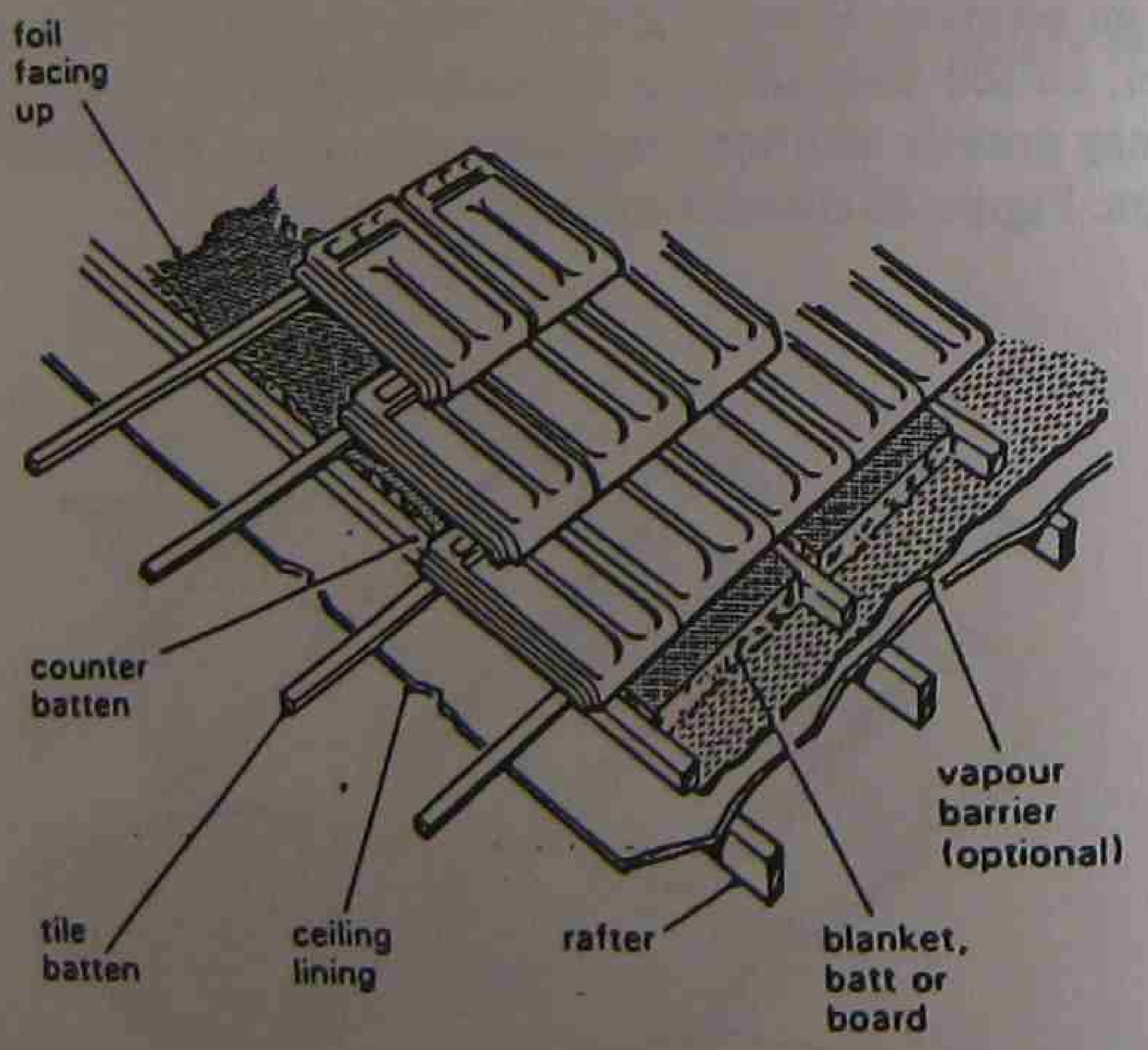


Figure 12 - Bulk insulation and reflective foil used under a tiled roof where rafters are exposed.
(Source: Glass, Mass and Insulation Council, 1985).

Another alternative for exposed rafters is the use of polystyrene and reflective foil. In this case, the counter batten is fixed directly through the polystyrene insulation, providing an air space below the foil (see Figure 13).

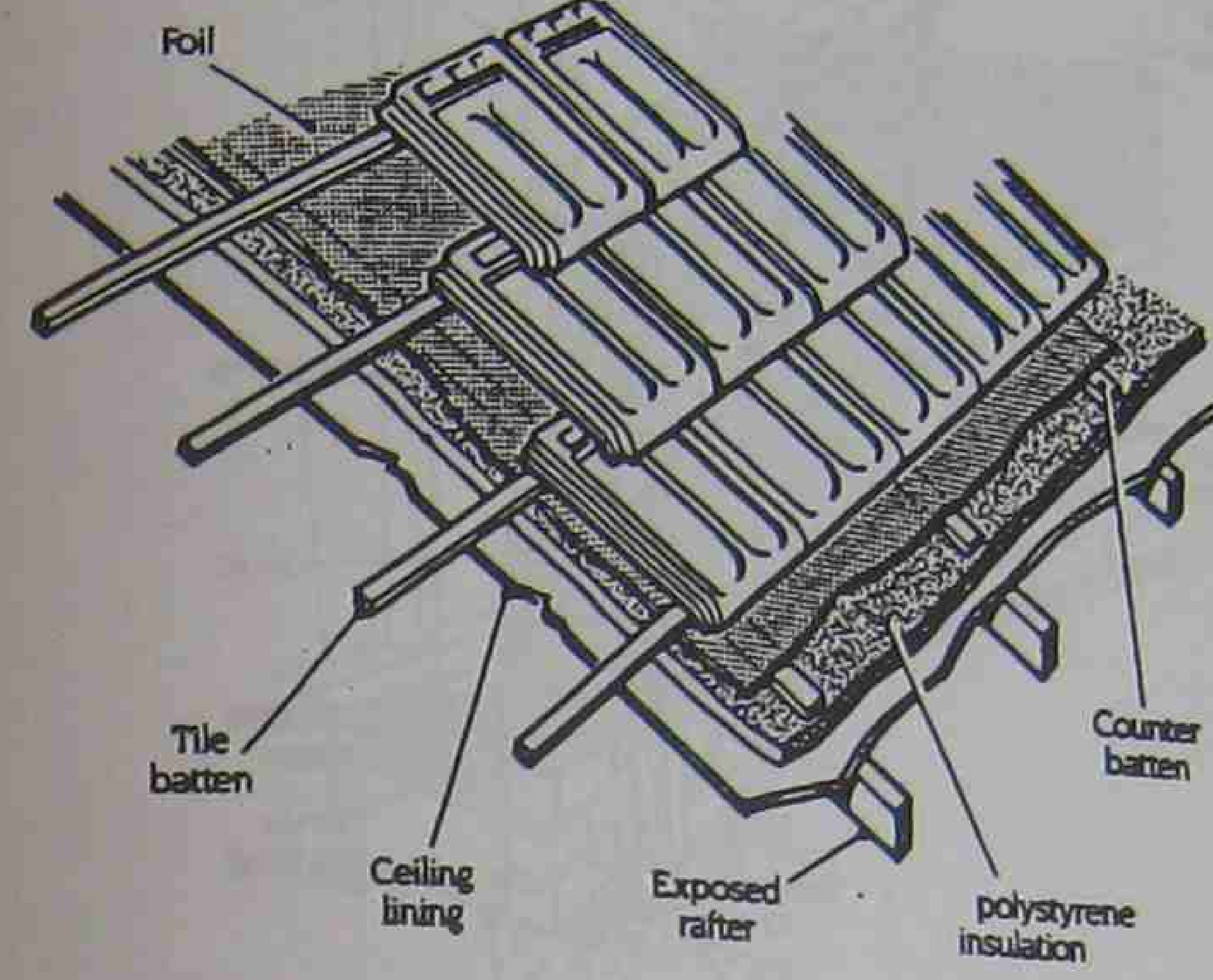


Figure 13 - Insulating with polystyrene and reflective foil where rafters are exposed.
(Source: Energy Victoria, 1991).

4.2.2 Walls

Figures 14, 15, 16 and 17 illustrate the installation of insulation in **brick veneer walls**. Reflective foil installation using a fixing disc is shown in Figure 14.

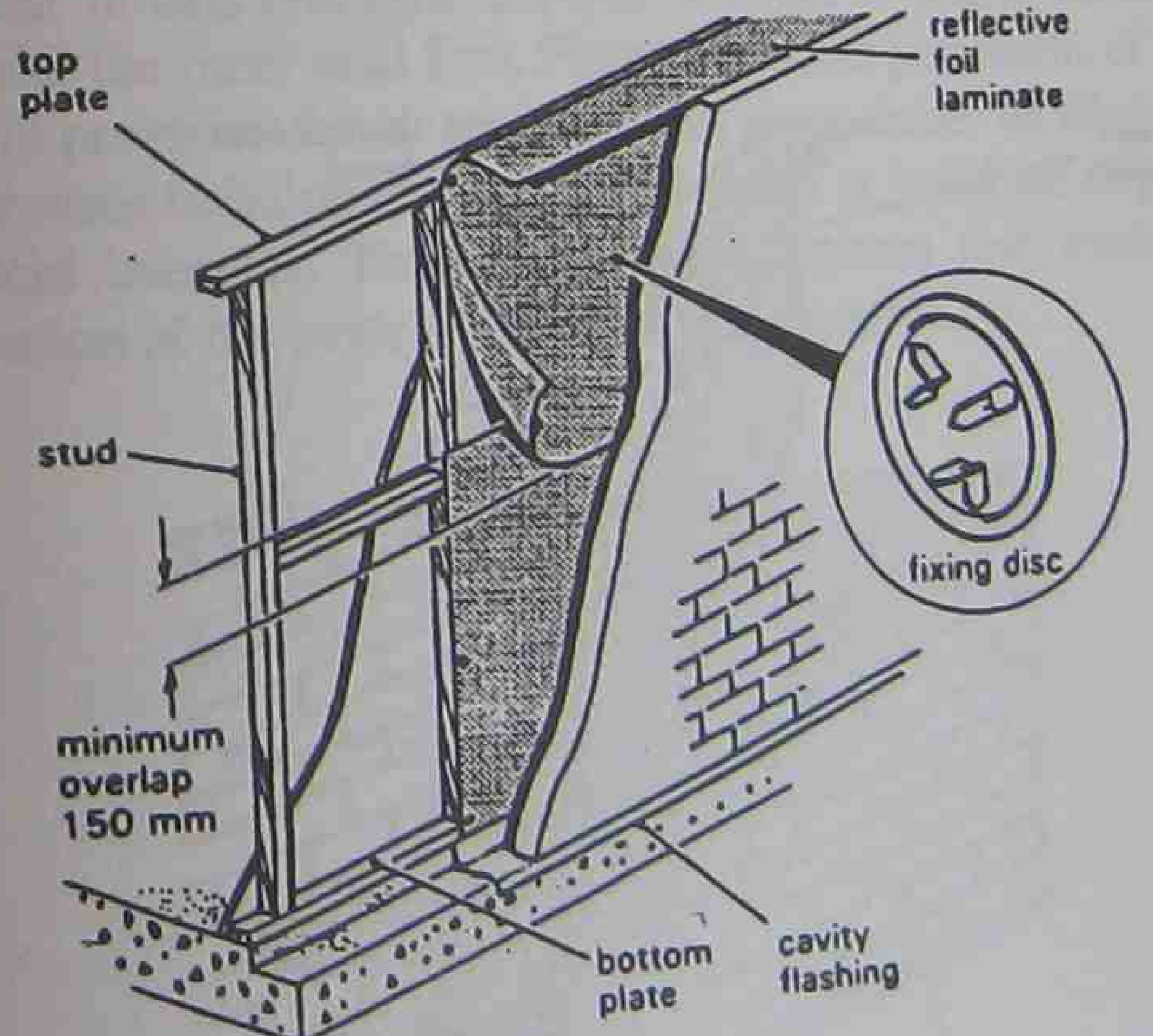


Figure 14 - Use of foil across studs.
(Source: Glass, Mass and Insulation Council, 1985).

Figure 15 shows the installation of batts using a polypropylene lashing fixing method. The polypropylene lashing is stapled to the bottom plate, the nogging and the top plate. It holds the batt in place, maintains the cavity and prevents the transmission of moisture.

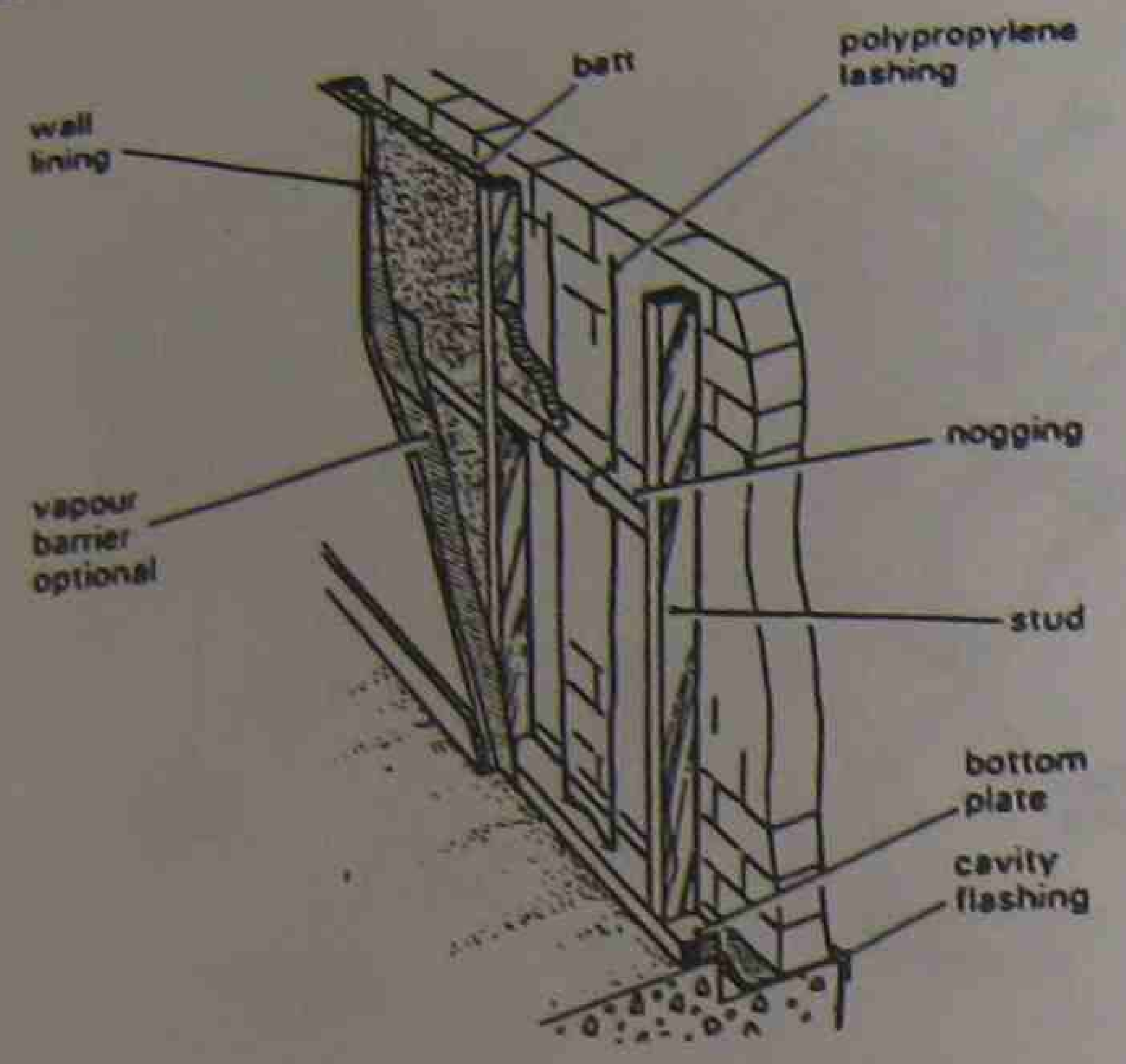


Figure 15 - Use of batts between studs.
(Source: Glass, Mass and Insulation Council, 1985).

Figure 16 shows the use of polystyrene boards with flexible edges that help to hold them in place. Care should be taken to ensure a tight fit and an adequate gap between the boards and the bricks. The boards are self-supporting and water-resistant so they do not need any strapping or a vapour barrier.

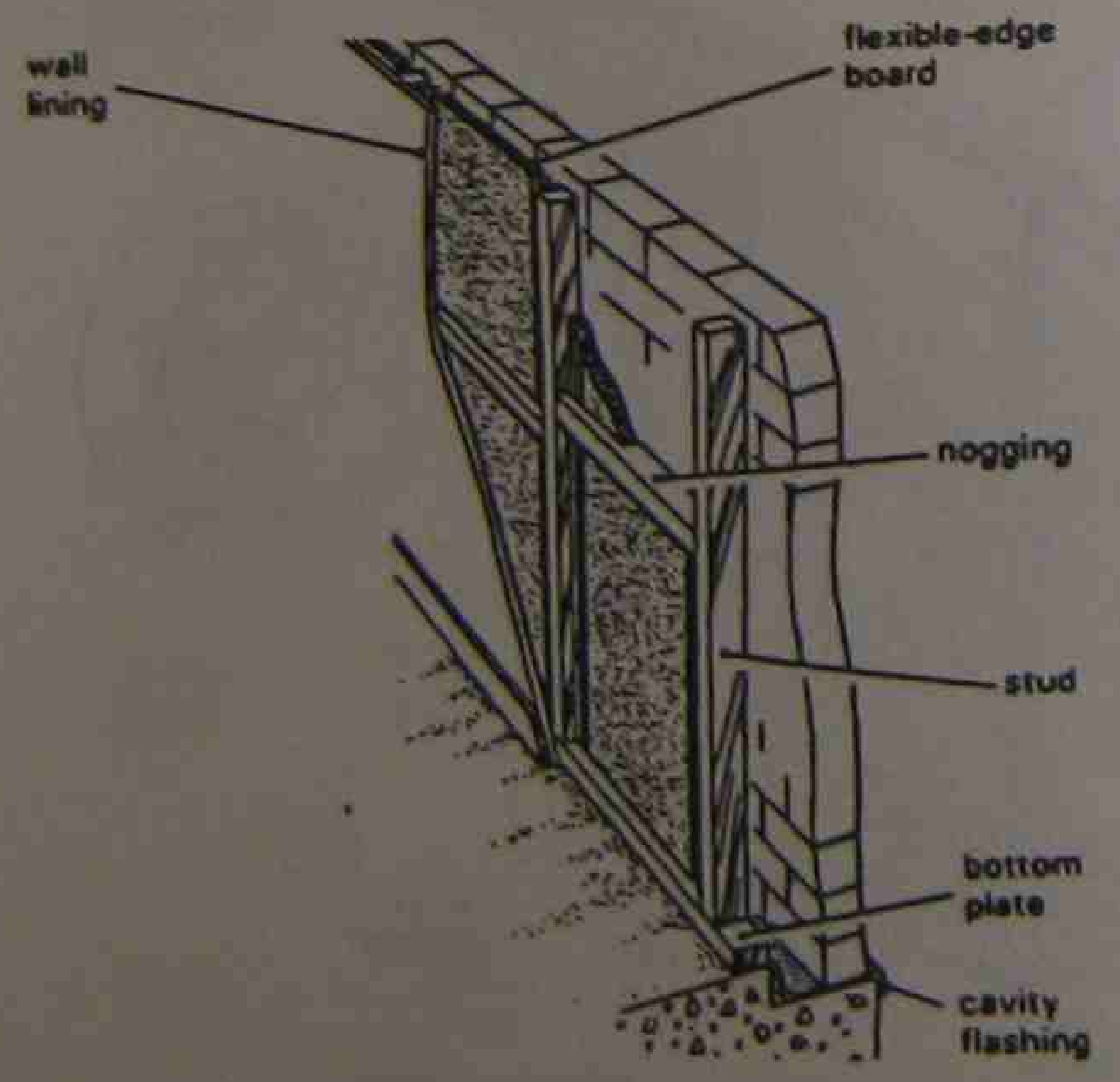


Figure 16 - Use of polystyrene boards between studs.
(Source: Glass, Mass and Insulation Council, 1985).

Polystyrene boards may also be used across wall studs, in a brick veneer wall, as shown in Figure 17.

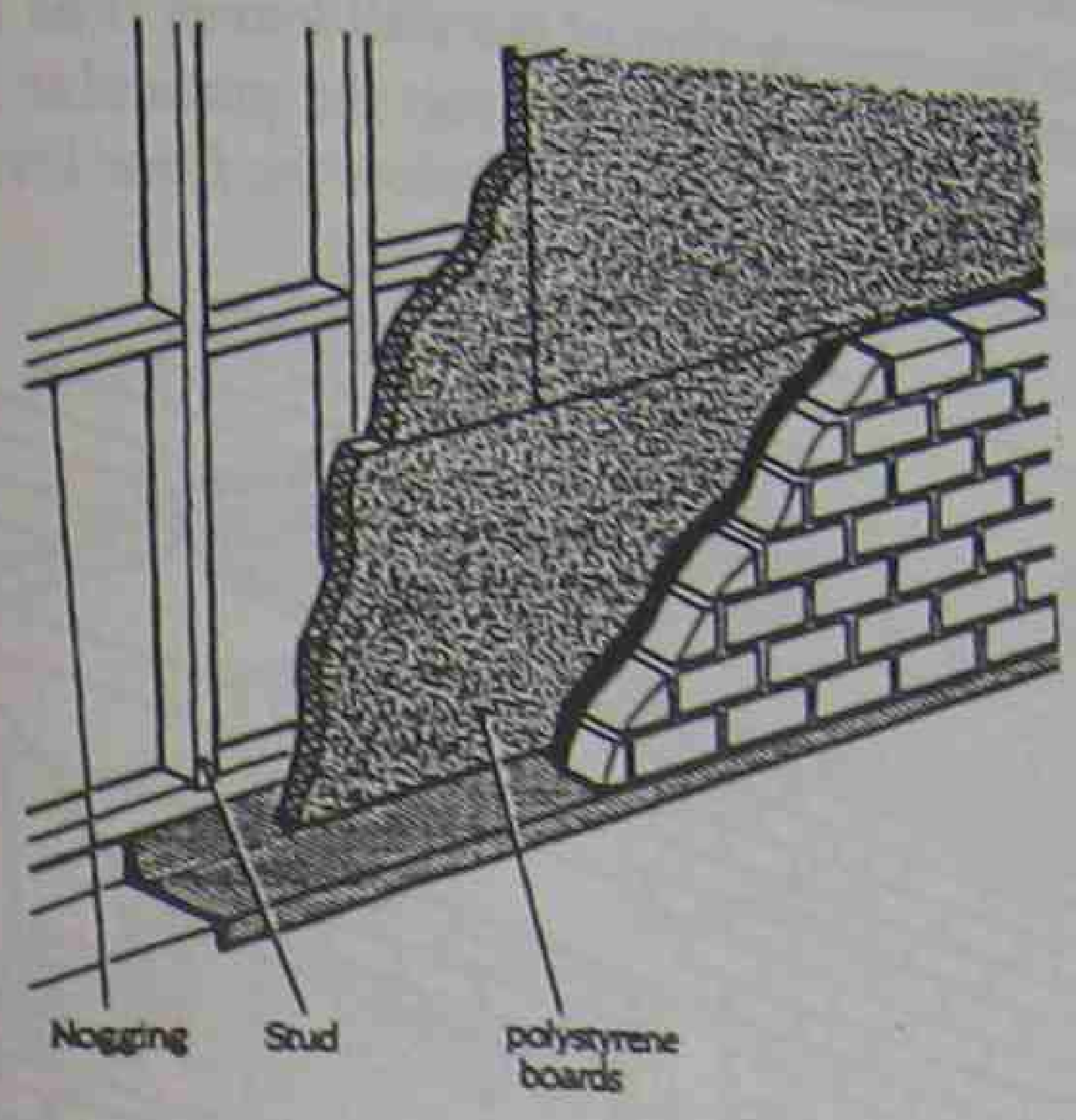


Figure 17 - Use of polystyrene boards across studs.
(Source: Energy Victoria, 1991).

For full **masonry walls**, insulation may be installed with or without cavity. In both cases, care should be taken to clear all mortar debris, clean joints of protruding mortar, and protect the installed board or batt from mortar debris. This creates a cavity which maintains a higher R-value and stops moisture saturating the batt. The inner leaf should lead the outer leaf in lifts that suits the type of board or batt to be installed. Current practice is to build the outer wall first. Figure 18 shows placement of batt or board in full masonry with provision for air space. The air space should be allowed according to provisions in relevant building regulations. The batts or board are clipped to the inner leaf at convenient intervals. The cavity flashing ensures that water resulting from moisture penetration of the outer leaf runs off to the outside.

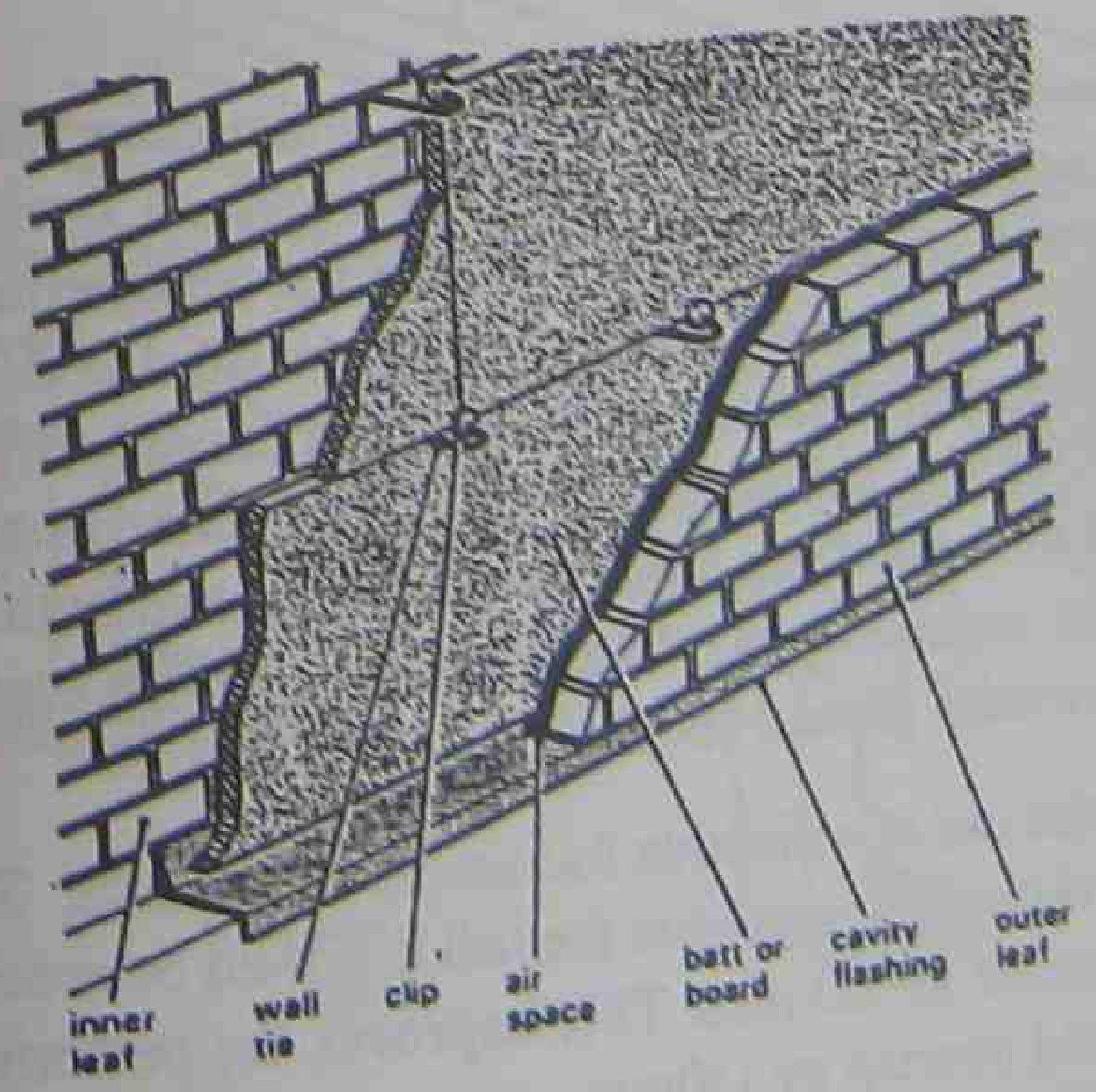


Figure 18 - Cavity insulation with air space.
(Source: Glass, Mass and Insulation Council, 1985).

Figure 19 shows the insulation of a masonry wall without an air space - the cavity is filled by insulation. The construction of the wall leaves is as shown in the figure. The outer leaf leads the inner leaf in lifts that suit the particular insulation batt, board or blanket used. The insulation should extend below the floor level to reduce the bridging effect through the slab.

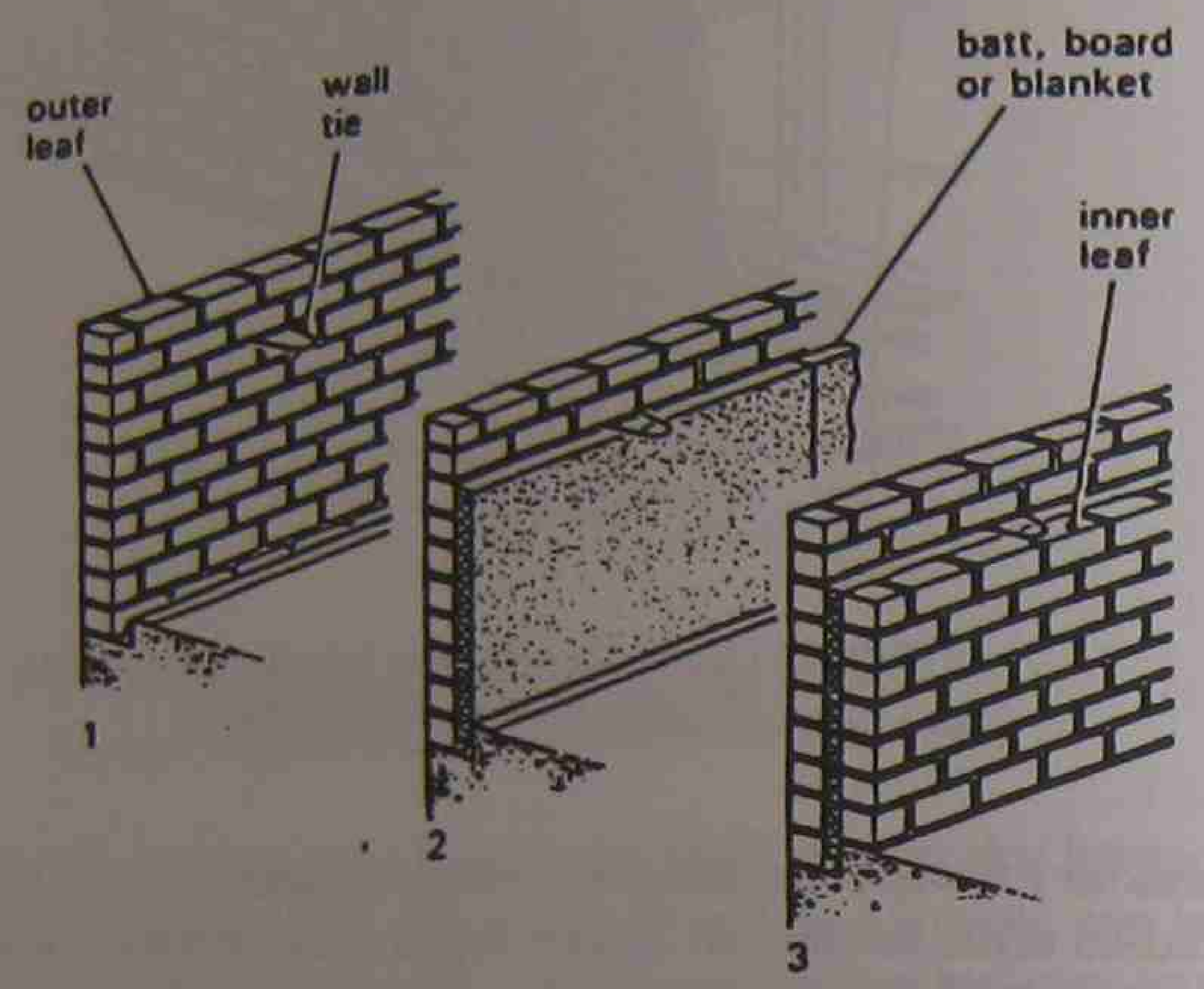


Figure 19 - Installation sequence for cavity insulation without air space.
(Source: Glass, Mass and Insulation Council, 1985).

Solid brick walls may be insulated by building a frame on the inside of the brick to support bulk insulation. A foil vapour barrier on the inside surface of the brick is recommended.

4.2.3 Floors

Timber floors have a low thermal resistance, when compared to building elements containing cavities. Slab-on-ground construction is an option which improves the effective thermal resistance of the floor. Suspended timber floors, suspended concrete slabs and concrete slab-on-ground floors may all be insulated. Insulation of suspended timber floors is particularly beneficial during winter in cold climates and during summer in hot climates. Effective insulation may include the provision of a good underlay and carpet. Enclosing the underfloor space reduces air movement under the building and may also assist in regulating building temperature. The reason for this is that the sub-floor space provides ground coupling.

Figure 20 shows the use of reflective foil across floor joists. The foil has perforations for ventilation. It should be noted that the foil is dished between joists, to the extent of about 50mm, to create air cavities. This improves the performance of the insulation. Sheets of foil should overlap by 150mm.

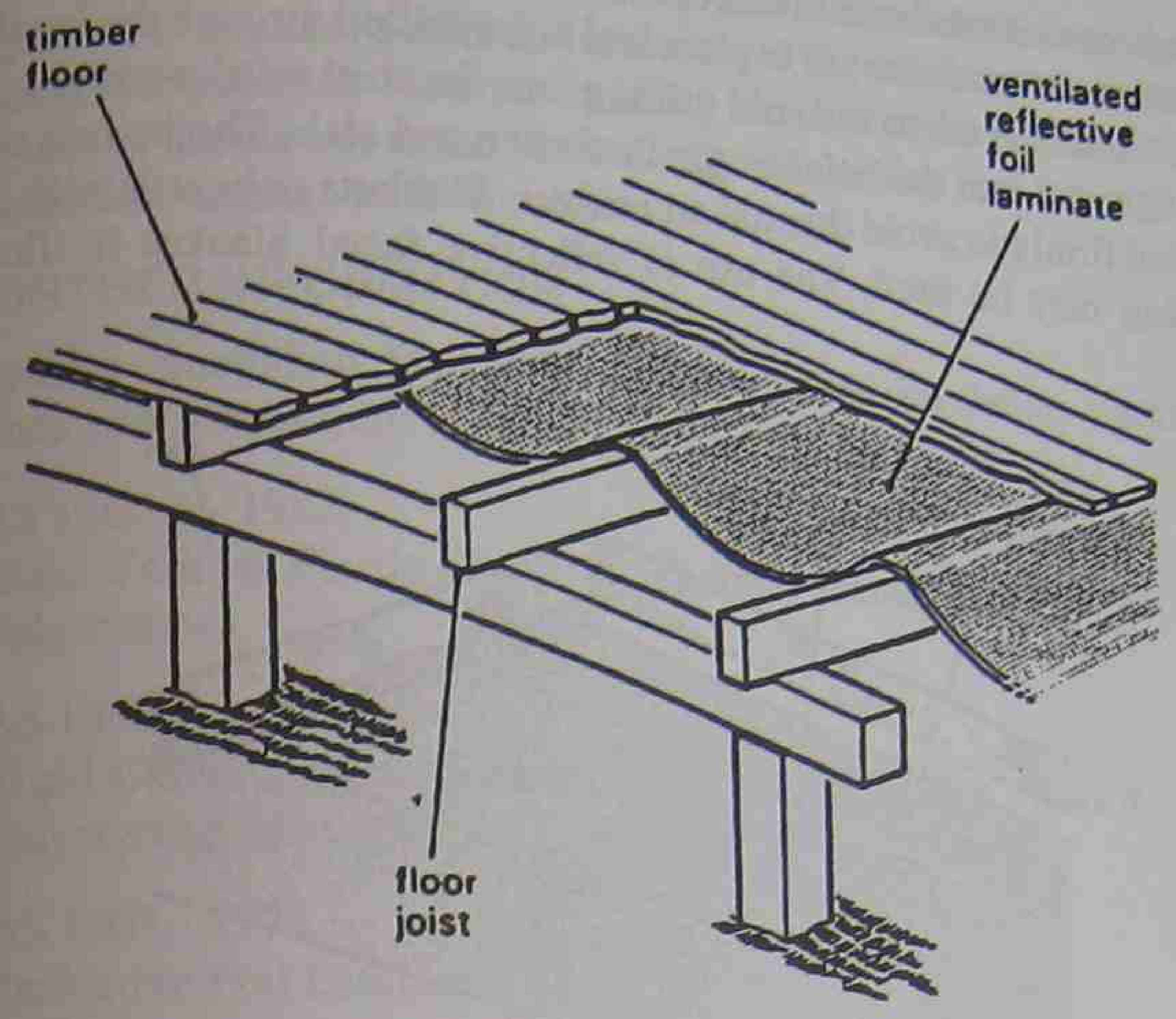


Figure 20 - Use of down-facing reflective foil across floor joists.
(Source: Glass, Mass and Insulation Council, 1985).

Use of batt or blanket and reflective foil is shown in Figure 21. The foil is laid first, then the close-fitting bulk insulation is pushed into place.

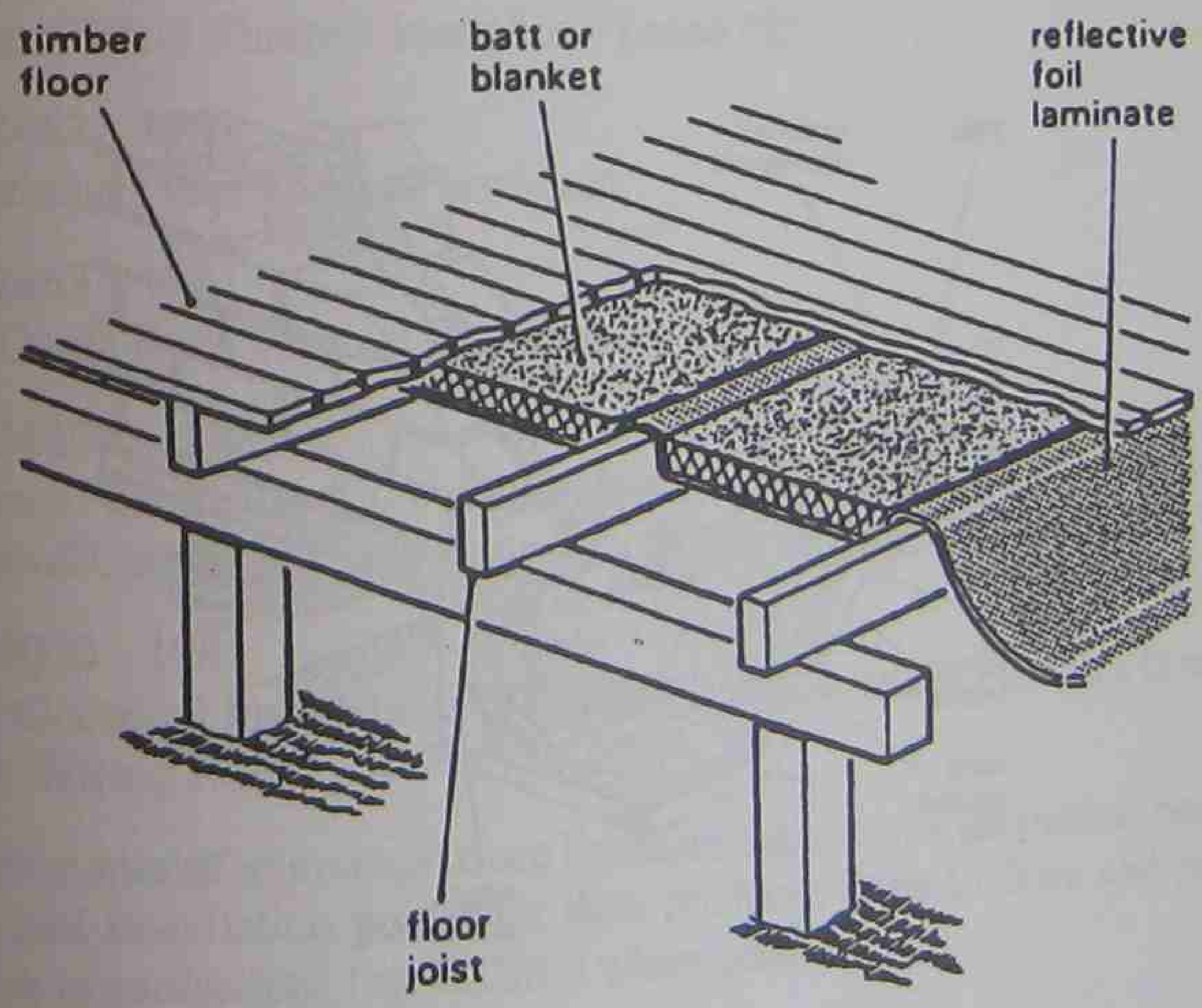


Figure 21 - Use of down-facing reflective foil and bulk insulation between floor joists.
(Source: Glass, Mass and Insulation Council, 1985).

For **suspended concrete slabs**, blankets or boards are fixed under the slab with retaining pins. The blankets or boards are put in place and holes drilled through the insulation into the slab. Care should be taken to avoid drilling into the steel reinforcement. Retaining pins are then inserted into the holes in the insulation and slab. The boards or blankets should be butted firmly to avoid thermal air bridges. Blankets or boards with or without reflective facing may be used. The use of reflective faced blanket is illustrated in Figure 22.

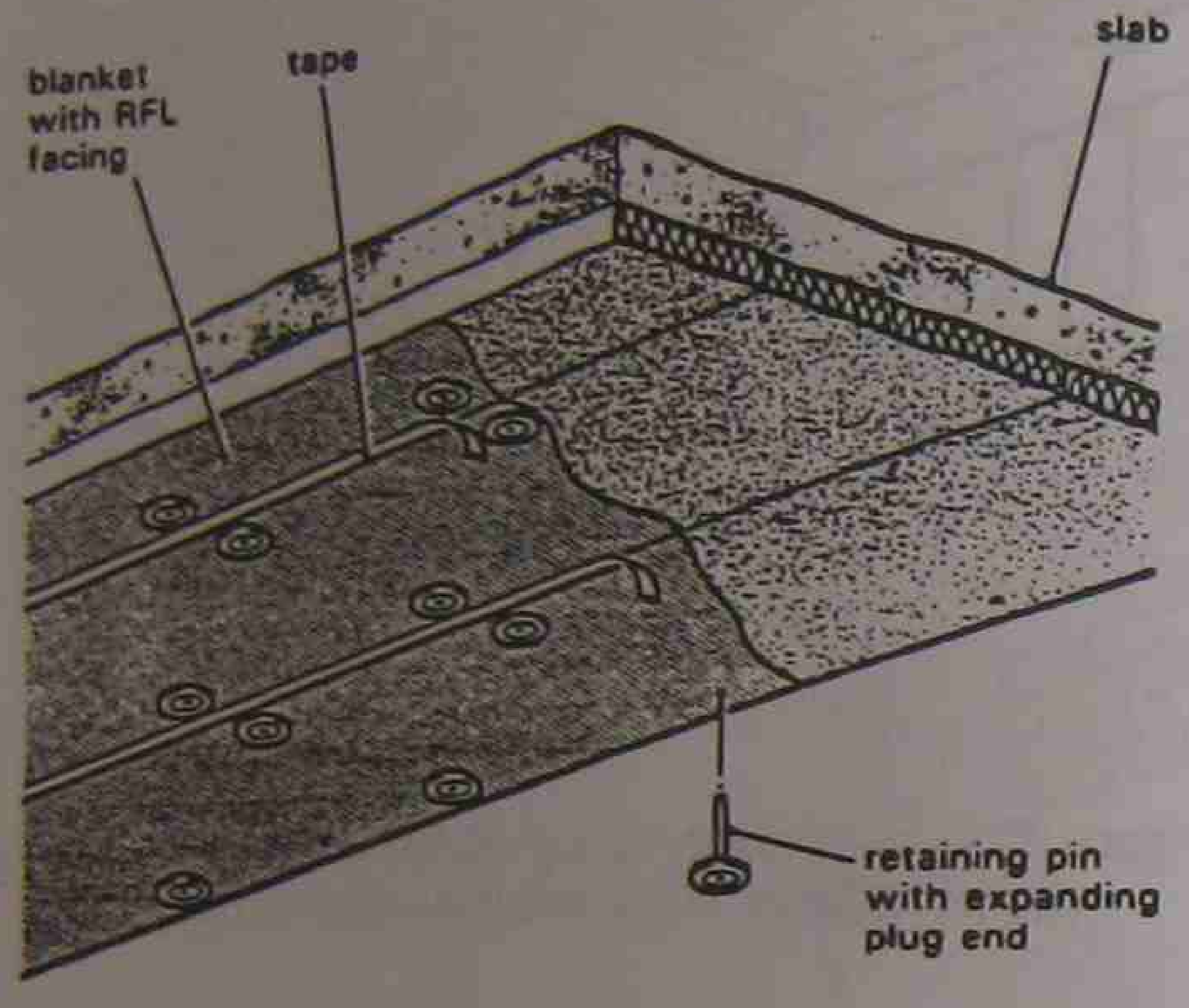


Figure 22 - Use of blankets under a suspended concrete slab.
(Source: Glass, Mass and Insulation Council, 1985).

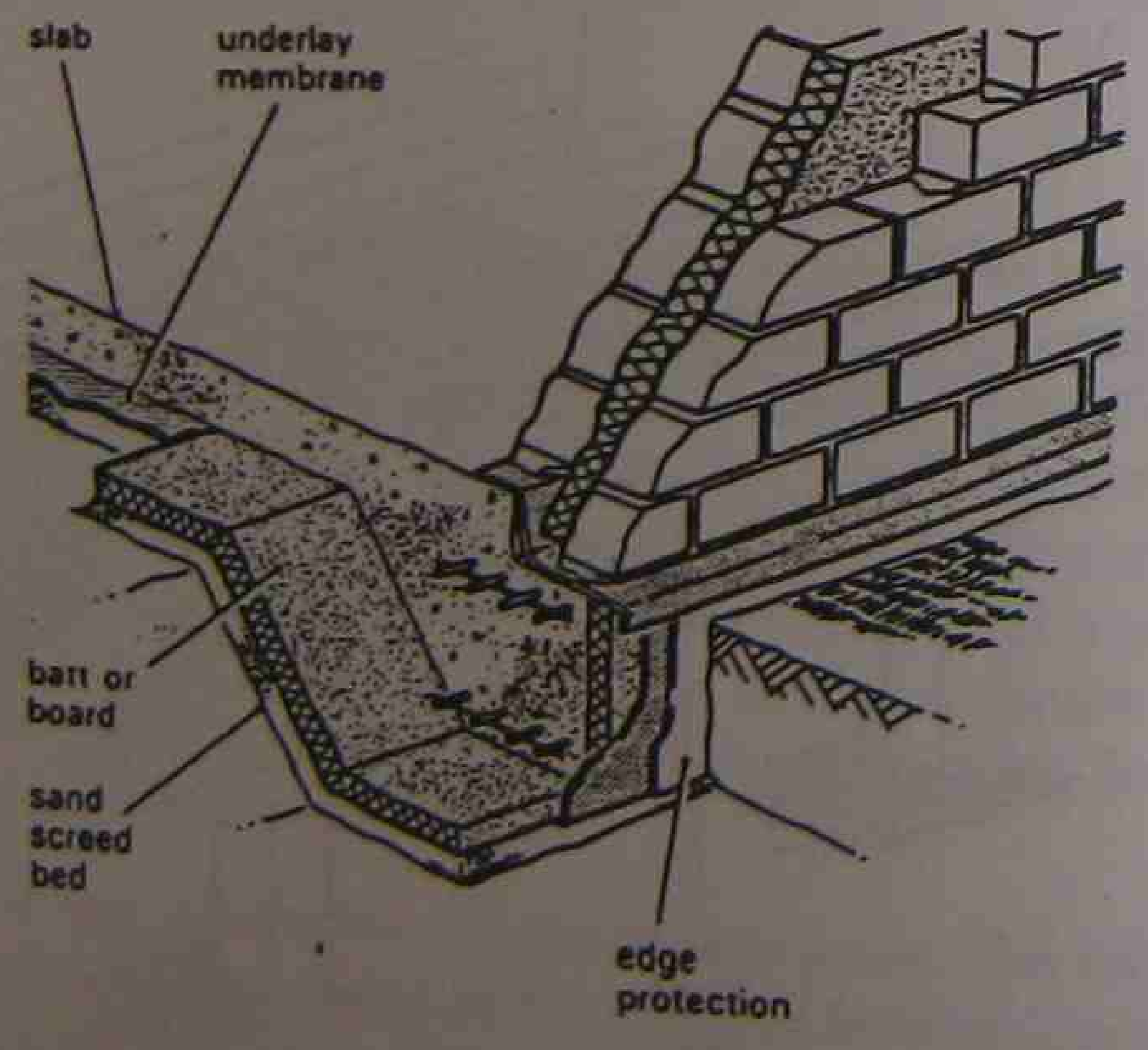


Figure 23 - Perimeter insulation of a concrete slab.
(Source: Glass, Mass and Insulation Council, 1985).

For areas, especially in the southern states, where heat losses from the edge of the **slab-on-ground** is marked, perimeter insulation of the slab is recommended. Figure 23 shows such and application. Note the underlay membrane, the position of batt or board, the placement of insulation at the vertical edge of the slab and the edge protection to avoid mechanical damage to the insulation.

5 FURTHER INFORMATION

The following Australian Standards are relevant to insulation packaging, design, performance and installation:

AS 1366.3 - 1982
Rigid Cellular Plastic Sheets for Thermal Insulation - Part 3 - Rigid Cellular Polystyrene.

AS 1366.4 - 1989
Rigid Cellular Plastic Sheets for Thermal Insulation - Part 4 - Rigid Cellular Polystyrene - Extruded (RC/PS-E).

AS 1903 - 1976
Reflective Foil Laminate.

AS 1904 -1976
Code of Practice for Installation of Reflective Foil Laminate in Buildings.

AS 2352 - 1980
Glossary of terms for Thermal Insulation of Buildings.

AS 2459 - 1982
Organic Fibre Insulating Board.

AS 2461 - 1981
Mineral Wool Thermal Insulation - Loose Fill.

AS 2462 - 1981
Cellulosic Fibre Thermal Insulation.

AS 2463 - 1981
Sea Grass Bulk Thermal Insulation.

AS 2627.1 - 1983
Thermal Insulation of Dwellings - Design Code Part 1 - 1983 Thermal Insulation of Roof/Ceiling in Dwellings which require Heating.

AS 3000 - 1981
The Electrical Installations of Buildings, structures and Premises (known as the SAA Wiring Rules).

Most insulation manufacturers produce literature outlining the properties, performance, dimensions and installation guides for their products. Refer to these and publications from research organisations (eg. CSIRO) where possible.

Thermal Mass and Storage

1 INTRODUCTION

Thermal mass can be used in buildings to moderate the internal swings in temperature due to changing external temperatures. The dynamic performance of buildings is discussed here in contrast to the steady state long term performance examined in Unit 10.

Variations in heat flow and temperature associated with indoor and outdoor thermal environments causes heat to be stored within building elements and to be subsequently released. Materials that store heat have high thermal capacitance and function in a more complex way to materials simply having a high thermal resistance.

Changes in outdoor temperature create delayed and reduced indoor temperature changes. This stabilising effect is greatest for massive (heavyweight) buildings, particularly where the thermal mass is in direct contact with the indoor air space. Thermal comfort will therefore improve during the colder part of the winter day and warmer part of the summer day. However, if a building is to be heated or cooled intermittently, this stabilising effect will delay the desired temperature changes. It may also increase the amount of energy required to affect the temperature change. Similarly, a more massive building will take longer to recover from the effects of a prolonged hot or cold spell.

This Unit provides an understanding of heat storage theory and the practical application of thermal mass in housing. It completes discussion of the detailed thermal behaviour of buildings.

2 HEAT STORAGE THEORY

Thermal energy may be stored during the heating, melting or vaporising of a material, with the energy becoming available when the process is reversed. Energy storage accompanied by a rise in temperature is called sensible-heat storage. Energy storage during a phase change (the transition between solid, liquid and vapour states) is known as latent-heat storage.

2.1 Sensible-Heat Storage

The ability of a material to store sensible-heat is described by its specific heat capacity (s) which is the amount of energy required to raise a kilogram of the material by one Kelvin; its unit is J/kgK. The volumetric heat capacity (c) obtained by multiplying the specific heat by the density, is the amount of energy required to raise a unit volume of material by one Kelvin; its unit is J/m^3K.

For two materials of equal volume each subjected to the same temperature rise, the one with the greater volumetric heat capacity will store more heat. Conversely, if they both absorb the same amount of heat, the one with the greater value of c will show a smaller temperature rise.

Consider a building material in which uni-directional heat flow is assumed to take place over length L. Together, thermal capacitance and thermal resistance completely specify the thermal behaviour of the material. Thermal capacitance determines the amount of stored or released heat and thermal resistance determines the rate at which heat is transferred.

Thermal capacity:

$$C = cL$$

where c is the volumetric heat capacity
L is the thickness .

Thermal resistance (as discussed in Unit 4):

$$R = L / k$$

where k is the thermal conductivity.

If the temperature changes are cyclic, then the thermal resistance determines the average rate of heat flow over a long period.

Most building components such as walls and roofs, consist of different layers of materials, including air gaps. Thermal resistances of composite materials may be obtained by adding the resistance of each layer. Thermal capacitances, however, are not additive.

2.2 Latent-Heat Storage

Latent-heat storage materials can provide spatially dense storage of low-grade heat. They include salt mixtures and paraffins which are easily melted.

These substances require the addition of energy if the solid structure is to be broken down to form a liquid. The energy required for melting is called the latent heat of fusion. When the liquid solidifies, the substance emits the heat of fusion.

Low temperature (20°C) phase change materials are particularly important for thermal design applications, as the material is in the transitional state within typical comfort zone temperature limits. If phase change materials are carefully selected (in terms of melting temperature and heat of fusion) and carefully positioned in the building (in relation to direct sunlight) they may stay in phase change mode for a large proportion of the time.

Such materials help to even out indoor temperatures better than sensible heat storage materials, as no temperature change in the material occurs during phase change. Also, the materials typically hold more heat and discharge over a longer period.

Section 2.3 discusses the detailed thermal characteristics of a range of latent heat storage materials.

2.3 Characteristics of Thermal Storage Materials

Materials used for sensible-heat storage in passive solar systems include rock, adobe, brick, concrete and water (e.g., in a drum wall). (Unit 12 discusses the use of a pebble bed and water storage in active design). Table 1 gives the physical characteristics of some common sensible-heat storage materials.

As Table 1 shows, specific heat capacities for solid materials do not vary much compared to the large variations in density so that (for a given thickness) thermal capacitance is largely a function of density. For this reason, the term thermal mass is often used to refer to materials with high thermal capacitance.

Storage Medium	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)
Concrete	2240	1130	0.9 - 1.3
Rock	2640	880	1.7 - 4.0
Brick	3000	1130	5.07
Water	960	4200	0.4 - 0.6

Table 1 - Characteristics of materials commonly used for sensible-heat storage. (Source: Kreider and Kreith, 1981).

Table 2 lists characteristics of some common latent-heat storage materials. The use of Calcium Chloride Hexahydrate, $CaCl_2.6H_20$, (a waste product from some industrial processes) for thermal storage has been investigated at the Australian National University. Stable formulations of this material have been proven at the temperature of 30°C, with newer formulations having melting points as low as 23°C under test.

Storage Material	Melting Temperature (°C)	Heat of Fusion (kJ/kg)	Density (kJ/m^3)		Specific Heat Capacity (J/kgK)		Thermal Conductivity (W/mK)	
			Solid	Liquid	Solid	Liquid	Solid	Liquid
Glauber's Salt Eutectic	13	146	1470	N/A	1420	2680	N/A	N/A
$CaC1_2.6H_20$	27	190	1800	1560	1460	2130	1.09	0.54
$Na_2SO_4.10H_20$ Glauber's Salt	32	225	1460	1330	1760	3300	2.25	N/A
Paraffin Wax (Sunoco P-116)	47	209	820	770	2890	2510	0.14	N/A
NOTE: N/A means not available.								

Table 2 - Characteristics of materials commonly used for latent- heat storage. (Source: Kreider and Kreith, 1981).

2.4 Thermal Properties and Terminology

As heat enters a solid massive wall, each layer of particles absorbs a certain amount of heat before any heat is transmitted to the next layer, creating a delaying (or capacitance) effect. With stable indoor and outdoor conditions, a thermal gradient would be established across the wall and the capacitance effect would disappear after a settling down period. That is, the heat flow would be controlled only by the resistance of the wall. If the time delay of the heat pulse is comparable in size to the period of changes in temperature on the heat input side of the wall, the peak input time may be passed before the temperature wave reaches the other side. Some of the heat stored in the massive wall may therefore flow backwards and be emitted on both sides. Figure 1 illustrates a sequence of temperature gradients within such a wall as a time sequence.

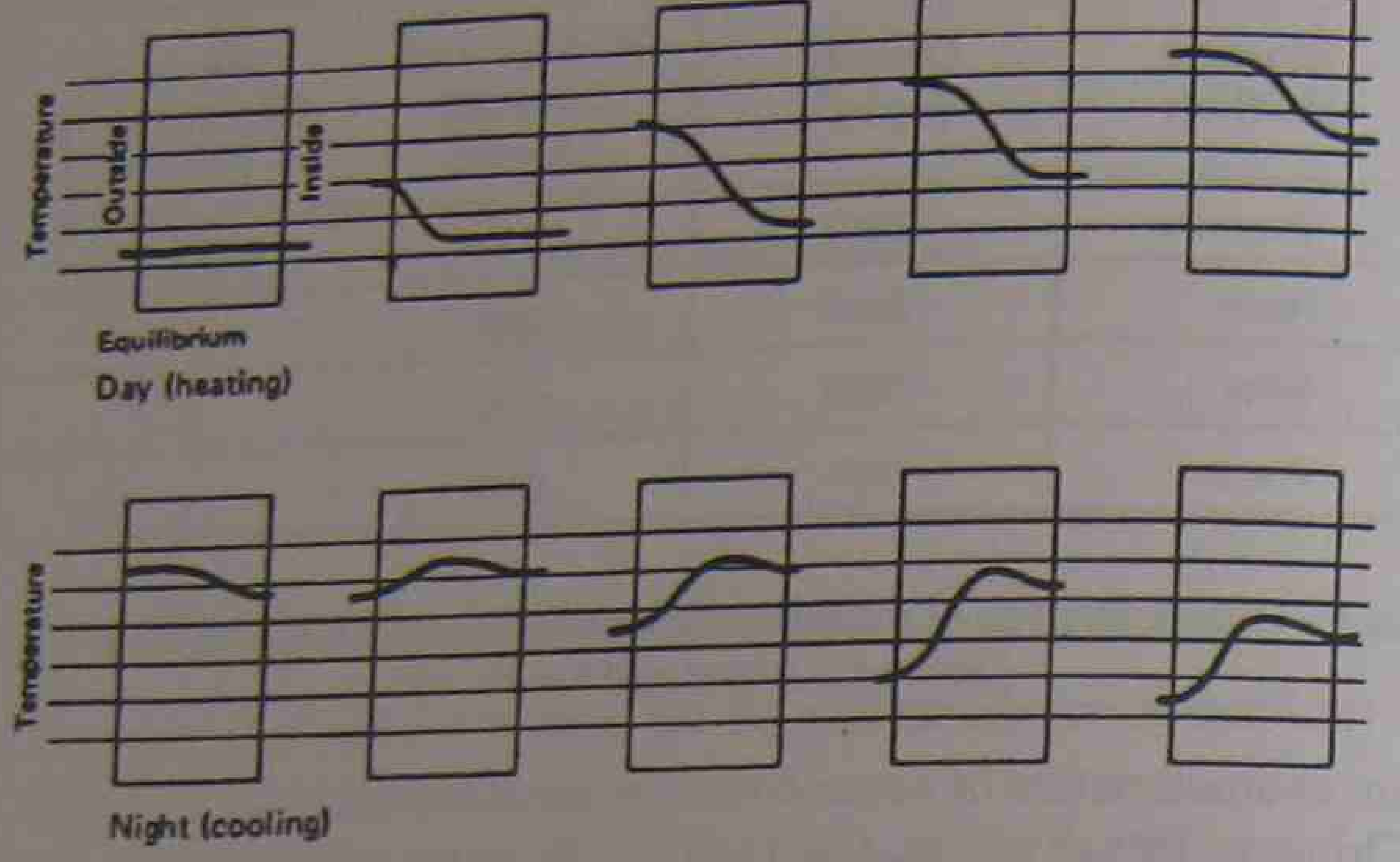


Figure 1 - Time sequence of temperature gradients in a massive wall during the day and night. (Source: Szokolay, 1980).

2.4.1 Time Lag, Decrement Factor and Thermal Admittance

Figure 2 shows an idealised variation of heat flow over a 24-hour cycle for a massive material (solid line) and for a material of zero thermal capacity (dotted line). Two parameters are established in Figure 2. These are the time lag (ϕ) and the decrement factor (μ).

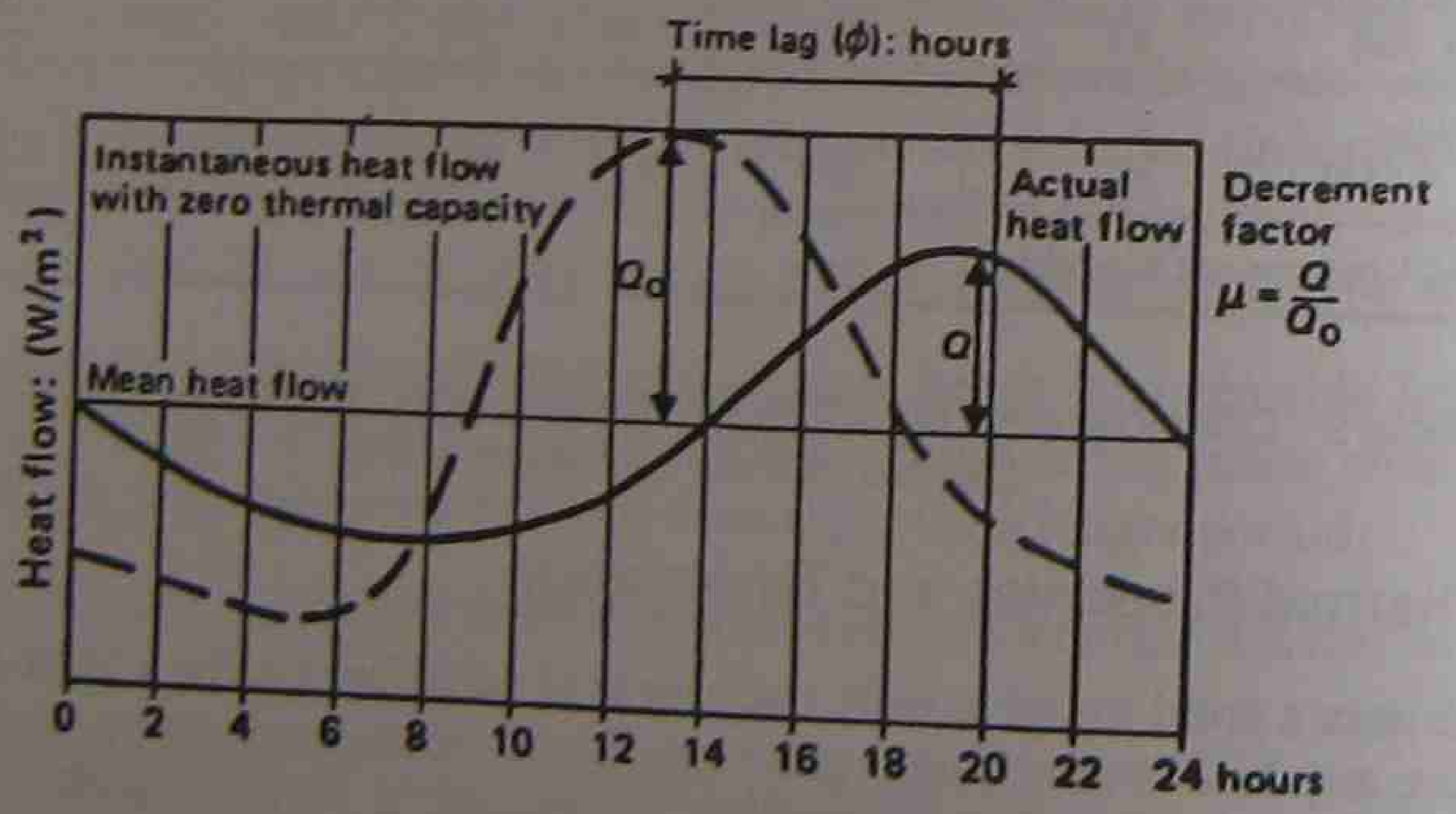


Figure 2 - 24-hour heat flow cycle illustrating time lag and decrement factor. (Source: Szokolay, 1980).

The time lag is the delay of the heat flow peak, in hours, behind the heat flow peak that would occur in a wall of zero thermal mass. The decrement factor is a measure of the attenuation of the amplitude of the heat flow peak resulting from the use of thermal mass. Both of these parameters depend on the type of construction.

Figure 3 provides information on the time-lag characteristics of massive walls or slabs of uniform density, as a function of thickness. It shows that time lag varies directly with the thickness of the material. So, as mass increases the time lag also increases. The small table at the top left-hand corner of Figure 3 shows that the addition of an insulating layer increases the time lag. The addition of insulation on the heat input side of the mass (external insulation) increases the time lag by 1.0 to 1.5 hours. Internal insulation increases the time lag by 0.5 to 1.0 hour.

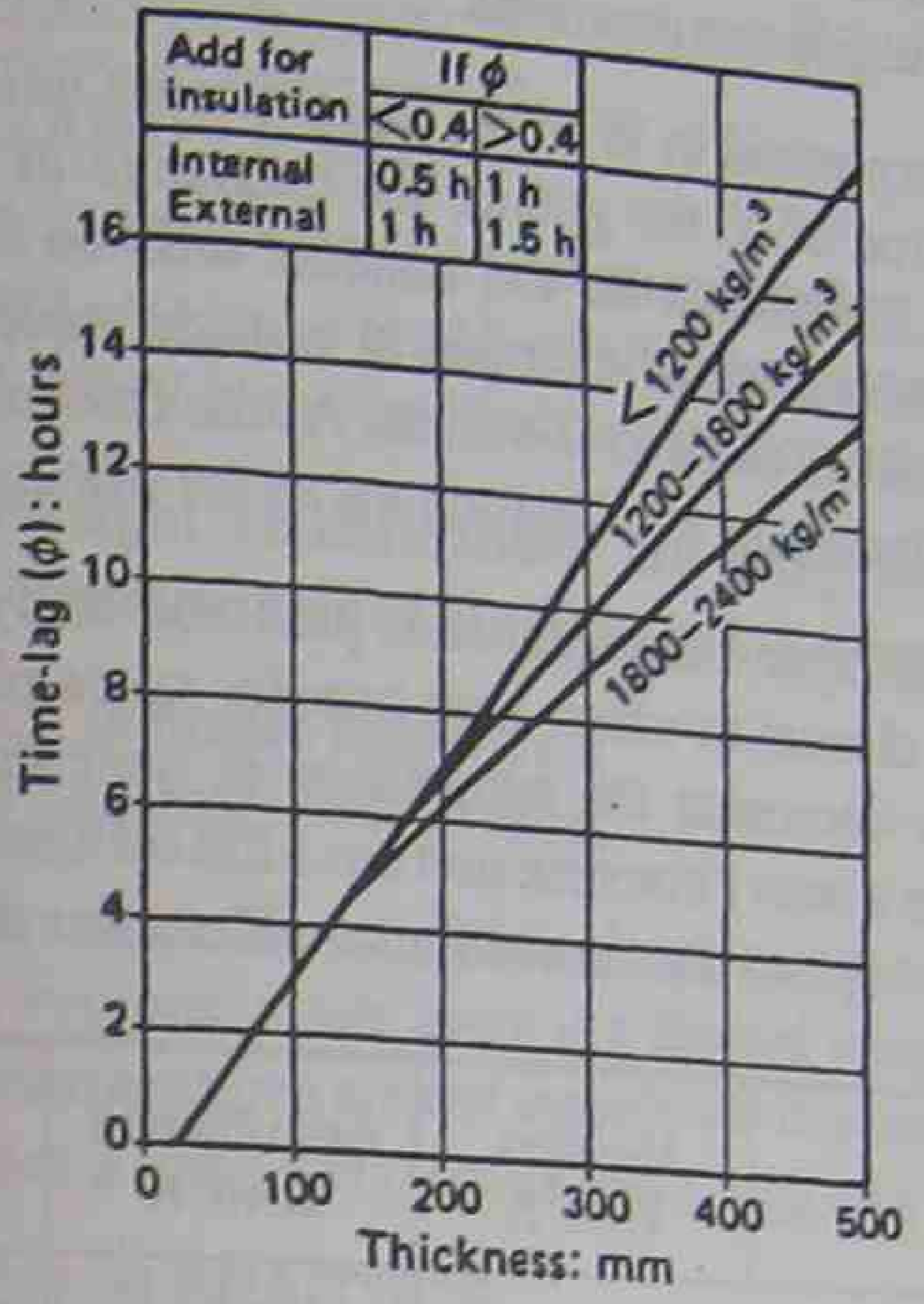


Figure 3 - Graph of material thickness versus time lag. (Source: Szokolay, 1980).

Figure 4 shows how the decrement factor varies with material thickness and the placement of insulation. The decrement factor decreases rapidly with increasing thicknesses up to about 400mm, after which there is little change. The addition of insulation, particularly on the heat input side, decreases the amplitude of the heat flow peak.

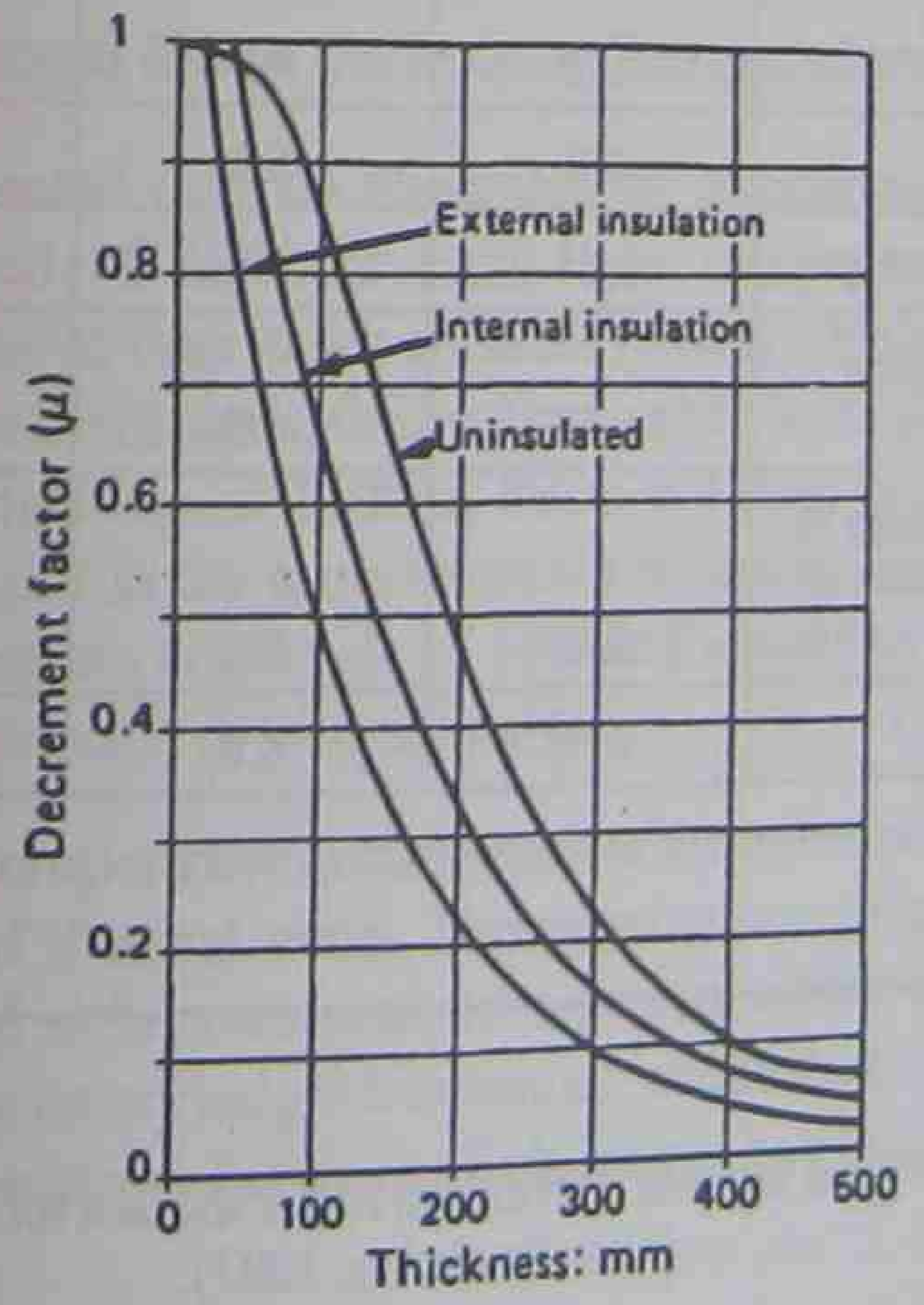


Figure 4 - Graph of material thickness versus decrement factor. (Source: Szokolay, 1980).

As suggested in the above graphs, the time lag and decrement factor are influenced by the sequence of layers of material. Analysis of heat flows becomes more complicated with multi-layers of different materials, as is the case for most building elements.

Thermal admittance (Y) is a measure of the rate of heat flow between the internal building surface and the space it surrounds when a temperature difference exists. This ability to absorb or release heat affects the stability of internal temperature in response to a sinusoidal change in outside temperatures.

Thermal admittance, expressed in W/m^2K, has the same units as thermal transmittance (U). The larger the value of Y, the greater the exchange of heat between the building structure and the air it contains so the smaller will be the change in internal air temperatures as a consequence of changes in outside temperature. Thin single layer constructions have Y-values close to U-values. As the thickness of the building element increases, the Y-value increases to a limiting value for thicknesses greater than 100mm.

The admittance of multi-layer constructions is predominantly influenced by the thermal properties of the layer closest to where heat transfer takes place. Insulating the surface of a wall or slab floor decreases the admittance to near that of the insulation alone. Insulation placed within a heavy construction has little influence on the admittance value. Table 3 compares time lag and decrement factor values for different building elements.

	U-value W/m^2K	Admittance W/m^2K	Time-lag hours	Decrement factor
Brick wall single skin 105 mm	3.28	4.2	2.6	0.87
Brick wall single skin 220 mm	2.26	4.7	6.1	0.54
Cavity brick wall	1.47	4.4	7.7	0.44
Cavity brick wall, 25 mm insulation in cavity	0.72	4.6	8.9	0.34
Brick veneer wall	1.77	2.2	3.5	0.77
Brick veneer wall, 25 mm insulation in cavity	0.78	1.1	4.1	0.71
Window, single glazed	5.0	5.0	0	1
Pitched metal roof, flat ceiling	2.54	2.6	0.3	1
Pitched metal roof, flat ceiling 50 mm insulation	0.55	1.0	0.7	0.99
Suspended timber floor close to ground, controlled ventilation of underfloor space *	0.61	2.0	0.8	0.98
Concrete slab on ground *	0.62	6.0	>24	0

* 15 x 7.5 m floor

Table 3 - Comparison of time lag and decrement factor values for different building elements. (After Szokolay, 1987).

2.4.2 Response Factor

The response factor (F_r) is a measure of the ability of the building to change its internal temperature in response to changes in external temperatures. This will depend on the total heat transmittance of the building envelope, the ventilation rate and the ability of the structure to absorb or release heat (total heat admittance). It is the admittance which is dominant in influencing the response factor:

$$F_r = \frac{\Sigma(AxY) + 0.33NV}{\Sigma(AxU) + 0.33NV}$$

where $\Sigma(AxU)$ is the total heat transmittance,
$\Sigma(AxY)$ is the total heat admittance, and
$0.33NV$ is the ventilation heat flow rate.

Lightweight and heavyweight classifications are assigned to buildings as being appropriate in particular climatic regions. In terms of the response factor:

$F_r \approx$ 2.5 indicates lightweight
$F_r \approx$ 6 indicates heavyweight.

The theoretical minimum value of F_r is 1, while the practical achievable maximum limit is around 10. In climatic regions where there is a diurnal temperature swing of at least 8°C and where average temperatures are not outside the human comfort zone, an energy efficient house would have a low (AxU) value and a high (AxY) value.

3 HEAT STORAGE IN PRACTICE

Thermal mass should be placed on the inside surfaces of rooms in direct contact with the air. It is usually incorporated in walls and floors although it is possible to construct heavyweight ceilings. Some form of insulation should exist between the thermal mass and the exterior of the building, even if this is only an air cavity (walls) or earth (floor). Common forms of heavyweight construction include the cavity brick wall and concrete slab-on-ground floor.

3.1 Effect of Thermal Mass on Indoor Temperature

The effect of thermal mass may be illustrated by comparing the performance of two boxes, each constructed of different multi-layer components, subject to sinusoidal temperature fluctuations at their outer surfaces (walls). One box has lightweight walls consisting of 12mm weatherboards, timber frame and 10mm plasterboard. The other has heavyweight walls consisting of 110mm brick, a 50mm airspace, 110mm brick and 20mm plaster. Each box has the same thermal resistance. Temperature outside the box has a period of 24 hours, an amplitude of 10K and a mean of 24°C. There are no solar gains (on or through the wall) or internal gains.

Figure 5 compares the temperature outside each of the boxes with the temperature inside, and shows the effect of thermal mass. The massive box reduces the amplitude of the indoor temperature and delays its peak to a greater extent than the lightweight box. Temperatures within the heavyweight box remain within the comfort zone, while outdoor temperatures and temperatures inside the lightweight box become uncomfortable.

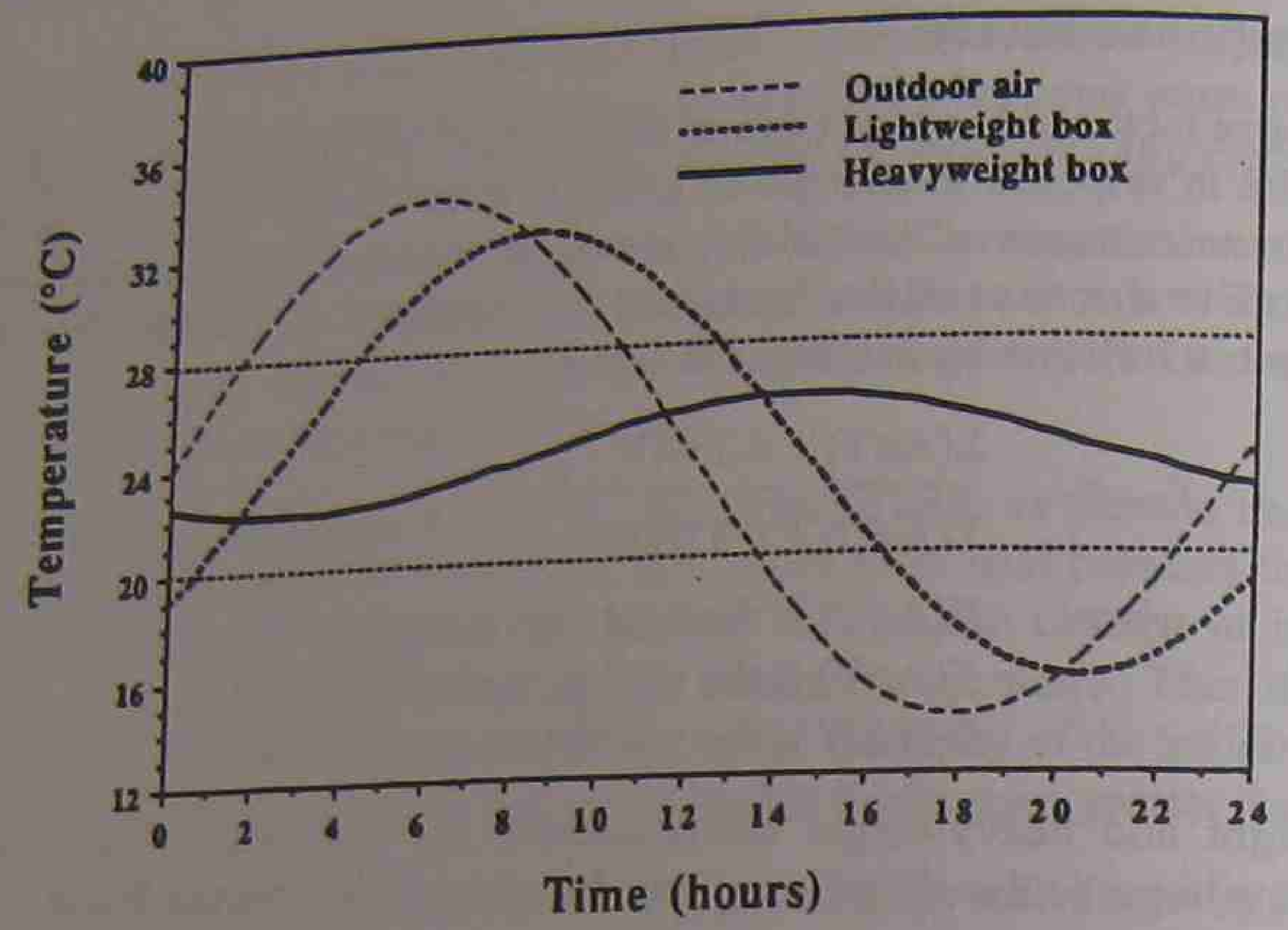


Figure 5 - Effect of thermal mass on temperatures inside a box, with dotted horizontal lines indicating the limits of the nominal comfort zone. (Source: Delsante, 1991).

Discussion in this section has related to idealised mass effects independently from the building as a whole. Subsequent sections build up a more realistic picture.

3.2 Interaction of Thermal Mass, Climate, North-facing Glass and Night-time Ventilation

The effects of thermal mass may not be beneficial if the outdoor temperature is well outside the comfort zone. Even if the outdoor temperature is close to the comfort zone, solar radiation transmitted through windows and absorbed on outer surfaces may cause overheating. A combination of large diurnal temperature swings (usually more than 8 degrees) and mean temperatures within the comfort zone are both required for thermal mass to be effective in summer. Reference to climatic data (see Unit 2) should be made to check whether these criteria are fulfilled for a specific location. It is generally accepted that thermal mass for temperature control is not useful in locations such as Darwin for example, where high summer minimum and maximum temperatures are outside the comfort zone.

The Glass, Mass and Insulation Council (1985) have produced guidelines for determining the maximum area of north-facing glass which is permissible for a given level of thermal mass in different climatic zones. These are specified in Table 4 for four different climatic regions and apply to a house with framed external walls, framed and/or masonry internal walls and concrete floors. The first part of Table 4 (Adelaide Plains) shows for example, that if internal masonry is equivalent to 80% of the floor area and if 80% of the northern concrete slab area has a hard surface, then the area of north-facing glass used may be up to 30% of the net floor area for each room.

It should be noted that mass areas in the northern zone only are taken into account in Table 4. Wall and floor mass areas in high ventilation locations (e.g., bathrooms and laundries) should not be taken into account. The area of floor and external wall mass is measured on one side only while internal walls must have both sides considered. Generally, larger areas of thermal mass are appropriate for larger areas of north-facing glass.

Adelaide Plains		Internal Masonry % of floor area						
		0	20	40	60	80	100	120
Slab	0	†	†	†	†	10	20	35
with	20	†	†	†	†	15	25	35
hard	40	†	†	†	†	20	30	40
surface	60	†	†	†	15	25	35	45
% of	80	†	10	15	20	30	40	*
total	100	10	15	25	40	*	*	*

Sydney		Internal Masonry % of floor area						
		60	70	80	90	100	110	120
Slab	0	†	†	†	†	†	10	20
with	20	†	†	†	†	†	15	25
hard	40	†	†	†	†	15	20	30
surface	60	†	†	10	15	25	30	35
% of	80	†	10	20	25	30	35	45
total	100	15	20	30	35	40	45	*

Melbourne		Internal Masonry % of floor area						
		0	20	40	60	80	100	120
Slab	0	15	20	30	40	*	*	*
with	20	20	30	40	*	*	*	*
hard	40	30	35	45	*	*	*	*
surface	60	40	*	*	*	*	*	*
% of	80	*	*	*	*	*	*	*
total	100	*	*	*	*	*	*	*

Canberra		Internal Masonry % of floor area						
		0	20	40	60	80	100	120
Slab	0	†	†	10	25	40	*	*
with	20	†	†	20	35	*	*	*
hard	40	†	15	30	40	*	*	*
surface	60	15	25	40	*	*	*	*
% of	80	30	40	*	*	*	*	*
total	100	*	*	*	*	*	*	*

* Although a glass area of 50% is technically feasible, its use is not recommended.

† A Five Star Design Rating is unlikely to be achieved in this climate category with this ratio of north facing glass to floor and/or wall mass.

Table 4 - Recommended maximum areas of north-facing glass as a percentage of net floor area (for a house with framed walls, framed and/or masonry internal walls and concrete floors) for Adelaide Plains, Sydney, Melbourne and Canberra climatic zones. (Source: Glass, Mass and Insulation Council, 1985).

Thermal mass is easily cooled by ventilation. A mass that has been heated during the day can be cooled at night by allowing breezes to blow over the surface. Windows and doors provide openings for natural ventilation.

3.3 Computer Simulation of Heavyweight and Lightweight Buildings

Walsh, Gurr and Ballantyne (1982) of the CSIRO simulated the relative performance of heavyweight and lightweight construction in seven areas of Australia (Alice Springs, Brisbane, Darwin, Melbourne, Perth, Wagga and Williamtown) using the ZSTEP computer program. Calculations were based on a "typical year" of climatic data from each location.

The building examined was a small, three-bedroom house with an insulated pitched tiled roof, of simple rectangular plan having large north-facing windows. Figure 6 shows the floor plan of the dwelling examined. Note the zoning of the house, with living areas to the north and sleeping areas to the south, following the general zoning principle discussed in Unit 1. Two modes of thermal performance were analysed: (1) when no heating or cooling were carried out and (2) when heating and cooling were carried out to give specified conditions in the living area.

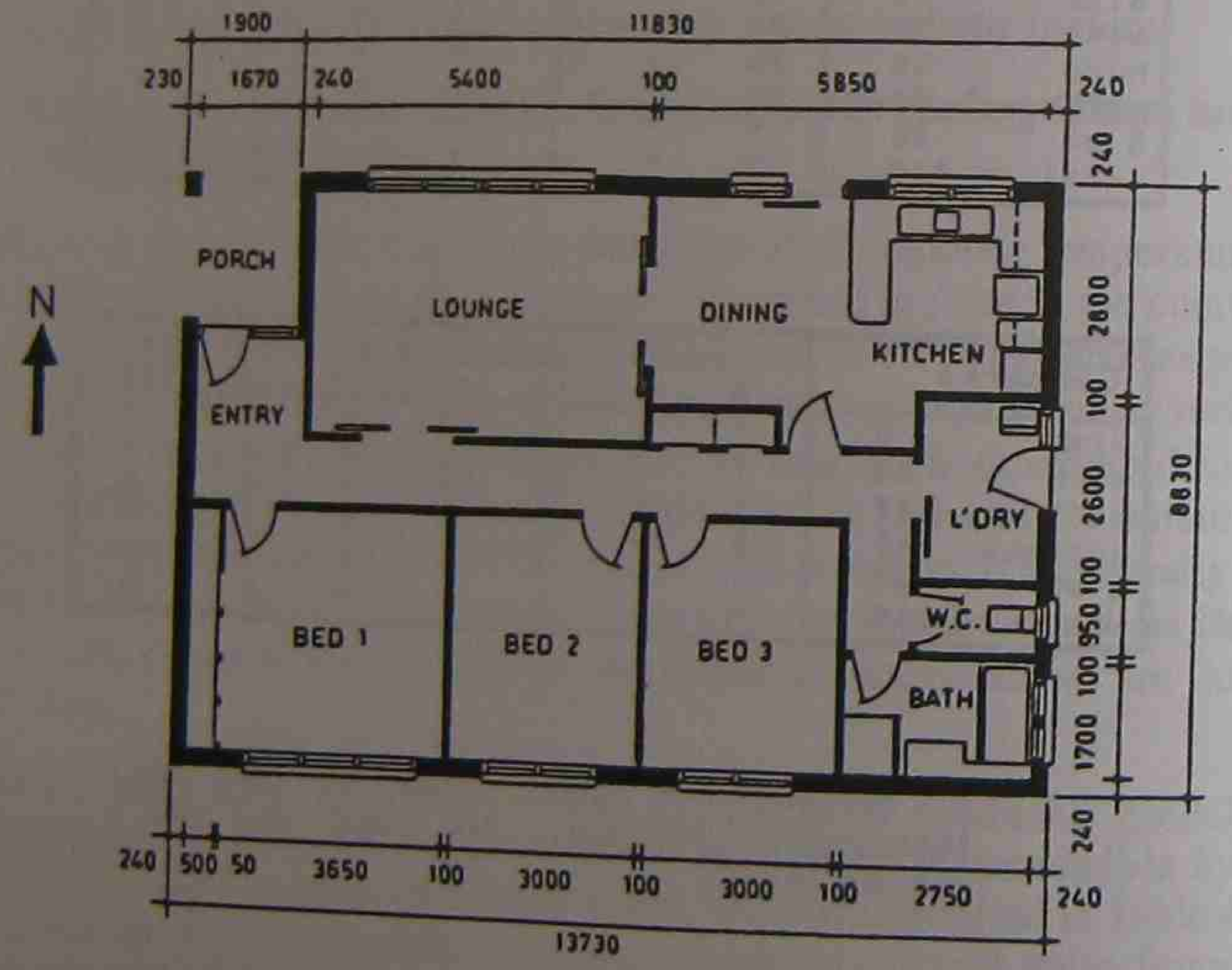


Figure 6 - Floor plan of the dwelling examined in the computer simulations. (Source: Walsh, Gurr and Ballantyne, 1982).

In the **unconditioned house** case, uninsulated brick veneer walls and suspended timber floors (lightweight construction) were compared with uninsulated cavity brick walls and concrete slab-on-ground floors (heavyweight construction).

Indoor temperatures were calculated for January and July (usually the warmest and coolest months) in the living and bedroom zones during the waking and sleeping hours respectively. Temperatures were grouped into 3K increments to coincide with a standardised thermal sensation scale using the following terminology:

MTC = Much Too Cool
TC = Too Cool
C = Cool
W = Warm
TW = Too Warm
MTW = Much Too Warm.

Results for Brisbane, Darwin and Melbourne are illustrated diagrammatically in Figures 7, 8 and 9 respectively, for heavyweight (solid line) and lightweight (dotted line) construction.

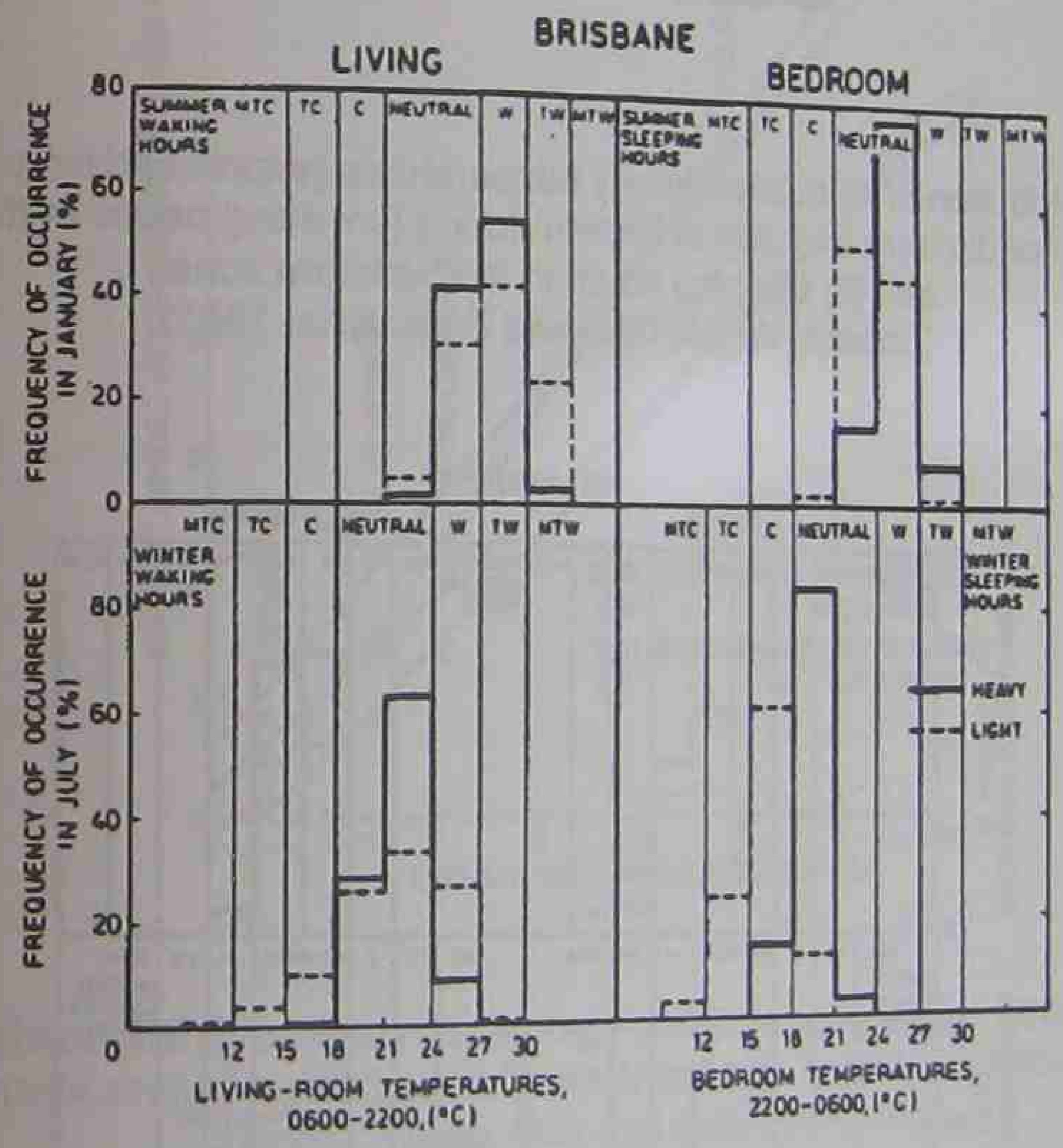


Figure 7 - Distribution of calculated hourly temperatures (expressed as a percentage of occurrences) for January and July in Brisbane during (i) waking hours in the living zone and (ii) sleeping hours in the bedroom zone. (Source: Walsh, Gurr and Ballantyne, 1982).

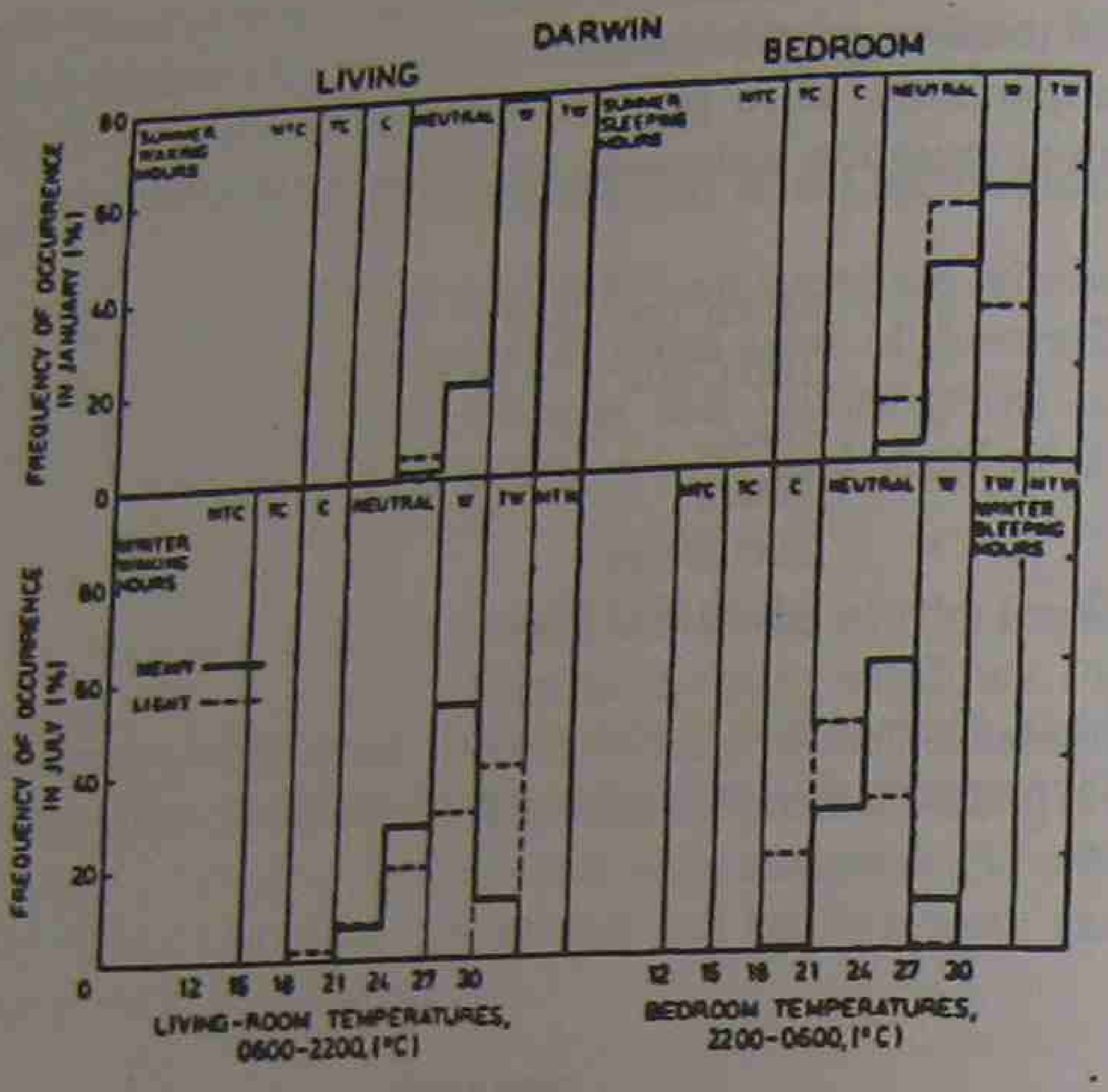


Figure 8 - Distribution of calculated hourly temperatures (expressed as a percentage of occurrences) for January and July in Darwin during (i) waking hours in the living zone and (ii) sleeping hours in the bedroom zone.
(Source: Walsh, Gurr and Ballantyne, 1982).

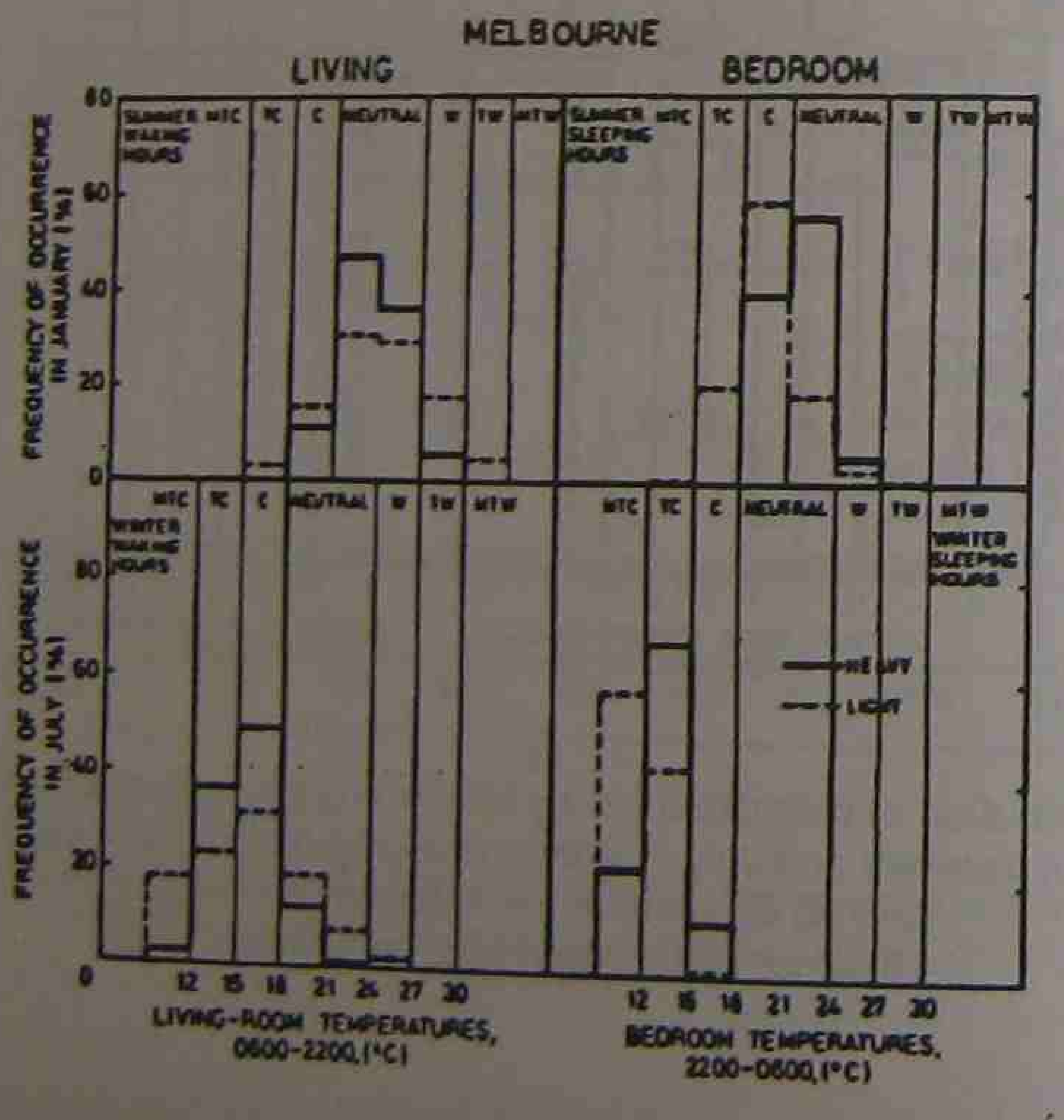


Figure 9 - Distribution of calculated hourly temperatures (expressed as a percentage of occurrences) for January and July in Melbourne during (i) waking hours in the living zone and (ii) sleeping hours in the bedroom zone.
(Source: Walsh, Gurr and Ballantyne, 1982).

In the **conditioned house** case, four basic types of construction were compared: brick veneer walls with timber floor, cavity brick walls with timber floor, brick veneer walls with concrete slab, and cavity brick walls with concrete slab. As well as comparing these four basic types of construction without insulation, several modes of insulation were also examined. Each of the four types was examined with (a) floors insulated below (b) walls insulated inside the cavity and (c) both floors and walls insulated. This gave a total of 16 construction types for examination.

Discussion of computer simulations for each construction type are beyond the scope of this Unit. However, annual heating and cooling requirements averaged over all of the construction types for different locations, are presented in the Figures below.

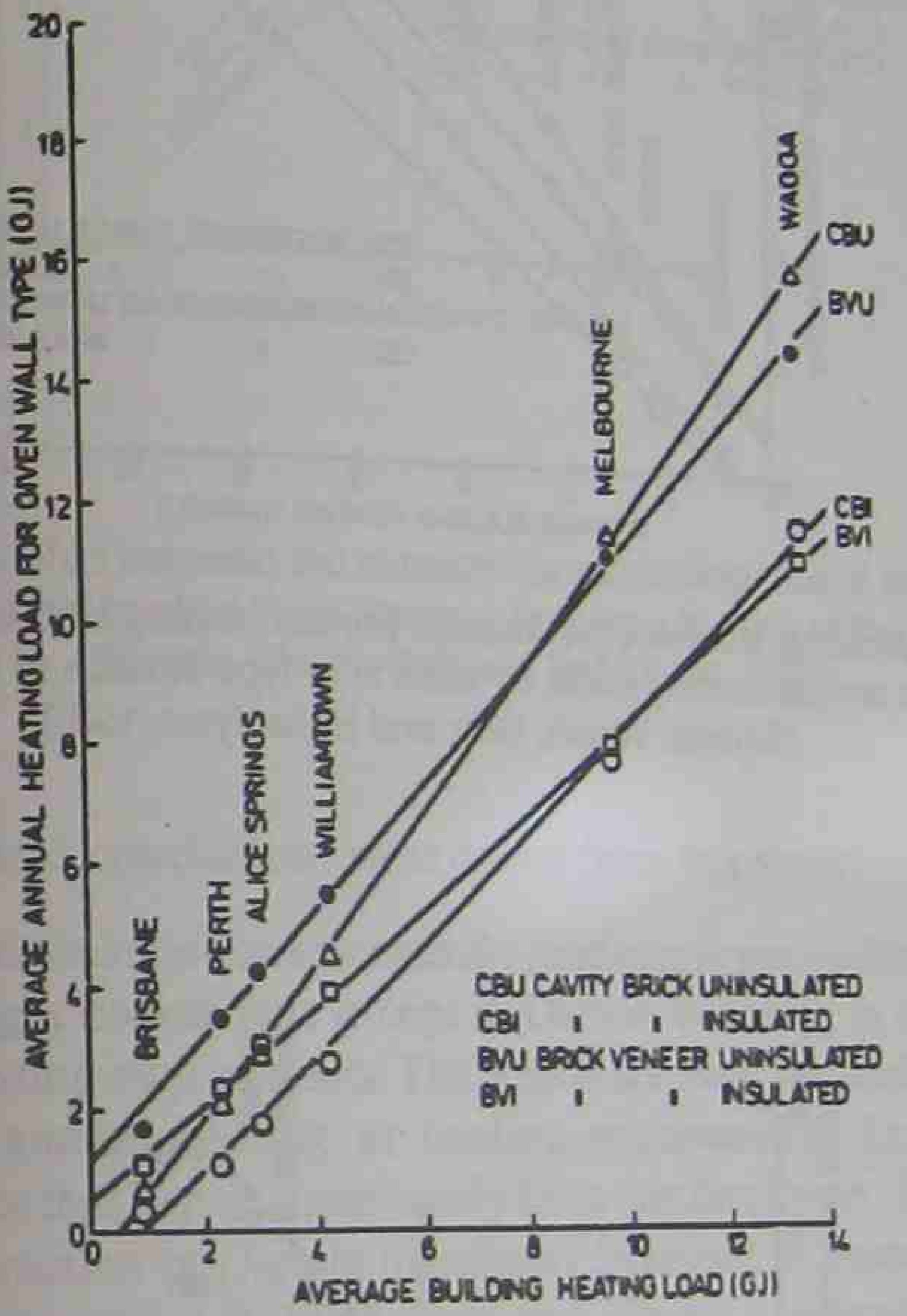


Figure 10 - Relationship between the average annual heating load of all buildings and the average annual heating loads for each wall type in each of six locations.
(Source: Walsh, Gurr and Ballantyne, 1982).

The ordinates for Figures 10 and 12 are average heating and cooling loads respectively for the four wall types under examination, irrespective of floor type. The ordinates for Figures 11 and 13 are average annual heating and cooling loads respectively for the four floor types under examination, irrespective of wall type. A series of trend lines is formed.

Darwin is excluded from Figures 10 and 11 because of its negligible heating requirements, while Darwin and Alice Springs have been excluded from Figures 12 and 13 because cooling requirements in these locations are considerably larger than for other locations.

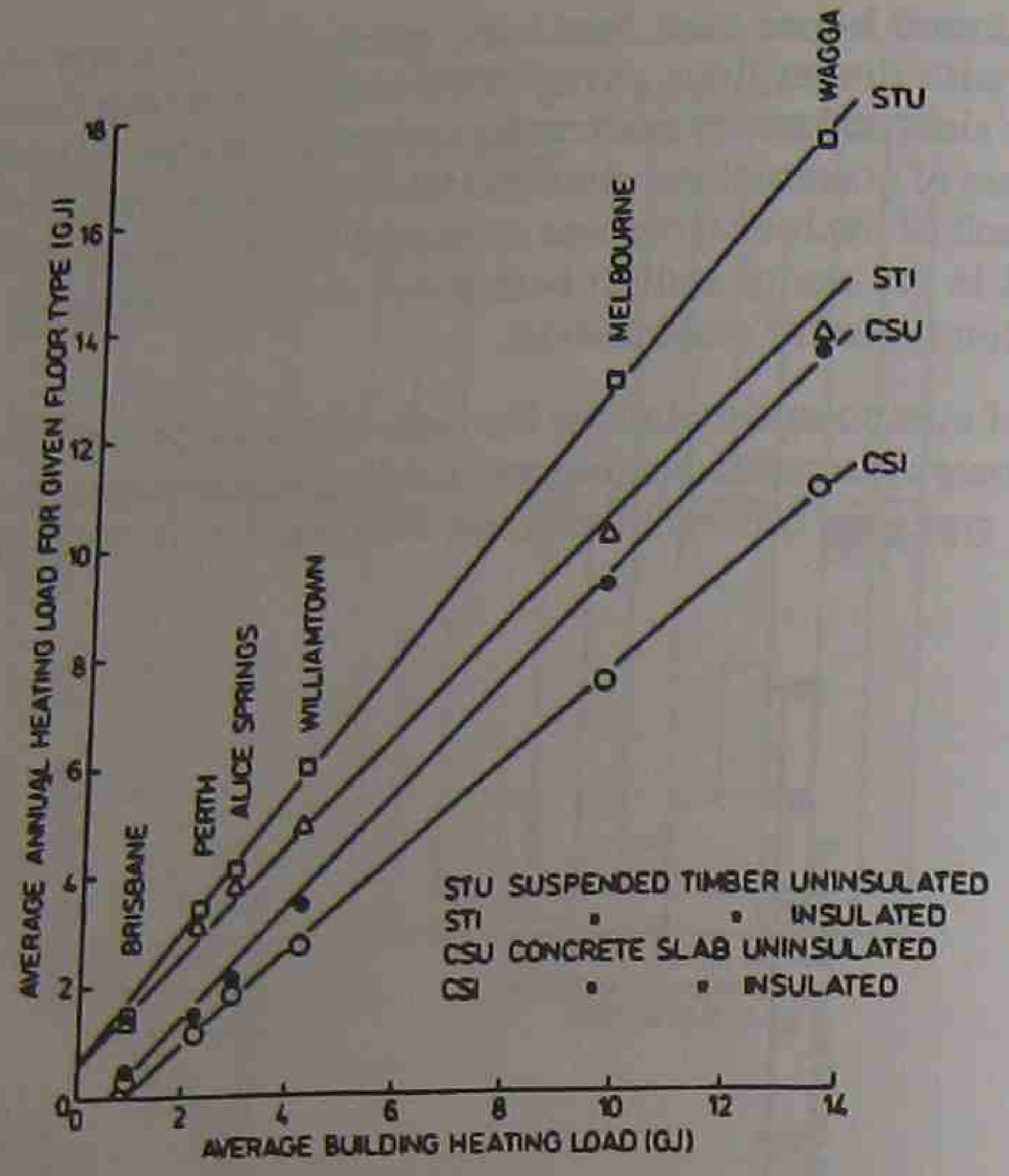


Figure 11 - Relationship between the average annual heating load of all buildings and the average annual heating loads for each floor type in each of six locations. (Source: Walsh, Gurr and Ballantyne, 1982).

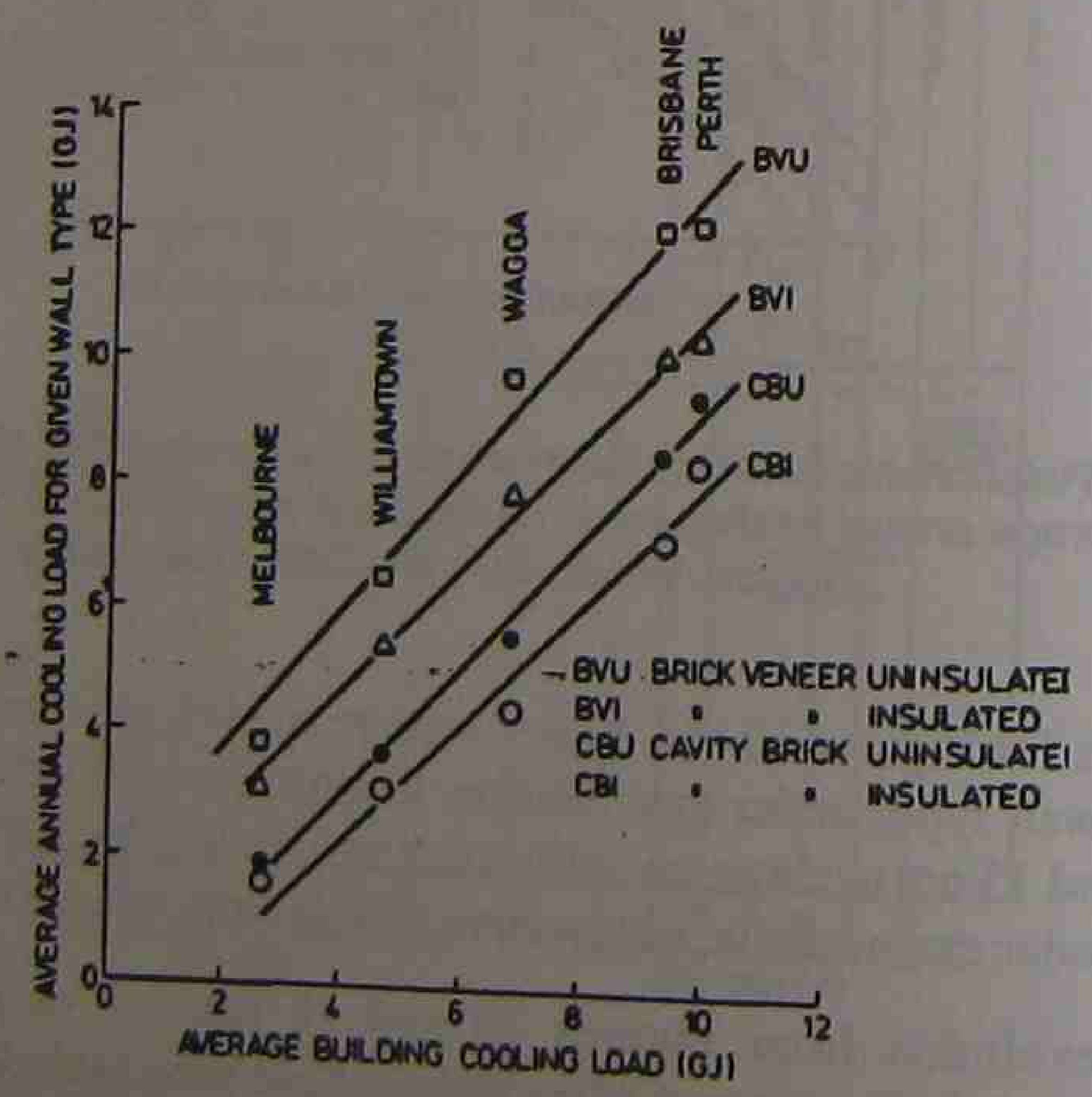


Figure 12 - Relationship between the average annual cooling load of all buildings and the average annual cooling loads for each wall type in each of five locations. (Source: Walsh, Gurr and Ballantyne, 1982).

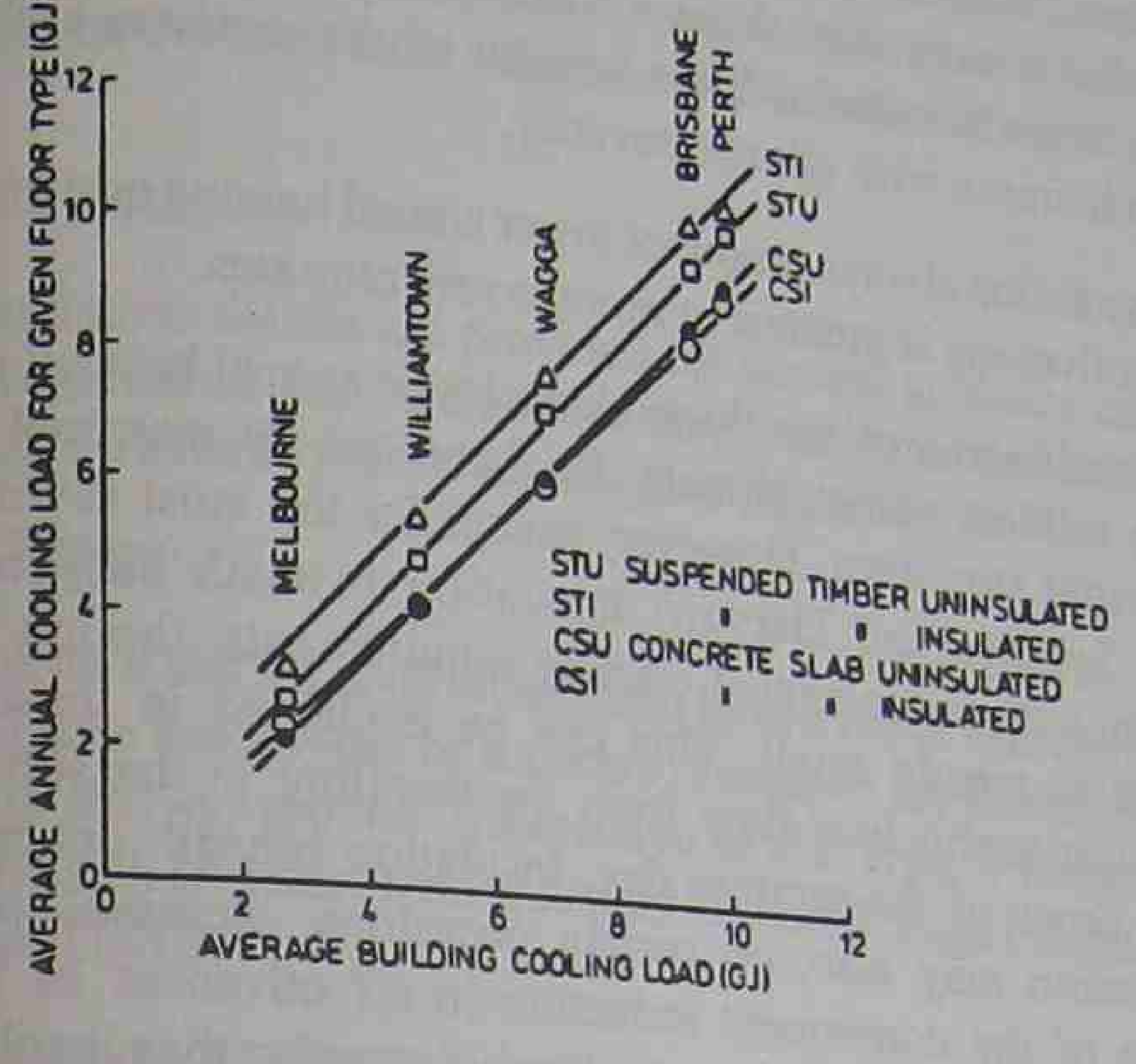


Figure 13 - Relationship between the average annual cooling load of all buildings and the average annual cooling loads for each floor type in each of five locations. (Source: Walsh, Gurr and Ballantyne, 1982).

The following **general conclusions** were drawn from this study:

(1) Cavity brick construction consistently produces lower cooling requirements than its lightweight counterpart except in Darwin but may, in some circumstances, increase heating requirements. The effects are least beneficial in those locations with high annual heating or cooling requirements, i.e., with mean daily temperatures that depart significantly from comfort levels. Thus the use of cavity brick construction in Darwin marginally increases or decreases annual cooling requirements, whilst in Melbourne and Wagga it generally increases annual heating requirements. The latter increase is minimised if walls are insulated and concrete slab floor construction is used. Significantly beneficial effects are achieved in those locations with mean temperatures more closely approximating comfort levels, e.g., Alice Springs in winter; Melbourne and Wagga in summer; Brisbane, Perth and Williamtown throughout the year. In such instances uninsulated cavity brick construction may often give lower annual requirements than insulated brick veneer construction. It should be noted that nowhere are total annual requirements increased through use of cavity brick construction.

(2) Concrete slab-on-ground construction consistently produces lower heating requirements than its lightweight counterpart generally to a significant extent. This is largely due to the very favourable orientation of the dwelling used in these calculations. This construction also consistently reduces cooling requirements, though the effect is very marginal in the severe Darwin climate and in other climates its significance is not as great as cavity brick construction. Again, the

slopes of trend lines for uninsulated floors are greater than for insulated floors. However, at least for cooling requirements, those for lightweight floors are somewhat greater than those for heavyweight floors. Thus, over the range of winter climates examined, the benefits of the concrete slab floor construction tend to increase with climate severity.

(3) Wall insulation always produces lower annual heating and cooling requirements. Its effectiveness is greatest in more severe climates.

(4) Floor insulation consistently produces lower annual heating requirements except for the mildest winter climate, Brisbane, where marginal increases occur in lightweight structures. However, except for the most severe summer climates (Alice Springs and Darwin) insulation beneath suspended timber floors invariably increases annual cooling requirements, though the amount of this increase is mostly small. This can be explained in terms of the insulation decreasing useful heat flow from the dwelling to the sub-floor space during certain times of the summer day. Insulation beneath concrete slab-on-ground construction may also, on certain occasions, increase cooling requirements because of the consequent reduction in effectiveness of the ground thermal capacity. The more common edge insulation rather than insulation under the total slab area might be expected not to produce the same deleterious results.

This model assumes that the floor is close to the ground and that the space underneath receives only a small degree of ventilation. High set houses, or houses with a high degree of ventilation in the underfloor space will benefit from floor insulation.

4 INSTALLATION OF THERMAL MASS

A number of general principles should be followed for the effective installation of thermal mass. Some installation details are also discussed.

4.1 Installation Principles

Generally, thermal mass should be located:

- inside the insulated fabric of the building
- where it receives the sun's rays it should be dark coloured to increase heat gain in winter
- in the north-facing (living) zone, particularly in rooms which will benefit from heat gain during winter
- where furniture is unlikely to shade the mass and reduce its effect

Concrete slabs should be located directly on the ground, rather than being suspended, to take advantage of the large thermal mass of the earth beneath. The slab should be isolated from high water tables by agricultural drainage pipe, as water flowing past the slab will take heat away.

Fireplaces are best located away from external walls so that the masonry chimney can store heat and re-radiate it into the house rather than conduct it outside.

The absorptance, emittance and covering of thermal mass will affect its performance. Dark coloured thermal mass material will absorb more solar radiation than light coloured

material. Re-emission of heat via radiation does not depend on colour. Most non-metallic building materials radiate heat at about the same rate, while metallic surfaces radiate considerably less heat. Carpets will reduce heat entry and also slow its release. Hard floor coverings (e.g., tiles) on the other hand maximise heat transfer between the floor and the rest of the room.

4.2 Installation Details

The following installation details are provided for general guidance only. A check of local government regulations and reference to the Glass, Mass and Insulation Council (1985) manual should be made before the design is finalised.

4.2.1 Concrete Slabs

This section deals with slabs for level sites which have a fall of less than one metre over the building area. Three basic types of slabs are discussed: the footing slab, the footing slab-on- fill and the slab-on-ground. Irrespective of slab type, a waterproof polythene membrane under the slab and steel reinforcement is needed. Edge insulation for concrete slabs is discussed in Unit 7.

The footing slab involves a separate strip footing with a concrete floor placed directly on the strip. The footing slab-on- fill involves a low wall built up on the strip footing with compacted fill set inside the low wall. Neither of these footing slabs are recommended for unstable (reactive) soils.

Concrete slab-on-ground construction is a one piece floor slab and wall footing, as illustrated in Figure 14. The slab requires little formwork during laying, as the ground may be used to provide most of the profile for the thickened edge of the slab. On intermediate or reactive soil, the slab must be strengthened by the addition of an internal grid of beams forming part of the slab.

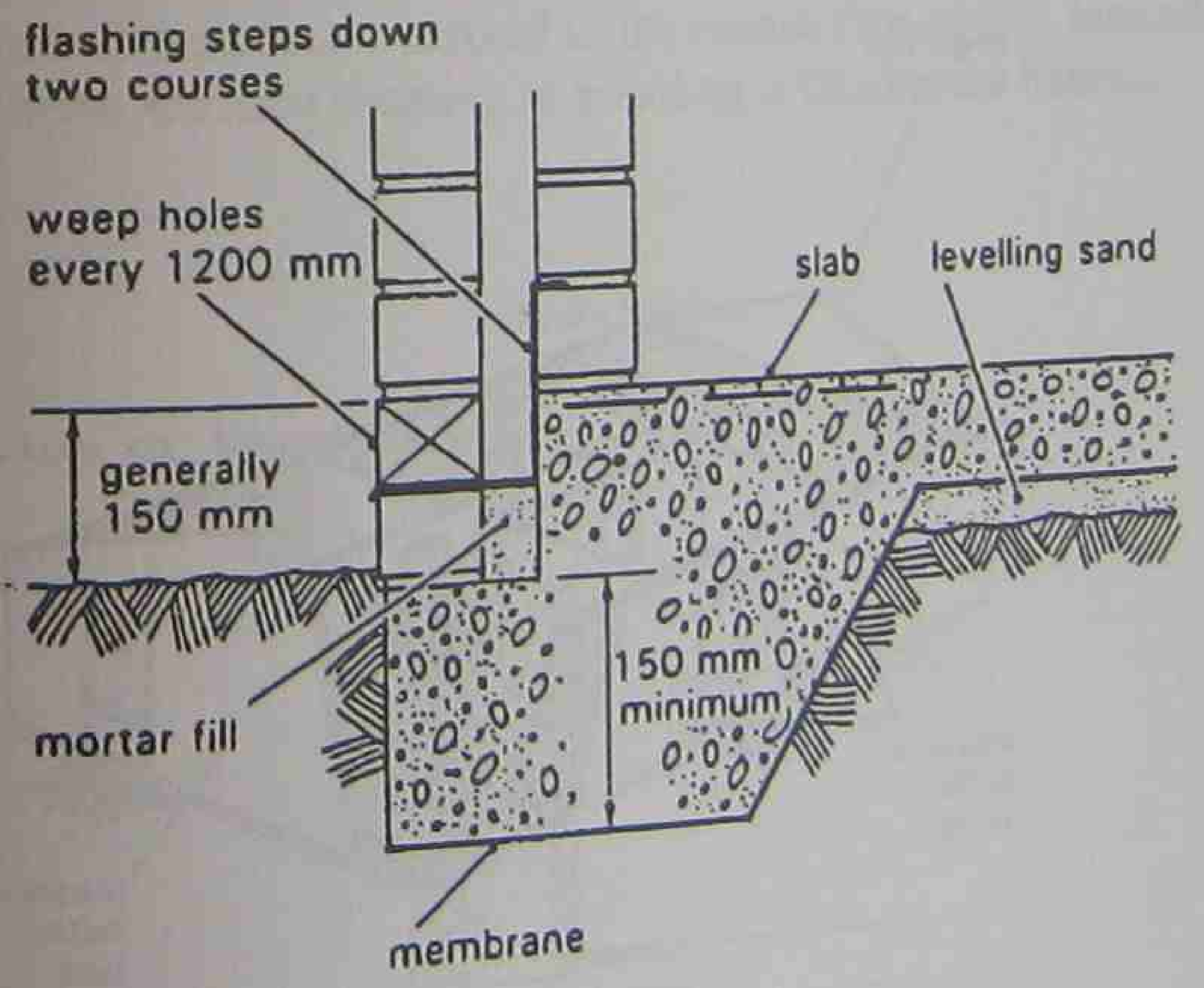


Figure 14 - Concrete slab-on-ground for stable soils. (Source: Glass, Mass and Insulation Council, 1985).

4.2.2 Masonry Walls

The greatest internal wall mass is provided by full masonry construction, i.e. cavity brick walls and single leaf internal walls, as shown in Figure 15.

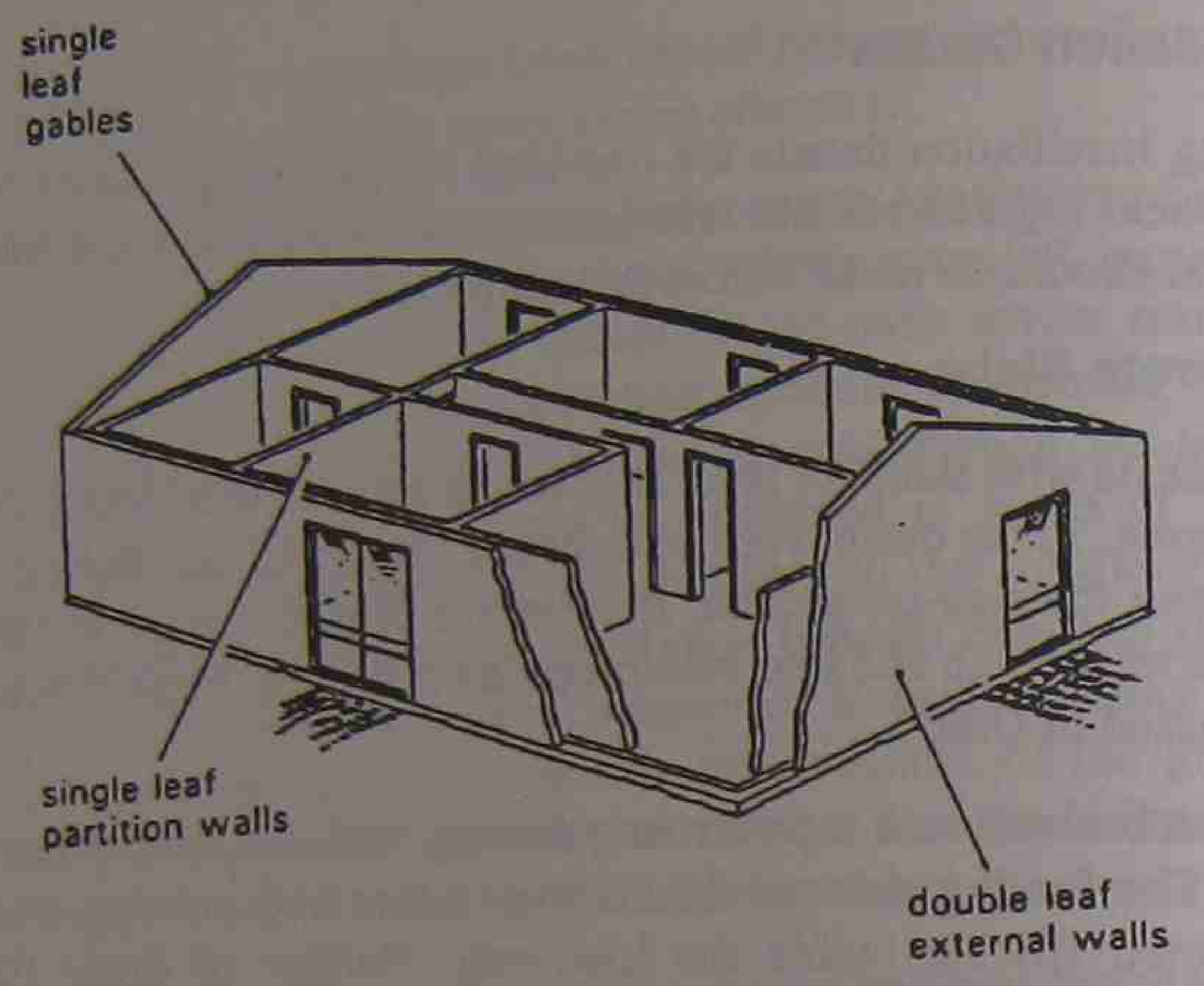


Figure 15 - Full masonry construction. (Source: Glass, Mass and Insulation Council, 1985).

4.2.3 Masonry Core and Features

A house with a masonry core has internal masonry walls separating rooms and is most conveniently built on a concrete floor, as shown in Figure 16. Masonry may also be used in feature walls, bench supports and oven towers to provide useful thermal mass.

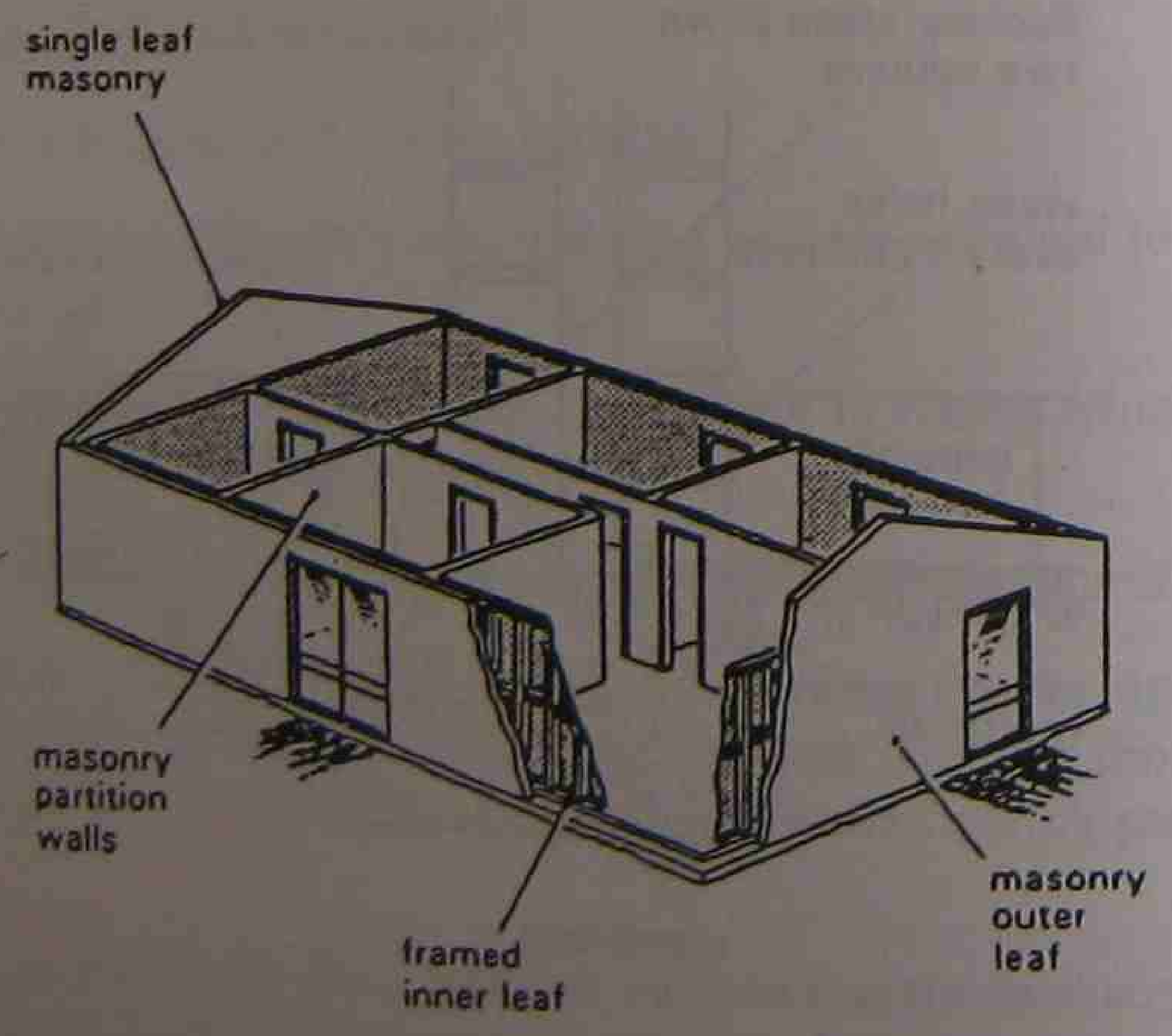


Figure 16 - Masonry core construction. (Source: Glass, Mass and Insulation Council, 1985).

4.2.4 Reverse Brick Veneer Walls

Previous discussion (mainly in section 2.4.1) has highlighted the general need for external insulation of massive walls to enhance thermal storage capacity. The innovative "reverse brick (or block) veneer" wall is based on this principle. According to Szokolay (1991) there are two basic methods of building such a wall.

The first construction method is shown in Figure 17. The stud frame is built in the traditional way, flush with the edge of the slab. This frame carries the roof load and is sheeted or boarded on the outside. The non-load bearing brick or block wall is located on the inside. A layer of insulation is placed in between.

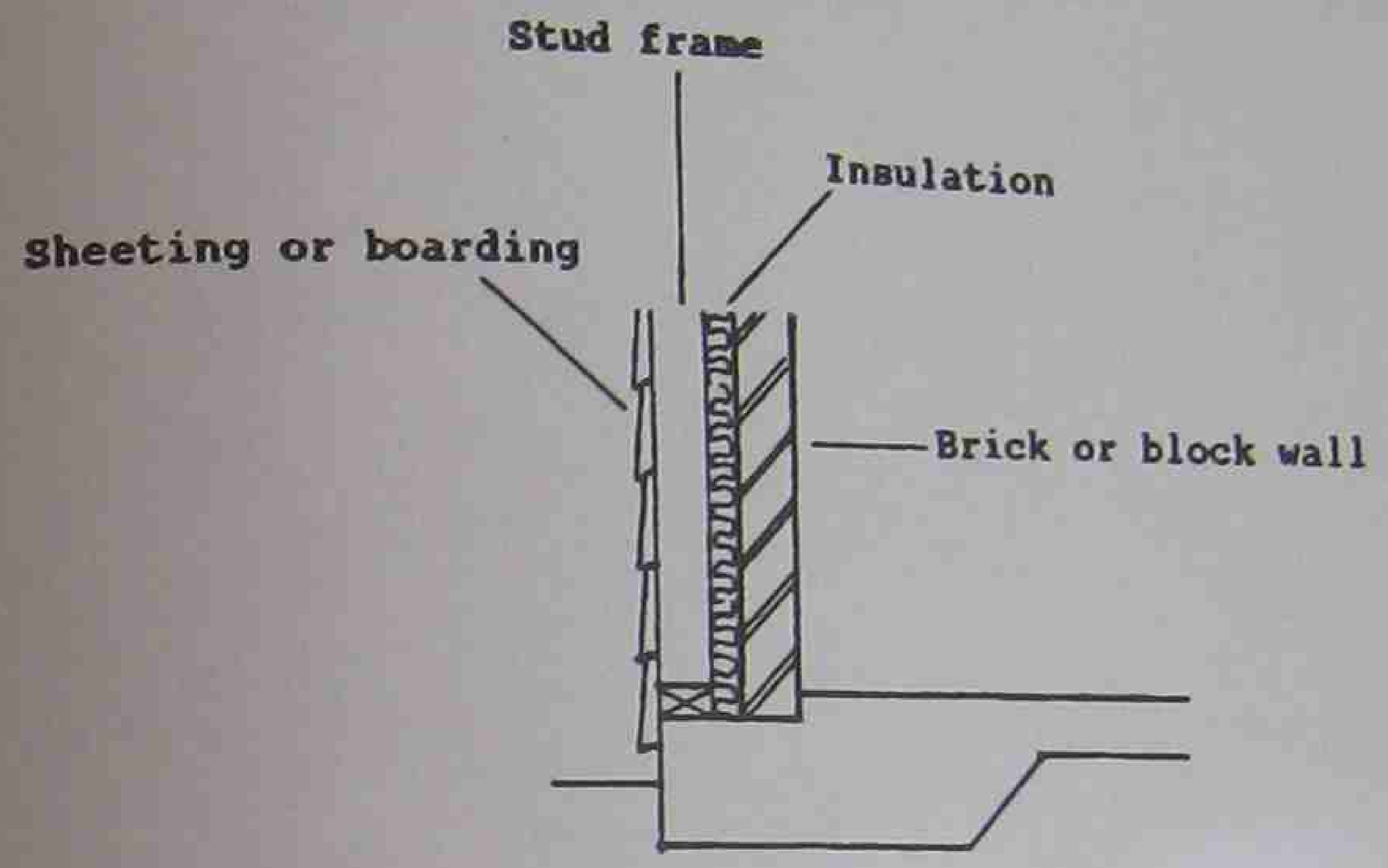


Figure 17 - Reverse brick veneer wall based on a stud frame. (After Szokolay, 1991).

The second construction method is shown in Figure 18. It consists of a load-bearing masonry (brick or block) wall set back 50mm from the edge of the slab. Vertical battens of 50mm x 50mm dimensions are fixed to the outside face of this. Insulation is placed between the battens. Outside sheeting or boarding is fixed to the battens.

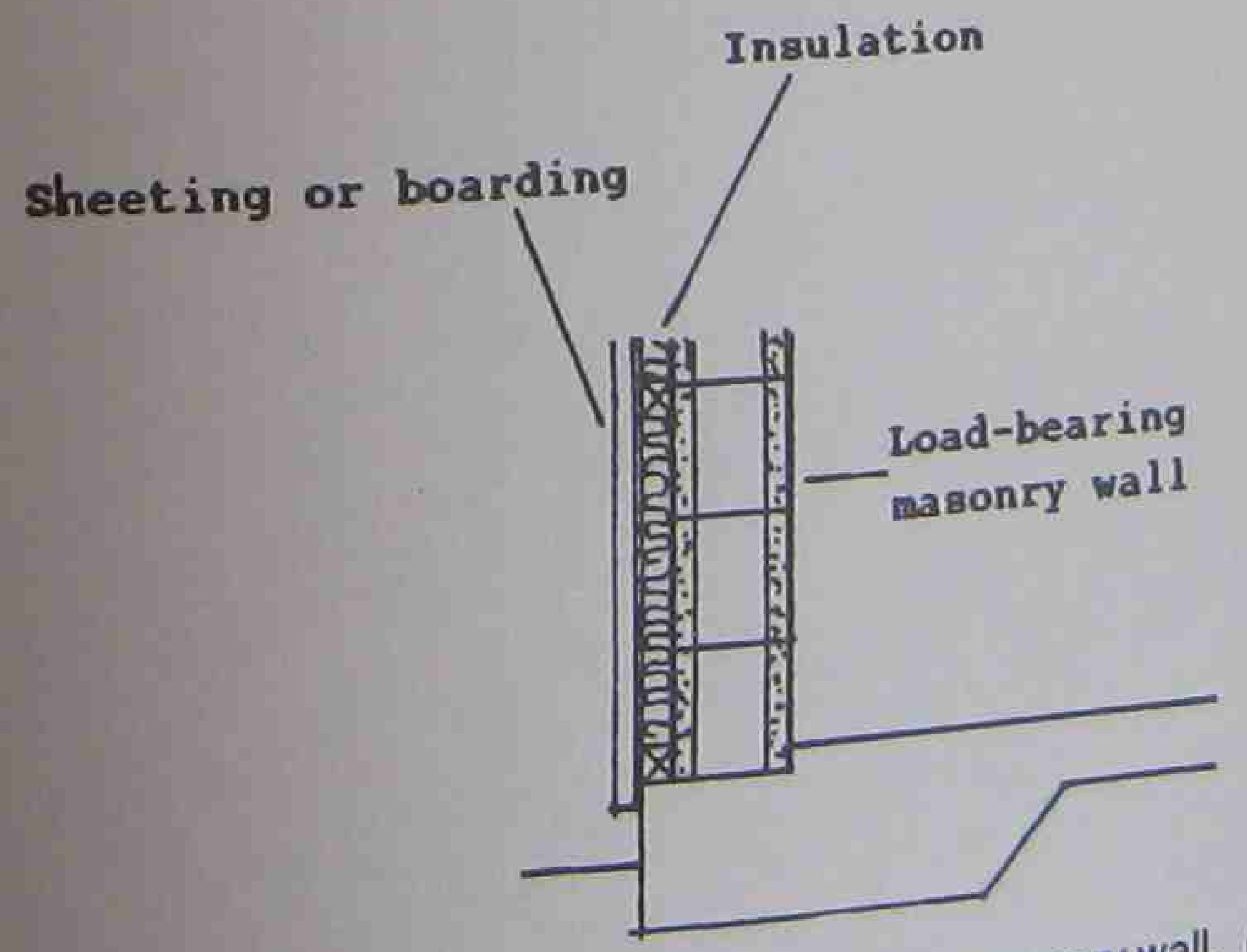


Figure 18 - Reverse brick veneer wall based on a masonry wall. (After Szokolay, 1991).

4.2.5 Water Walls

The water wall concept was briefly discussed in Unit 1. The water is typically contained in steel drums or cylinders which are stacked behind north-facing windows. Water has the benefit of distributing heat gains quickly by convection and so provides good heat storage with reduced surface temperatures compared to the masonry walls.

An innovative water wall house was built in Rokeby, Tasmania in 1980. This "Solarwall" project was a joint initiative of the Tasmanian Housing Division and the Tasmanian College of Advanced Education. The water wall consisted of several water-filled, polythene-lined, octagonal cylinders, standing like pillars from floor to ceiling next to the northern windows.

Unit 8

Design For Climate and Site

1 INTRODUCTION

This unit brings together the principles discussed in earlier units and applies them within the context of the design requirements for the different climatic regions of Australia. The unit then discusses how the building and grounds can be designed to suit a particular site in order to provide a high level of comfort within the constraints of the prevailing climatic conditions.

2 DESIGN FOR CLIMATE

Australian buildings sometimes reproduce features that may be neutral or even advantageous thermally in their country of origin but are inappropriate to Australian climatic conditions. Examples of these are the lack of eaves to shade walls and windows or the use of large picture windows. Similarly, designs that may work well thermally in one climatic region of Australia have been used for buildings in other regions. These have sometimes overheated in summer or have become very cold in winter.

Suburbs have been established where most of the buildings have dark coloured brick-veneer walls and dark tiled roofs and cosequently are extremely hot in summer unless they are air-conditioned. Some councils even have covenants which force the adoption of inappropriate design of this kind and will not grant permits to builders wanting to use light coloured insulated iron roofs or well insulated light coloured brick walls, or walls of any material other than brick.

On the other hand some unique styles have evolved which do address some of the features of the prevailing climate. An example of this is the use of verandahs to shade walls and windows, vented roof spaces and elevated floors to take advantage of cooling breezes in regions of Australia which have hot summers. Many of these inovations appeared early in the short history of European occupation. These designs can be improved upon with the use of modern materials and building techniques. The resultant modern hybrid appropriate to the climate of the region would certainly outperform the brickveneer tiled roof clones of our modern suburbs.

2.1 Australian Climates

The Australian landmass covers a large range of latitude from 9°S to 43°S. It is not surprising therefore to find a significant range of climates within the continent. Although nearly half of the landmass is in the tropics, most of the population resides in the temperate climatic zone. The only broad climatic classification not represented in Australia is the “cold climate” characterised by the need for heating of buildings most of the time.

2.2 Climatic Variables

Climatic variables which must be taken into account when designing a building for a particular climatic region are temperature, humidity, air speed, solar radiation and micro-climate effects.

With the exceptions of the polar and subpolar regions where it is always cold and the tropics where it is always hot, the seasons are characterised by being warm to hot in summer and cool to cold in winter. In addition to this seasonal variation of **temperature** is the diurnal temperature variation due to the heating effect of the sun. Day-time temperatures are always higher than night-time temperatures but the size of the diurnal swing depends on factors such as proximity to the sea and altitude.

High **humidity** can cause summer discomfort by reducing the evaporation of sweat to provide a cooling effect. High summer humidity can be a problem in subtropical and temperate areas particularly in locations close to the sea. Evaporative cooling will be ineffective during periods of high humidity. Low humidity can cause discomfort by producing dryness around the eyes, nose and mouth.

Convection and evaporation heat transfer is greatly increased when **air is moving**. In cold temperatures the wind is given a wind-chill factor which increases with increasing wind speed and decreasing temperature. Cold winds in winter will make it more difficult to heat a building. Hot winds in summer will also make it more difficult to maintain comfort conditions in buildings. Cool breezes in the late afternoon or evening can bring relief in hot summer conditions. Air movement during hot conditions can enhance comfort by providing reduced skin temperatures when sweating takes place.

Winter **sunshine** is important if buildings are to take advantage of solar gain for heating. Shading of windows and the use of light colours for roofs and walls will reduce summer overheating in all locations.

The **micro-climate** of a particular site can have a significant effect on the way the prevailing climate is modified by local factors such as altitude, shading by mountains or trees, funnelling of winds etc. This is discussed in more detail in the section Designing for Site.

2.3 Building Design Variables

The performance characteristics of buildings can vary radically depending on the design and materials used in the construction. The main variables which affect performance are listed below. How these are used depends on the climate.

Insulation reduces the rate of heat gain and heat loss due to temperature difference between the inside and the outside of a building. The rate at which the air in a room is heated via sunlight entering windows depends on the insulating properties of the room surfaces. Similarly the rate at which a building can be heated or cooled by means such as fires or airconditioning is dependent on the degree of insulation and where it is placed. All buildings can benefit from the use of roof insulation.

Thermal mass affects the rate at which the internal temperature changes in response to external changes in temperature or internal heating or cooling.

Ventilation or air movement within the building enhances the cooling effect of sweating in hot conditions. Air exchange between the building and the outside causes the temperature of the building to get closer to the external temperature.

Window size and placement affect the amount of air movement through the building if the windows can be opened. Solar heat gain as well as heat gains and losses due to temperature difference effects make the judicious use of windows critical to thermal performance.

The **orientation of glazing** affects the ability to successfully exclude the sun in summer while allowing it to penetrate in winter.

Shading reduces heat gain due to sunlight penetration of windows or solar absorption by walls.

The **colour** of the roof or walls effects the heat gain due to absorbed sunlight. Uninsulated surfaces transfer the most absorbed solar heat into the building.

The **proximity** of the building **to the ground** affects thermal behaviour in several ways. The ground is warmer in winter and cooler in summer than the average outside air temperature, so the heat exchange between the building and the ground due to temperature difference effects is less. Uninsulated floors located close to the ground or on the ground are affected by the thermal capacity of the earth beneath. High set houses are subject to higher wind speeds and so can achieve faster cooling when the outside air temperature has dropped.

2.4 Thermal Comfort Inside Buildings

Thermal comfort is determined by the heat exchange processes between the skin or clothes and the immediate environment. A person exposed to the sky will absorb radiant heat from the sun (day-time) and radiate heat to the sky and ground (day and night-time). Heat is also gained or lost via conduction to the surrounding air. Evaporation due to sweating provides cooling during hot periods if the humidity of the air is not too high. The rate of conduction and evaporation is greater if air movement is increased.

Once inside a building a person will be shielded from radiant heat exchange with the outside and comfort is primarily determined by **air temperature**, **air movement**, **humidity** and the **temperatures of the inside surfaces** of the room. An exception to this would be exposure to direct sunlight near a window.

Generally there is little discomfort caused by radiation exchange with the internal surfaces of the room if the air temperature is comfortable. This is because there is usually not a great difference between the air temperature and the surface temperature of the room. There are some notable exceptions however:

- ❑ If the surface of the room is highly conducting (ie., has a high admittance) the heat transfer through the surface is high enough to maintain a lower (or higher) surface temperature. One example of this effect is bare glazing when it is cold outside. Another is uninsulated roofing material when the sun is shining. This effect can be reduced by placing insulation near the surface.
- ❑ Heat absorbing glass windows can become quite hot when exposed to direct sunlight, and will radiate heat into the room.
- ❑ Some heaters rely predominantly on radiative transfer by providing a relatively small source with a high surface temperature, e.g. electric bar radiators.

In order to promote comfort conditions buildings should modify air temperature to within the comfort zone determined by the humidity. Air movement can provide comfort at somewhat higher temperatures. Radiant heat sources should be avoided in summer while radiant heat sinks should be eliminated in winter.

2.5 Quantifying Comfort

Thermal comfort is a complex function of temperature, humidity, air movement, radiant heat, individual physiology and the type of physical activity engaged in. If only temperature is to be considered as an indicator of comfort then the thermal neutrality concept can be used as discussed in Unit 2, section 3.8. Thermal neutrality (T_n) is given as:

$$T_n = 17.6 + 0.31 \times T_{av}$$

provided $$18.5 < T_n < 28.5^{\circ}C$$

The width of the comfort zone is taken as ± 2°C if T_{av} is the average annual temperature or ±1.75°C if T_{av} is taken as the average monthly temperature. Figure 1 shows the comfort zone for Brisbane. Also plotted is a wider band defined by the average maximum and minimum outdoor shade temperatures.

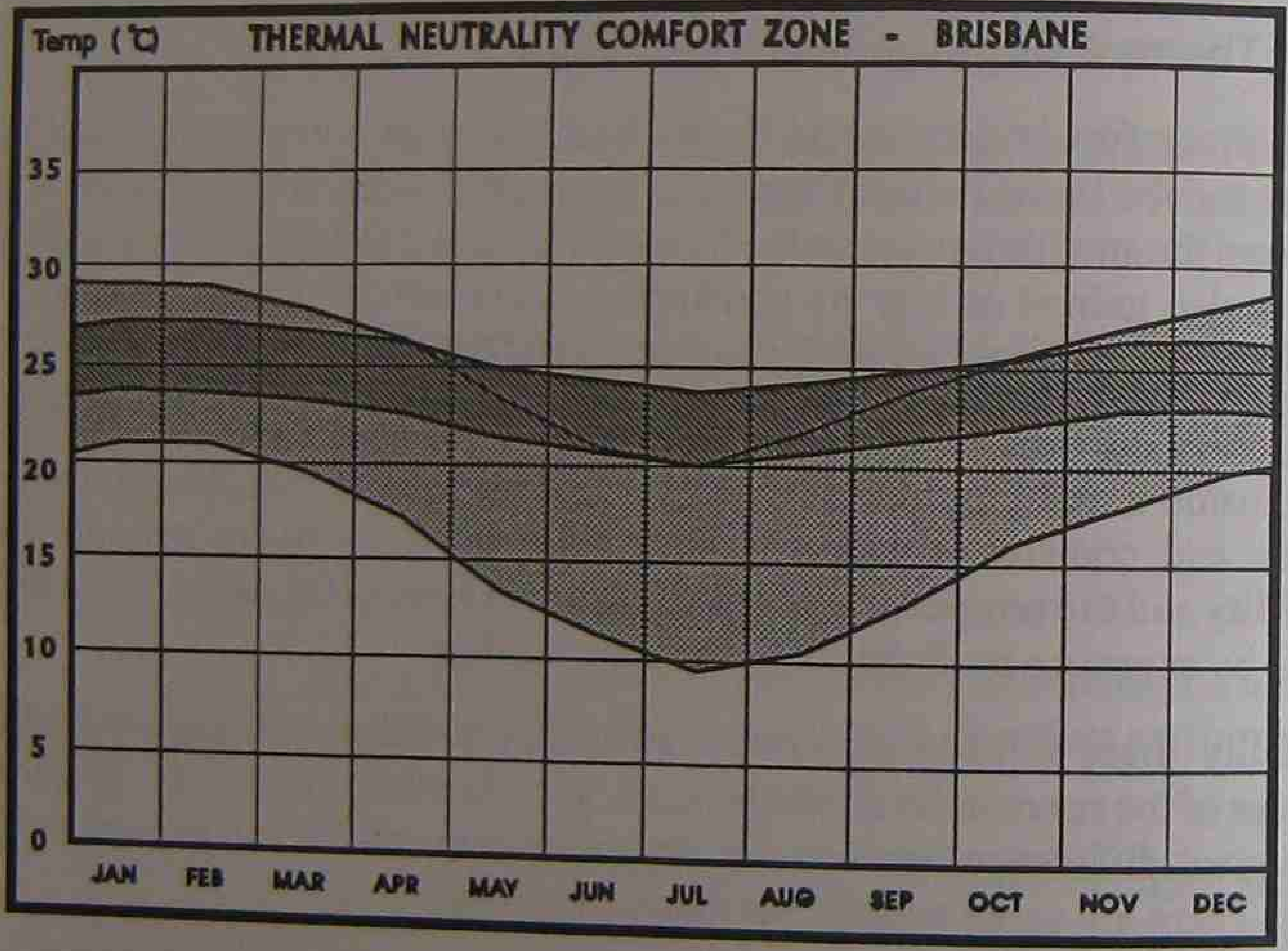


Figure 1 - The thermal neutrality comfort zone plotted for Brisbane.

It can be seen from the graph that the main thermal function of a building in Brisbane is to provide warmth in winter. The secondary function would be protection against radiant heat from the sun, particularly in summer. In fact, any reasonably sealed envelope will provide an average temperature at least 3°C greater than the average daily temperature. This increase in indoor temperature over what is indicated by the outdoor shade temperature band will make winter heating somewhat less necessary than indicated by the graph. Cooling in summer becomes more necessary to maintain the building within the thermal neutrality zone than is indicated by the average outdoor shade temperature band. Humidity is not considered as a factor using this method of calculating the comfort zone. However, as everyone who lives in Brisbane or has visited Brisbane in summer knows, it is the high humidity which makes the elevated temperatures uncomfortable.

A more useful way of determining how a building should behave in a particular climatic zone has been proposed in Szokolay, 1987. This method makes use of a comfort zone plotted as a function of both temperature and humidity on a psychrometric chart. Climate lines are drawn for each month between two points defined by the mean minimum temperature with 9.00 am humidity and the mean maximum temperature with 3.00 pm humidity. The envelope defined by these 12 lines indicates the prevailing temperature and humidity conditions. Figure 2 shows the comfort zone for Brisbane and the climate lines for January (1), April (4), July (7) and October (10).

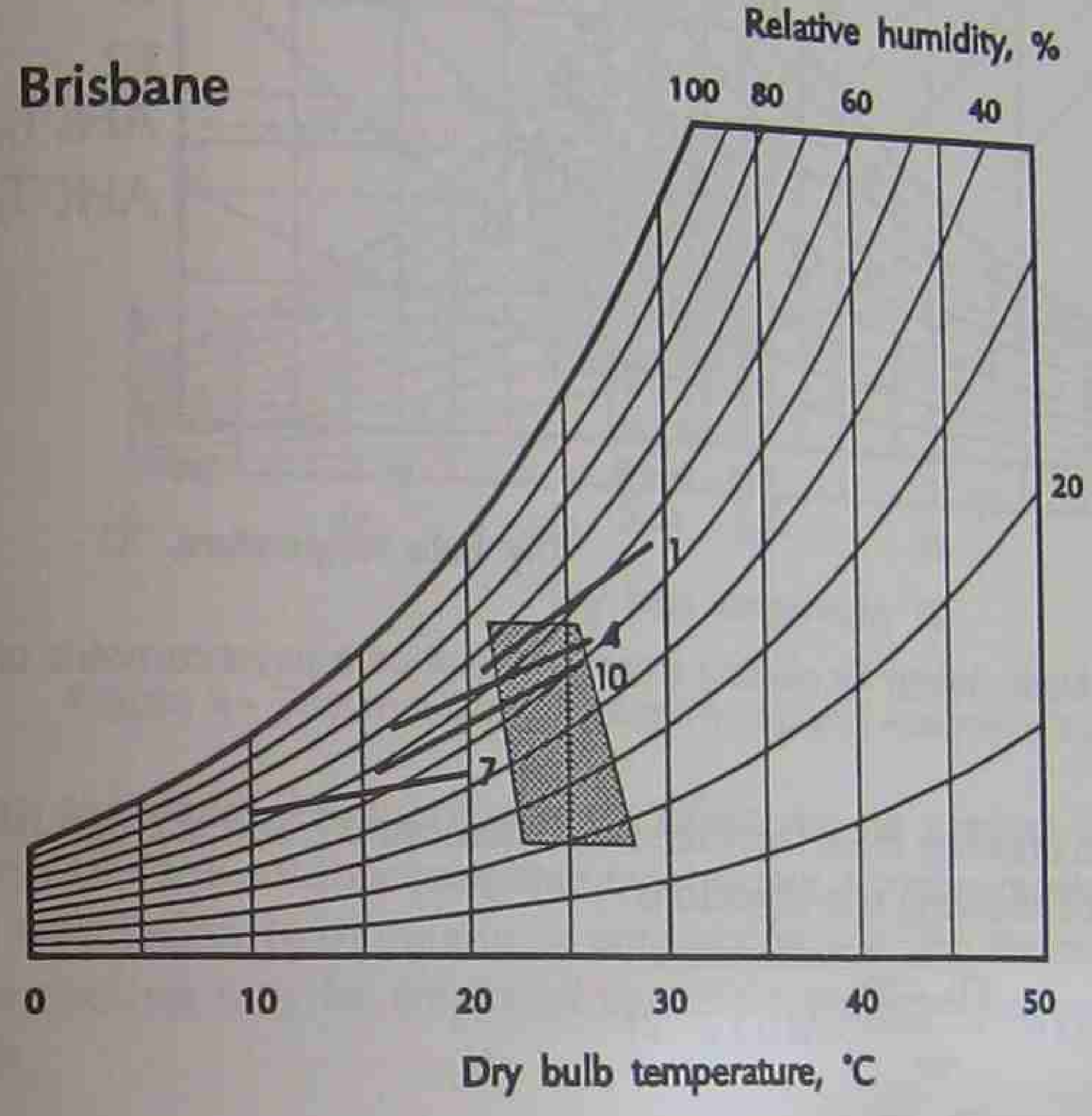


Figure 2. - Comfort zone and climate lines for Brisbane.

The thermal comfort zone can be plotted on a psychrometric chart using the following procedure. This should be read in conjunction with Figure 3.

- ☐ Calculate the thermal neutrality (T_n) from the mean annual outdoor temperature (T_{av}):

  $$T_n = 17.6 + 0.31 \times T_{av}.$$

- ☐ Plot T_n on the 50% relative humidity line.
- ☐ Plot the upper limit as $T_n + 2$ and the lower limit as $T_n - 2$ on the 50% RH line.
- ☐ Draw the upper and lower standard effective temperature lines through the upper and lower limits on the 50% RH line. These lines have a slope (m) given by:

  $$m = \frac{40}{T - 14}.$$

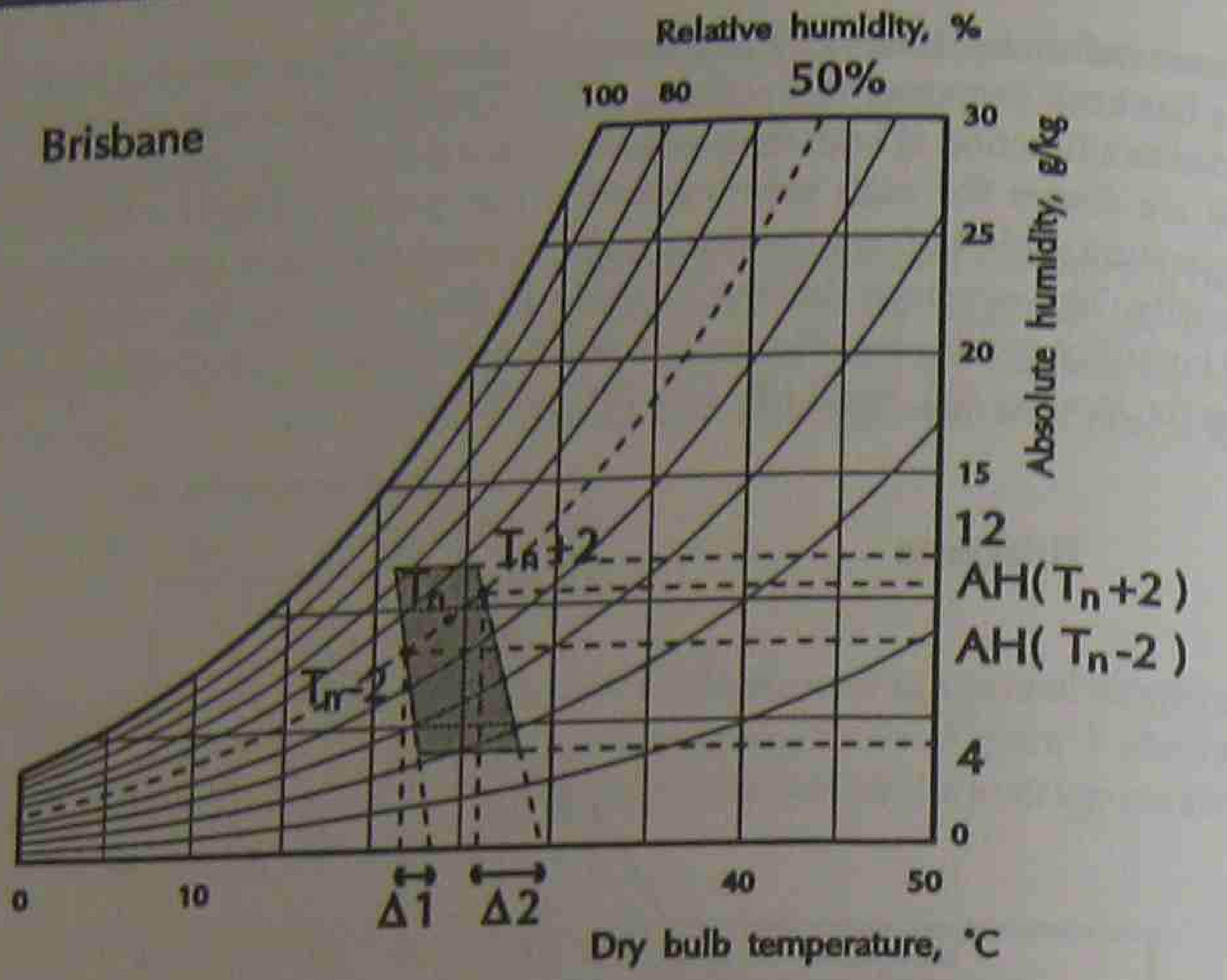


Figure 3 - Methodology for plotting a comfort zone on a psychrometric chart.

To aid in drawing these lines the two distances Δ1 and Δ2 can be found from the following two equations:

$$\Delta 1 = \frac{(T_n - 2)}{40} . AH(T_n - 2)$$

$$\Delta 2 = \frac{(T_n + 2)}{40} . AH(T_n + 2)$$

where AH(T) is the absolute humidity corresponding to a temperature T.

- ☐ Draw the upper and lower absolute humidity lines at 12 and 4g/kg respectively.

Figure 4 shows the comfort zones for various locations in Australia. It is interesting to note that people in Hobart start to feel uncomfortably hot under the same conditions that people in Darwin are just starting to feel comfortable after feeling too cold.

2.6 Comfort Strategy Evaluation

Many methods can be used to make a building thermally comfortable, the most common being the use of non ambient energy for heating in winter and cooling in summer.

The strategies examined here are:

- ☐ direct solar gain through windows
- ☐ thermal mass effect
- ☐ night-time ventilation in conjunction with thermal mass
- ☐ air movement within the building
- ☐ evaporative cooling

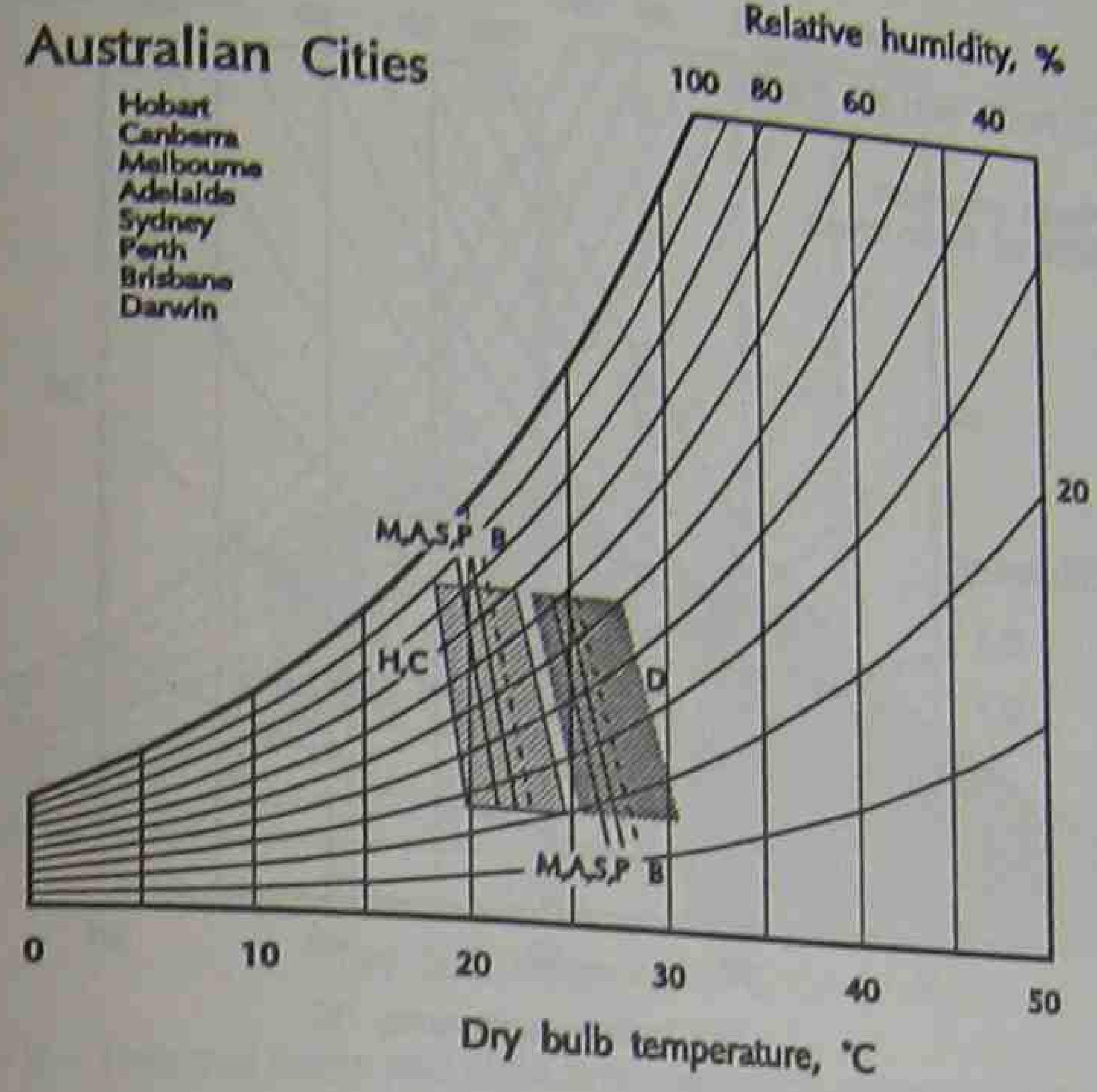


Figure 4 - Thermal comfort zones for various Australian locations.

Direct solar gain and the thermal mass effect can be used to increase the indoor temperature when the outdoor temperature is too low. Air movement within the building, night time ventilation (particularly in conjunction with the thermal mass effect) and evaporative cooling may be employed to achieve cooling when outdoor temperatures are too high.

Szokolay, (1987) has described a method for superimposing onto a psychrometric chart the outdoor conditions under which indoor comfort can be achieved using the various strategies mentioned above. The method will not be discussed in detail here, but the results of these calculations are presented for a number of Australian locations. Areas referred to as Control Potential Zones (CPZ) are plotted on the psychrometric chart. If a climate line for a particular month lies within a CPZ for a particular control strategy, then that strategy should enable the temperature and humidity inside the building to fall within the comfort zone for that month. This enables a building designer to determine which strategies are worthwhile pursuing in order to achieve comfortable conditions in specific types of climates.

Control potential zones are discussed in the following section with respect to the climate lines and comfort zone for Brisbane.

2.61 Direct Solar Gain

Figure 5 shows the CPZ for direct solar gain through north facing windows. It has been assumed that the north window area is 20% of the floor area and that the house is well insulated. Two efficiencies of solar energy collection, 0.5 and 0.7 are considered. The higher efficiency of 0.7 can be achieved with appropriate thermal mass and absorber surfaces.

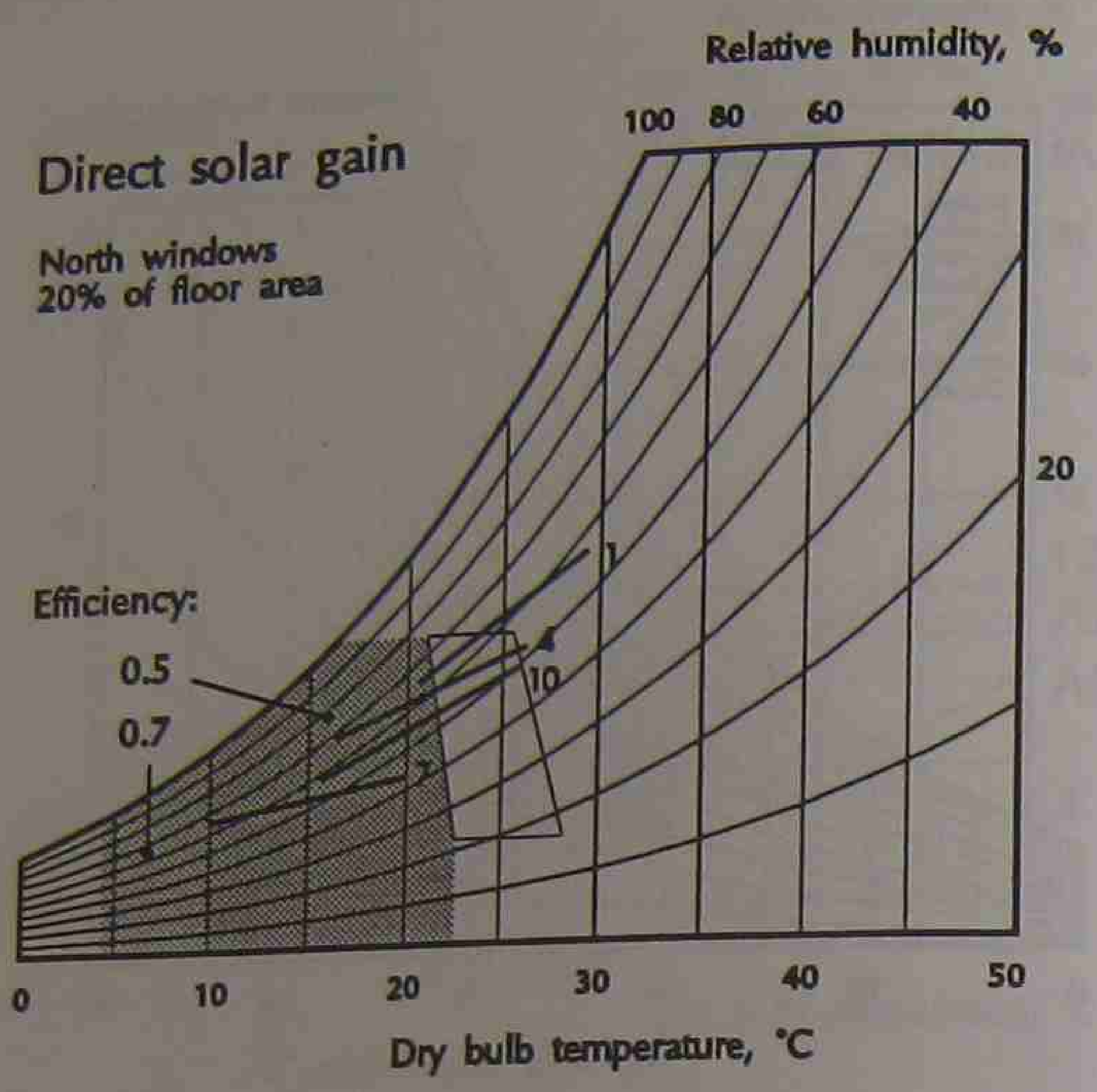


Figure 5 - Direct solar gain control potential zone.

The diagram shows that winter heating can be easily achieved with north facing windows in Brisbane. In fact great care must be taken to avoid overheating in summer. The window to floor area ratio should probably be less than the 20% used for the calculations, but this is largely determined by thermal mass and night time ventilation.

2.6.2 Thermal Mass

If the mean outdoor temperature falls within the comfort zone the inertia effect of substantial thermal mass in the building will maintain comfort conditions. The CPZ for the thermal mass effect is found by adding half of $T_{max} - T_{min}$ for the hottest month to establish the upper boundary and by subtracting half of $T_{max} - T_{min}$ for the coldest month to determine the lower boundary. The thermal mass CPZ is shown in Figure 6.

2.6.3 Night time Ventilation and Thermal Mass

A building which is closed during the day but ventilated at night will have a mean indoor temperature which is considerably lower that the mean outdoor temperature. Figure 6 shows the expected result of this strategy assuming an effectiveness of 0.8 for well designed buildings as suggested by Szokolay. The effectiveness depends on having sufficient thermal mass, the availability of night breezes and good cross ventilation, or fan forced ventilation. An effectiveness of 0.5 means that half of the average temperature range must be added to the upper temperature boundary in order to determine the upper CPZ boundary.

Figure 6 suggests that although thermal mass in Brisbane would be effective in winter it provides insufficient advantage in summer. On its own it can not deal with the extremes in humidity in January, even when night time ventilation is used.

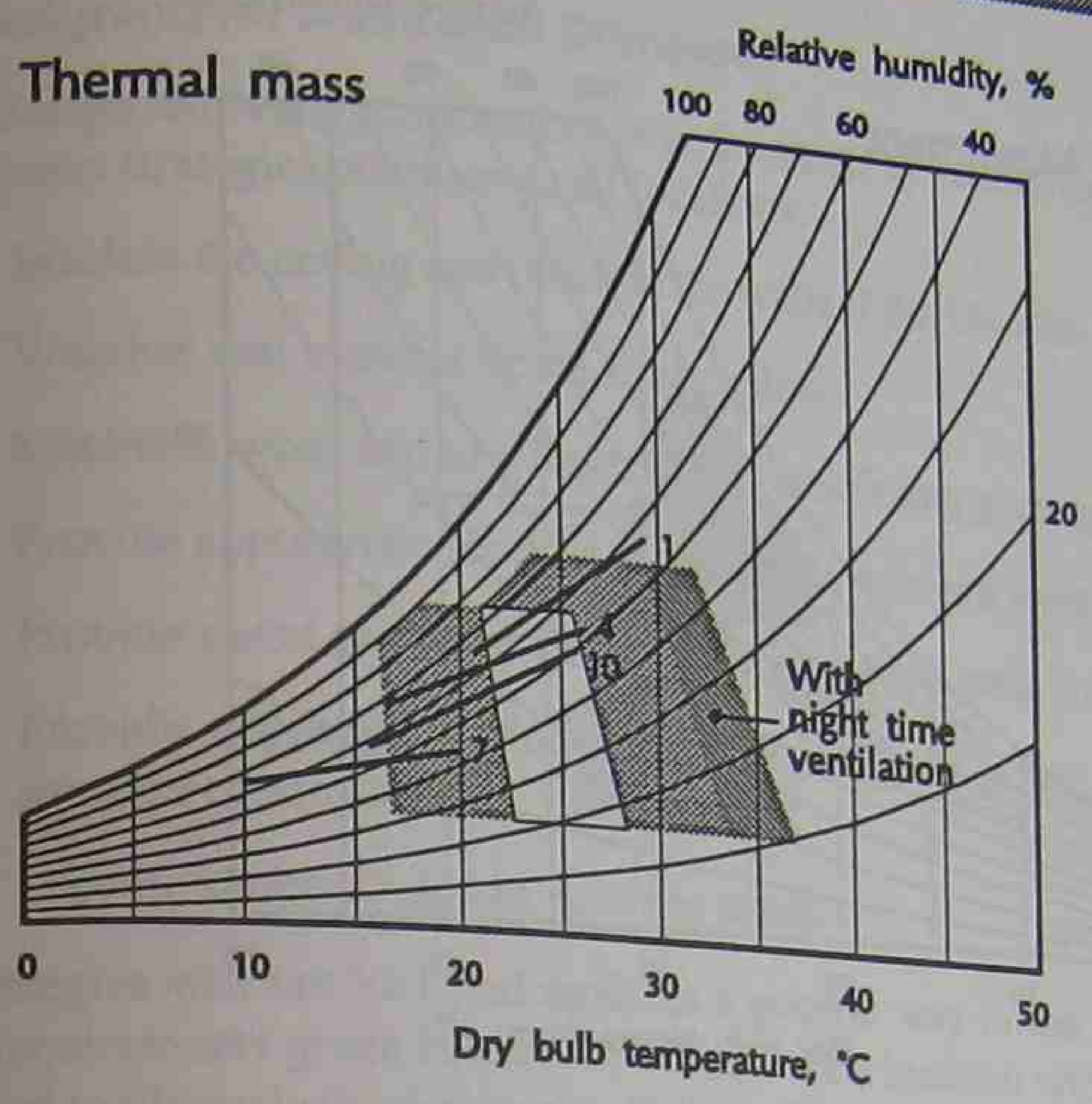


Figure 6 - Thermal mass and night-time ventilation control potential zone.

2.6.4 Air Movement

The cooling effect of air movement for people wearing light clothing engaged in "medium" activity can be determined from:

$$T = 6v - v^2$$

where T - effective temperature depression (°C)
v - air speed (m/s)

For these conditions an air speed of between 1 and 1.5 m/s is considered acceptable. This represents an effective temperature depression of between 5 and 6.75 °C. These values are added to the upper limit of the comfort zone. At very low humidity the additional evaporative effect provided by air movement is reduced. Humidity above 90% inhibits cooling through sweating even at high air speed. Figure 7 shows the air movement CPZ for both 1 and 1.5 m/s. It can be seen from this graph that air movement, provided via cross ventilation in the evening and at night and ceiling fans would be an effective strategy in Brisbane for controlling overheating in summer.

2.6.5 Evaporative Cooling

Evaporation reduces the dry bulb temperature by converting sensible heat to latent heat. However, this is accompanied by an increase in humidity. This is very effective in dry hot conditions. It is also an economically attractive way of cooling in these locations because it uses only a small fraction of the energy required to run vapour compression air conditioners.

Indirect evaporative cooling makes use of the cooling effect provided by evaporation but uses a heat exchanger so that there is no increase in humidity in the air entering the building. The effectiveness of either mode of evaporative cooling decreases as the ambient humidity increases. Evaporative cooling is least effective in locations where

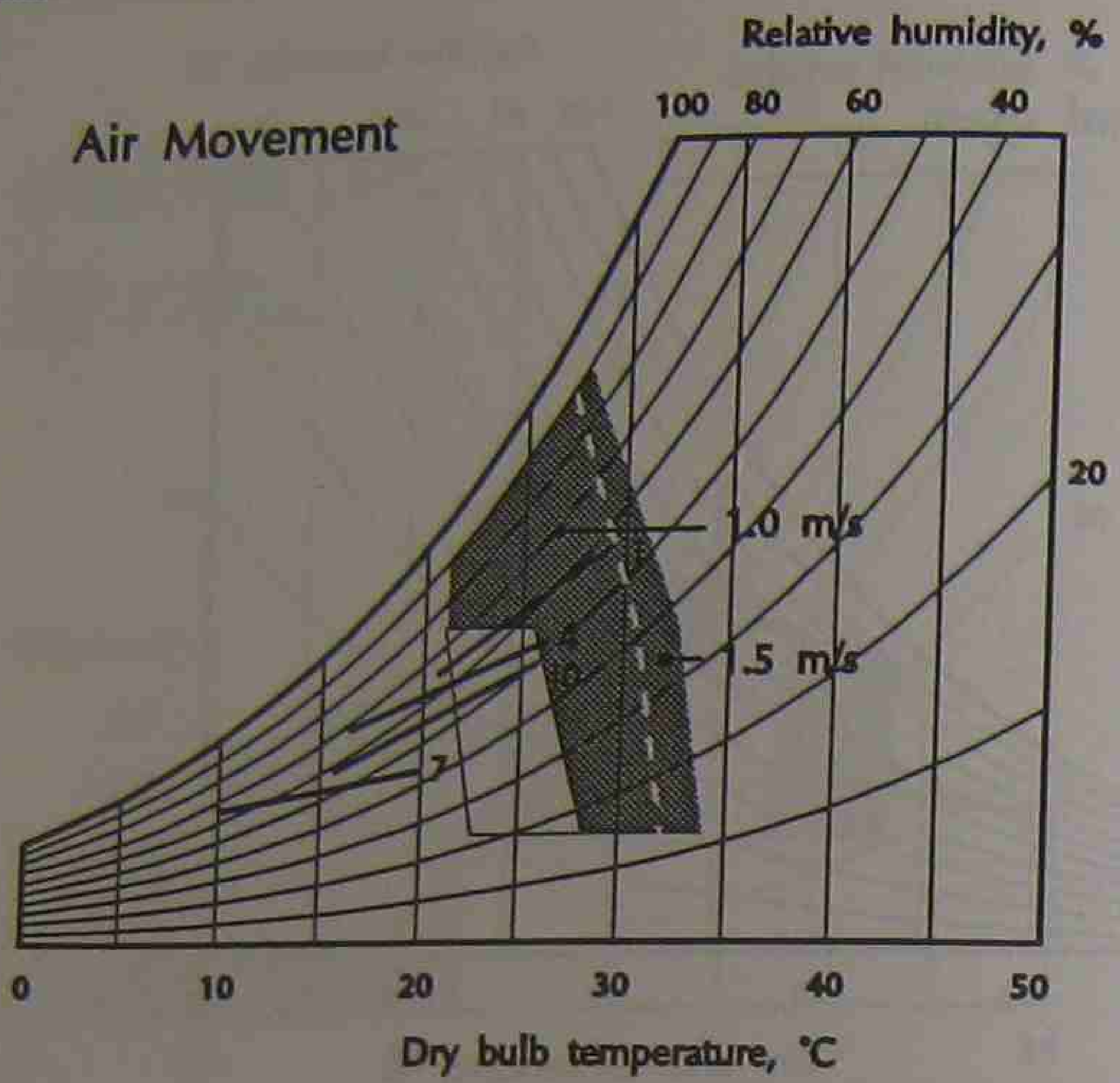


Figure 7 - Air movement control potential zone.

high temperatures are accompanied by high humidity. In these places the process can fail completely when it is needed most.

Figure 8 shows the effect of both direct and indirect evaporative cooling in Brisbane. Direct evaporative cooling is shown to be virtually valueless, while indirect evaporative cooling appears to be less effective than air movement alone in providing comfort conditions.

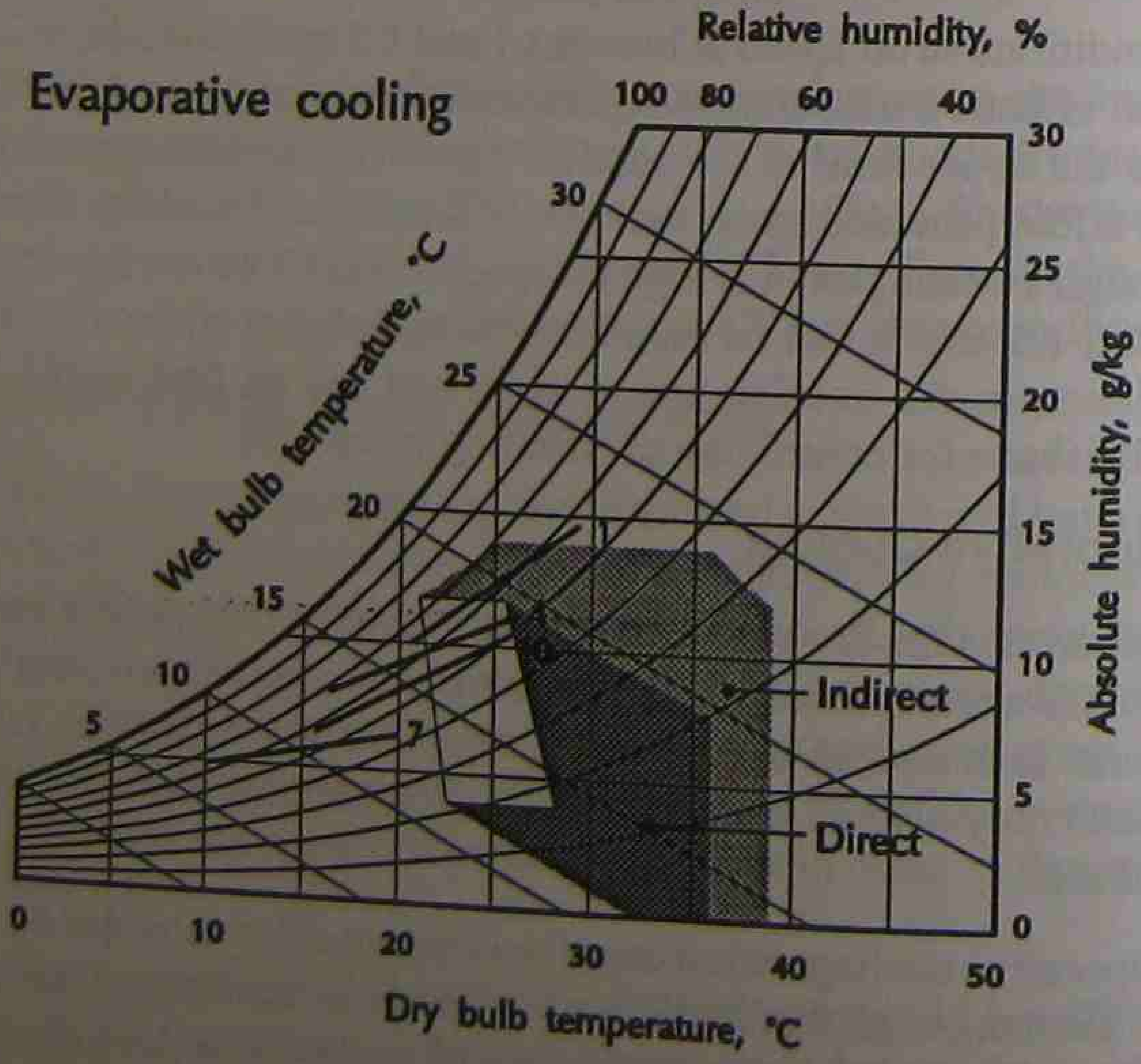


Figure 8 - Evaporative cooling control potential zone.

2.7 Designing for Australian Climates

Building design will vary considerably over the range of Australian climates. However there are some strategies common to all locations:

- Insulate the ceiling and insulate the walls if the U-value is too high.
- Weather seal external doors and windows.
- Minimise west, and to a lesser extent east facing glazing.
- Provide appropriate shading for all north, east and west facing glazing.
- Provide tinted or reflective glazing for east and west facing windows.
- Provide appropriate window and door openings for cross ventilation for summer conditions.
- Provide shelter from hot summer winds.

These strategies will not be listed again in a general way in the discussion of specific climatic requirements given below. An example of a location within each climatic type will be used to illustrate the design possibilities. The CPZ's examined will be direct solar gain at an efficiency of 0.7 with the area of the north facing windows being 20% of the total floor area, thermal mass effect with night-time ventilation of effectiveness 0.8, air movement at 1.5 m/s and direct evaporative cooling.

2.8 Temperate Climates

Temperate climates are characterised as having cool to cold days in winter with cold nights, and high day-time temperatures in summer with moderate nights. Humidity is moderate. Both winter heating and summer cooling strategies are necessary. This climate classification can be subdivided further, but some control strategies are common to all temperate climates:

- Direct solar gain is necessary, preferably from mid Autumn to mid Spring.
- Provide complete summer shading of all windows.
- Maximise glazing on the north side.
- Adequate thermal mass should be provided in accordance to the amount of northern facing glazing.
- Orient the building so that the long axis lies along the east-west axis.
- Provide access to cool summer breezes.
- Locate the living areas on the north side of the building.
- Use vegetation to shade the west facing walls.
- Provide sealed vents at the high spots of rooms which can be opened on hot days.

2.8.1 Cool Temperate Climate

Hobart and Canberra are both examples of locations which can be designated as "cool temperate". The extremes in both diurnal and seasonal temperature are greater in Canberra, which is further from the sea than Hobart.

From the psychrometric charts given in Figures 9 and 10 it would appear that a combination of direct solar gain and thermal mass would maintain comfort except for the coldest days when some additional heating would be necessary. More care is required in Canberra to avoid overheating in summer. Ceiling fans to provide air movement or night-time ventilation should be adequate for cooling.

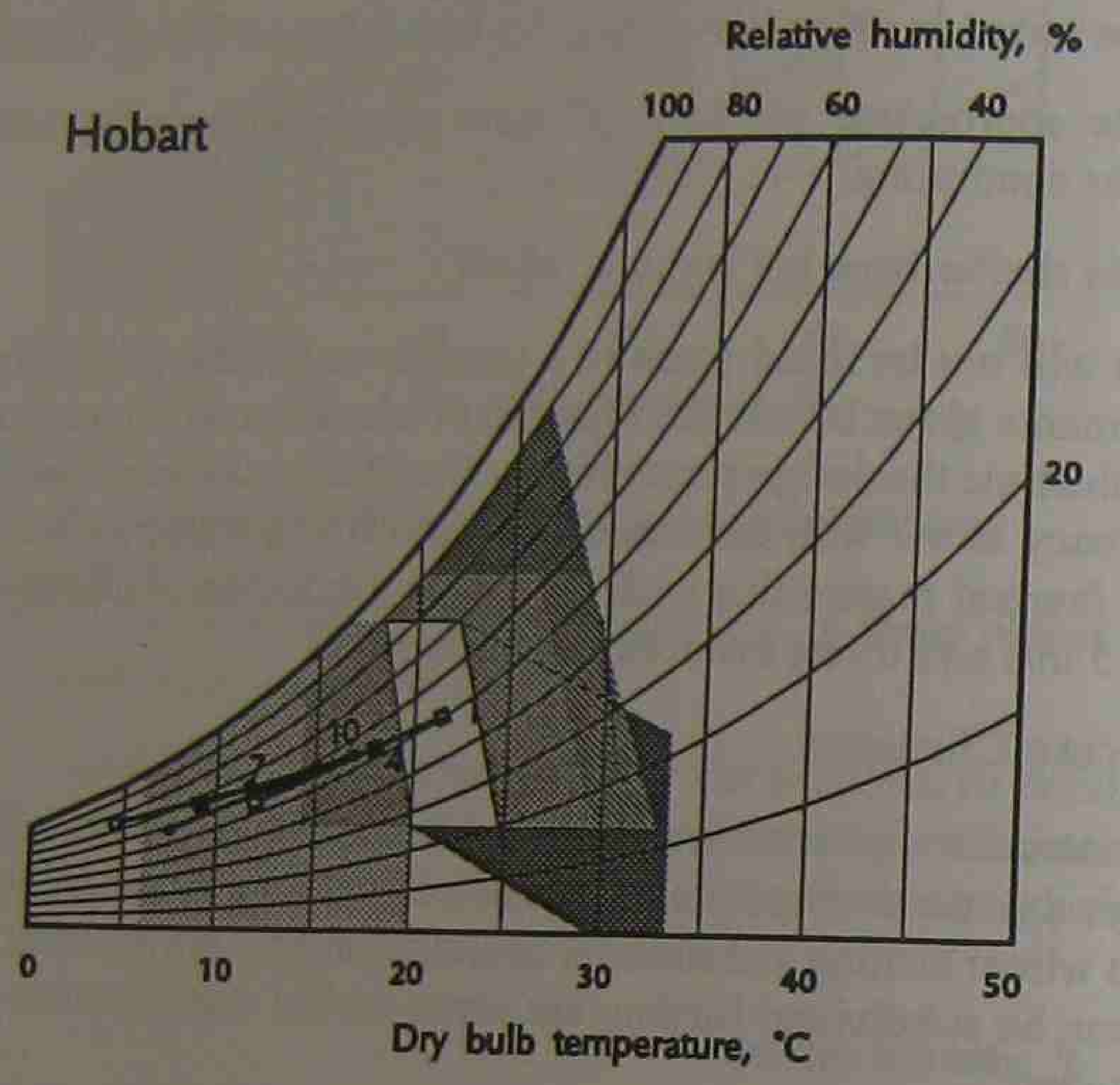


Figure 9 - Psychrometric chart for Hobart.

The north facing glazing should be between 20 to 35% of the floor area of the rooms containing them. Houses with low thermal mass should have the minimum of 20% to avoid overheating during the day. Heavy constructions using slab on ground floors and internal masonry can benefit from the higher percentage of window area. This may even be increased if a significant area of the floor has hard floor coverings. The Glass, Mass and Insulation Council recommend that in Hobart soft floor coverings should be used on concrete slabs which should also be fitted with edge insulation.

Timber floors should be insulated to R1.0 while external walls should include a minimum of R1.0 insulation. The minimum recommended level of ceiling insulation for this climate classification is R3.5.

2.8.2 Coastal Temperate Climate

Drysdale simply refers to this coastal temperate climatic zone as temperate. The classification "coastal" helps to distinguish it from "cool" temperate and "dry warm" temperate. Cities that fall within this classification are Melbourne, Adelaide, Sydney and Perth. Psychrometric charts for these locations are shown in Figures 11, 12, 13 and 14 respectively. Winter heating appears to be feasible using a combination of direct solar

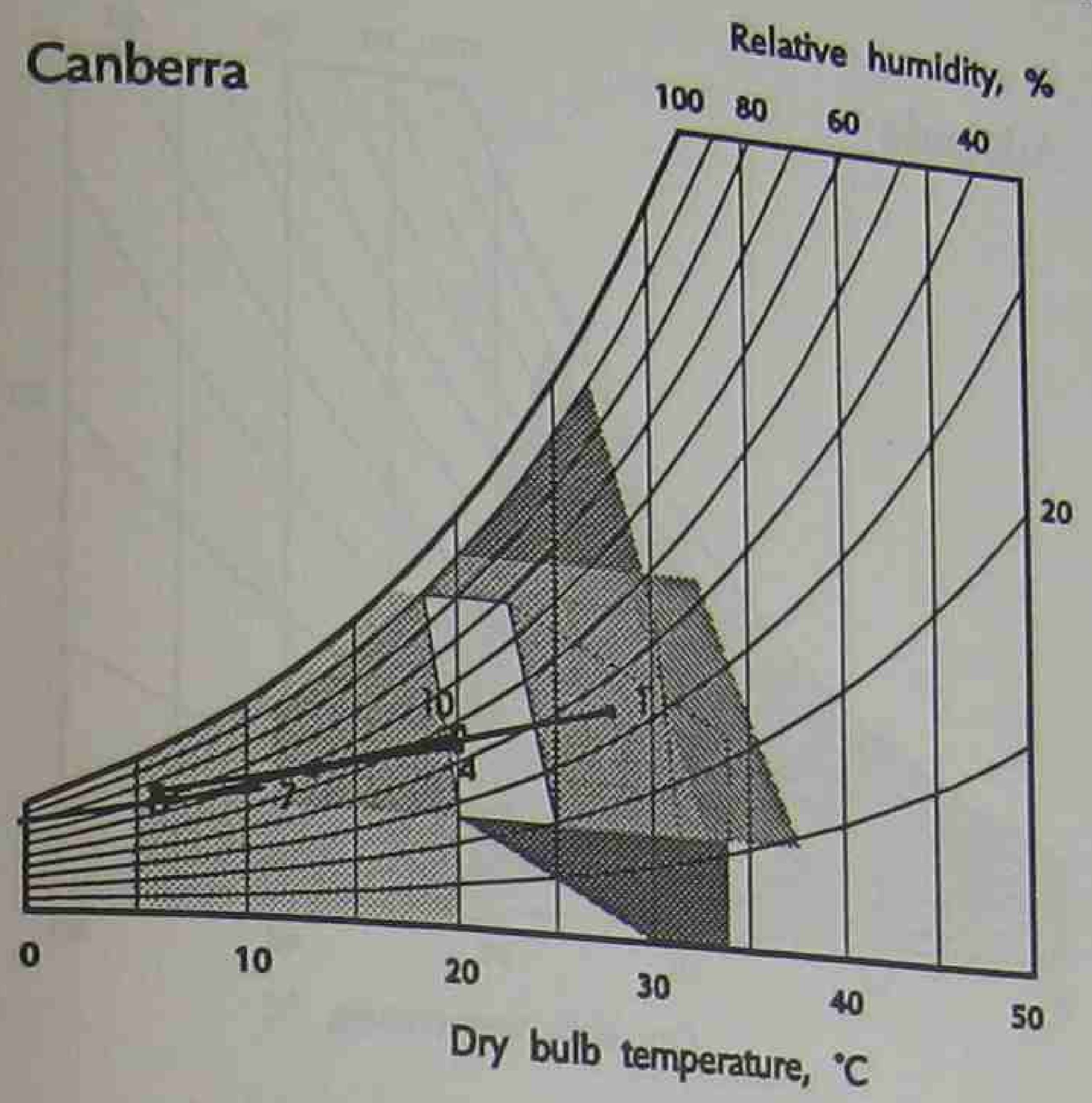


Figure 10 - Psychrometric chart for Canberra.

gain and thermal mass. There is less winter sunshine available in Melbourne so some additional heating may be required in the worst months. The thermal mass effect alone appears to be adequate to maintain comfort conditions in summer in these locations, with perhaps some additional night-time ventilation in Perth. Fans appear to be useful in maintaining comfort in summer when above average temperatures occur. Evaporative coolers would work in Melbourne and Adelaide but do not seem to be adequate on their own in Perth and Sydney. Both Perth and Sydney have humidities which are too high for comfort in summer although this is more of a problem in Sydney.

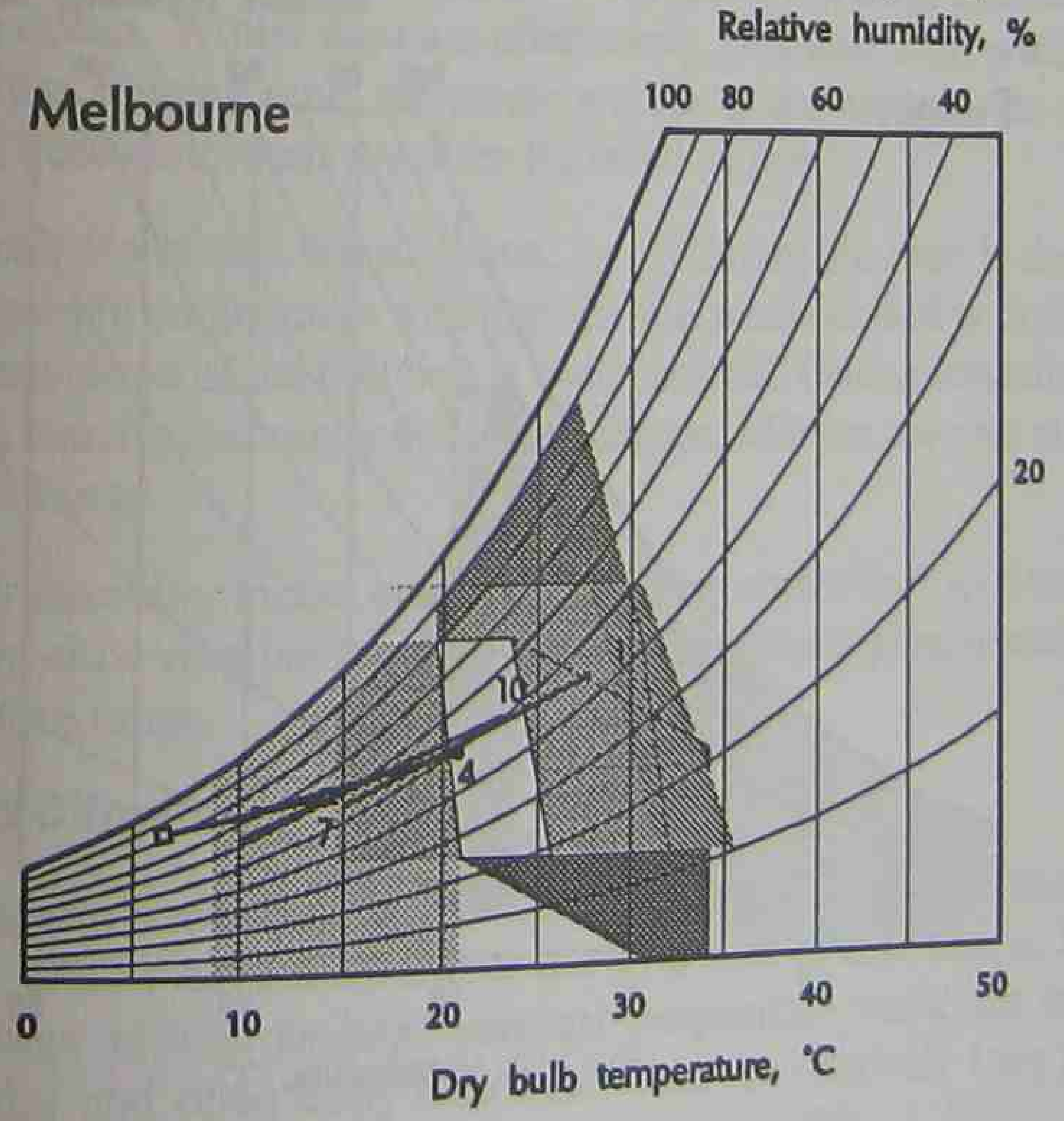


Figure 11 - Psychrometric chart for Melbourne.

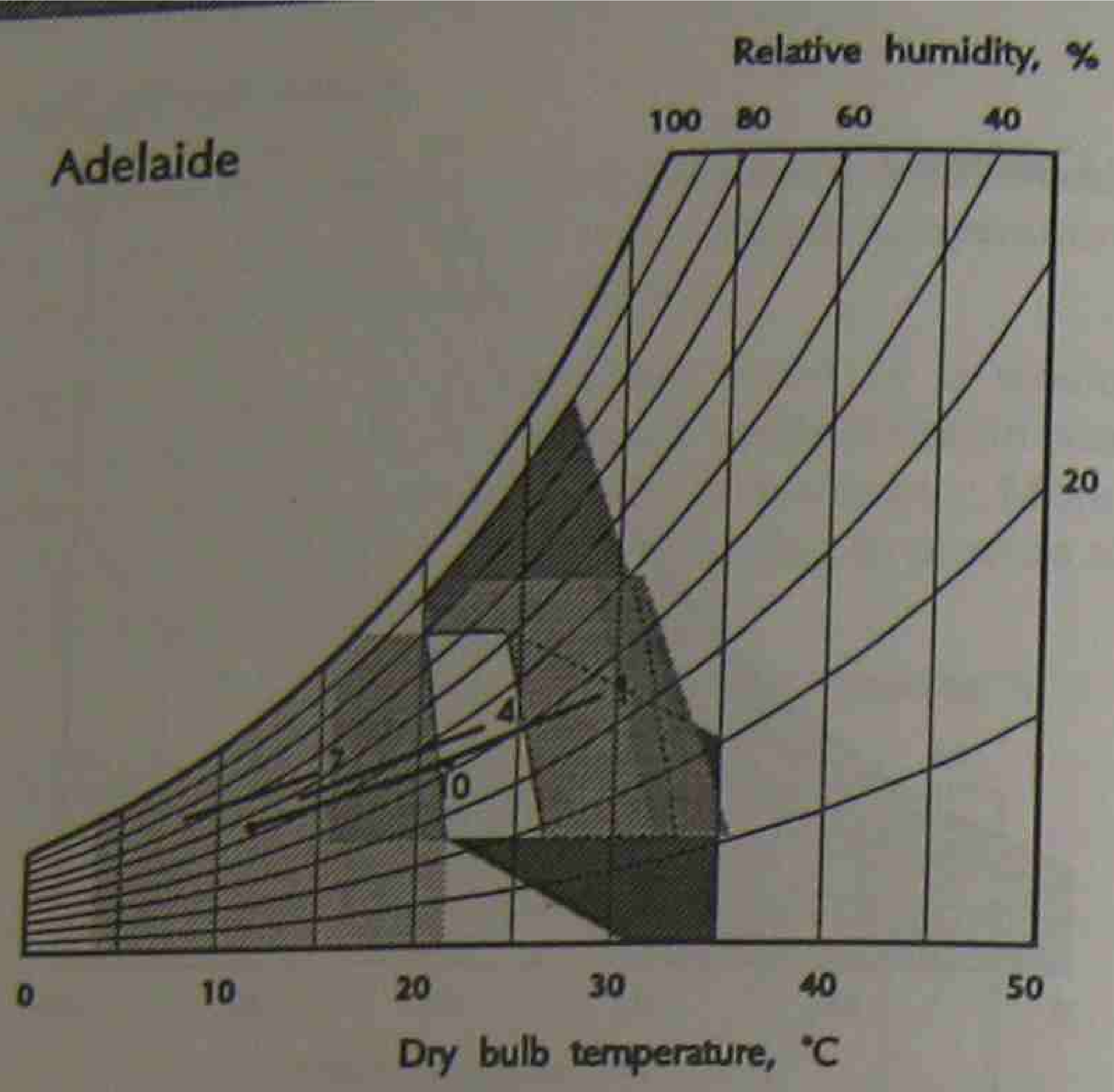


Figure 12 - Psychrometric chart for Adelaide.

North glazing as a percentage of the floor area of the room containing them range from 25 - 40% for Melbourne where there is not a lot of winter sun to 20 - 30% in Sydney which has adequate winter sun but where summer overheating could be a problem. Again, the amount of glazing depends on the amount of thermal mass in the room available to absorb the excess heat.

Only in Melbourne is there an advantage in insulating a timber floor to R1.0. It is not recommended that slab on ground floors be insulated or that timber floors be insulated

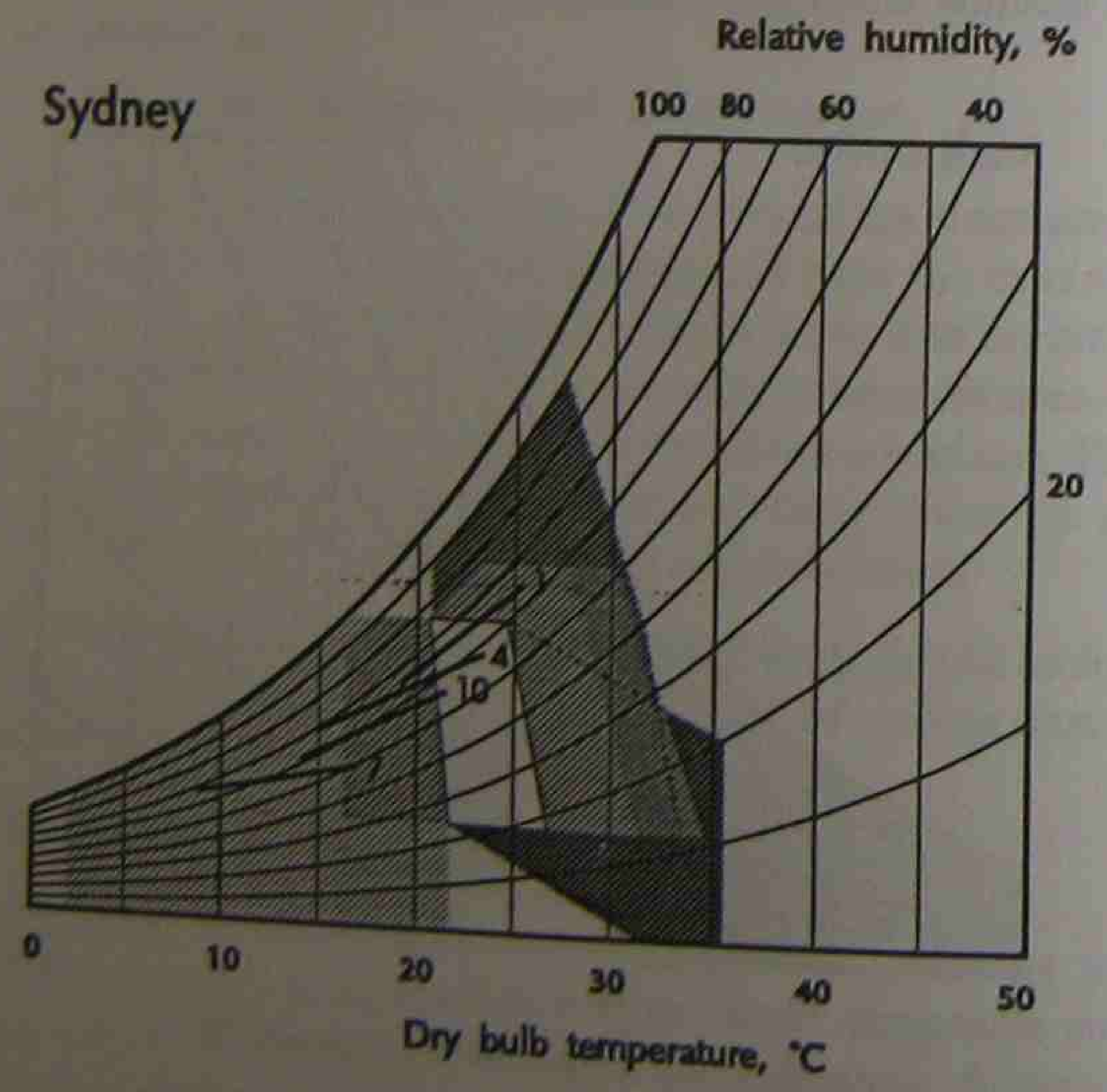


Figure 13 - Psychrometric chart for Sydney.

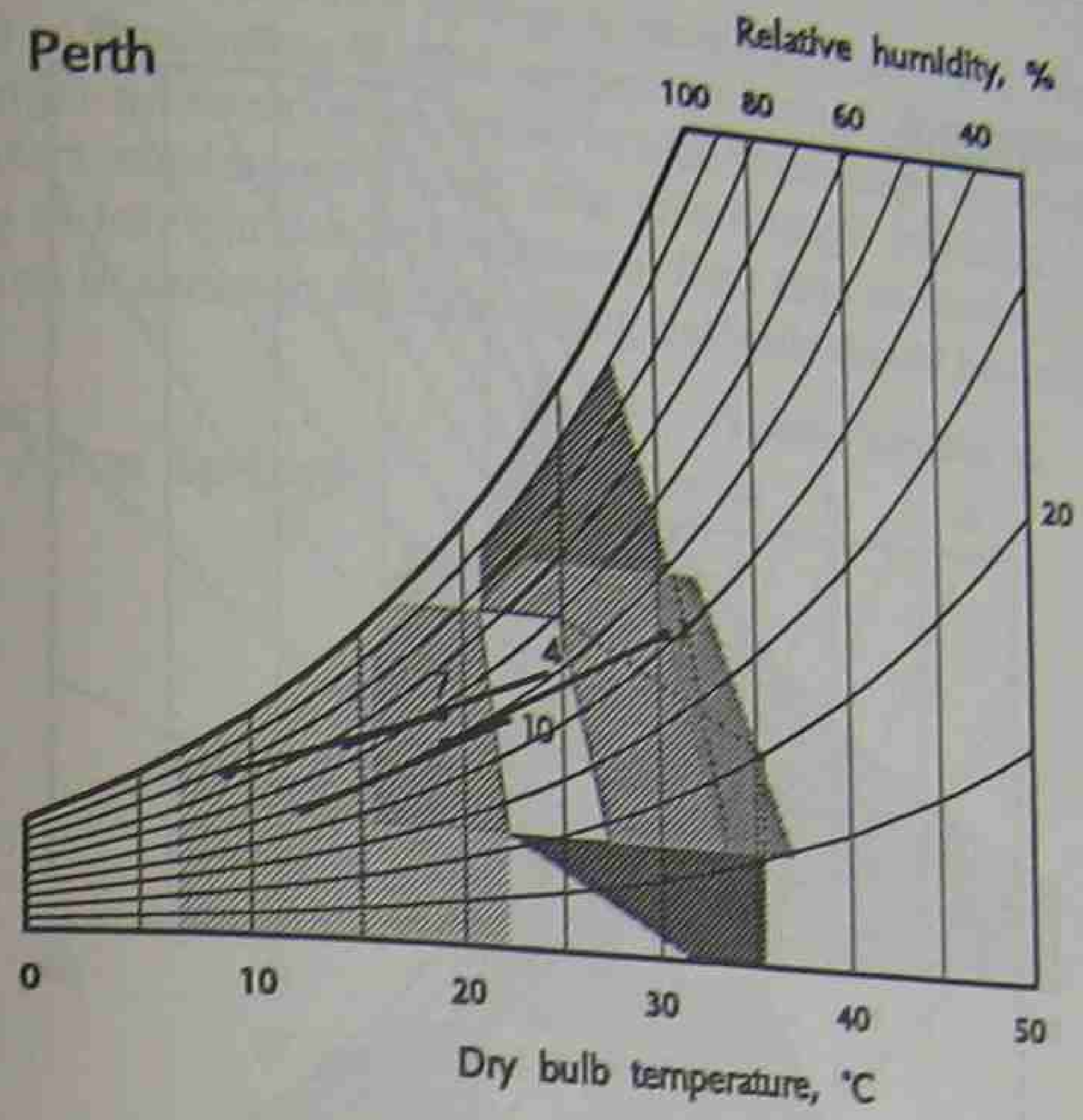


Figure 14 - Psychrometric chart for Perth.

in Adelaide, Perth or Sydney due to possible summer overheating. External walls should include a minimum level of insulation of R1.0. Minimum ceiling insulation levels range from R1.5 to R2.0 in Sydney to R2.5 in Melbourne.

2.8.3 Dry Warm Temperate Climate

This climatic zone differs from the coastal temperate zone in several ways. The diurnal temperature range is larger because these locations are further away from the moderating influence of the ocean. Winter days are often sunny. However clear winter skies allow rapid radiation loss causing rapid temperature drops as the sun loses its strength in the late afternoon. These conditions are often followed by frost.

Mildura is an example of this classification. Its psychrometric chart is shown in Figure 15. Direct solar gain in conjunction with high thermal mass can deal with the temperature extremes if the envelope of the building is well insulated. Ceiling insulation of between R2.0 and R3.5 is usually recommended in this climate. Mildura requires insulation at the lower end of this range.

The low summer humidity makes evaporative cooling attractive if air flow using fans is inadequate. Night-time ventilation is also useful for summer cooling because of the large diurnal temperature range.

2.9 Hot Arid Climate

Hot Arid climates are characterised as having very high day-time temperatures in summer with hot nights. Winter days are warm to hot with cool to cold nights. Large diurnal temperature swings as well as large seasonal temperature variations occur in these locations. Hot, dry and often dusty winds can blow for relatively long periods. Low relative humidity prevails due to the low and irregular rainfall.

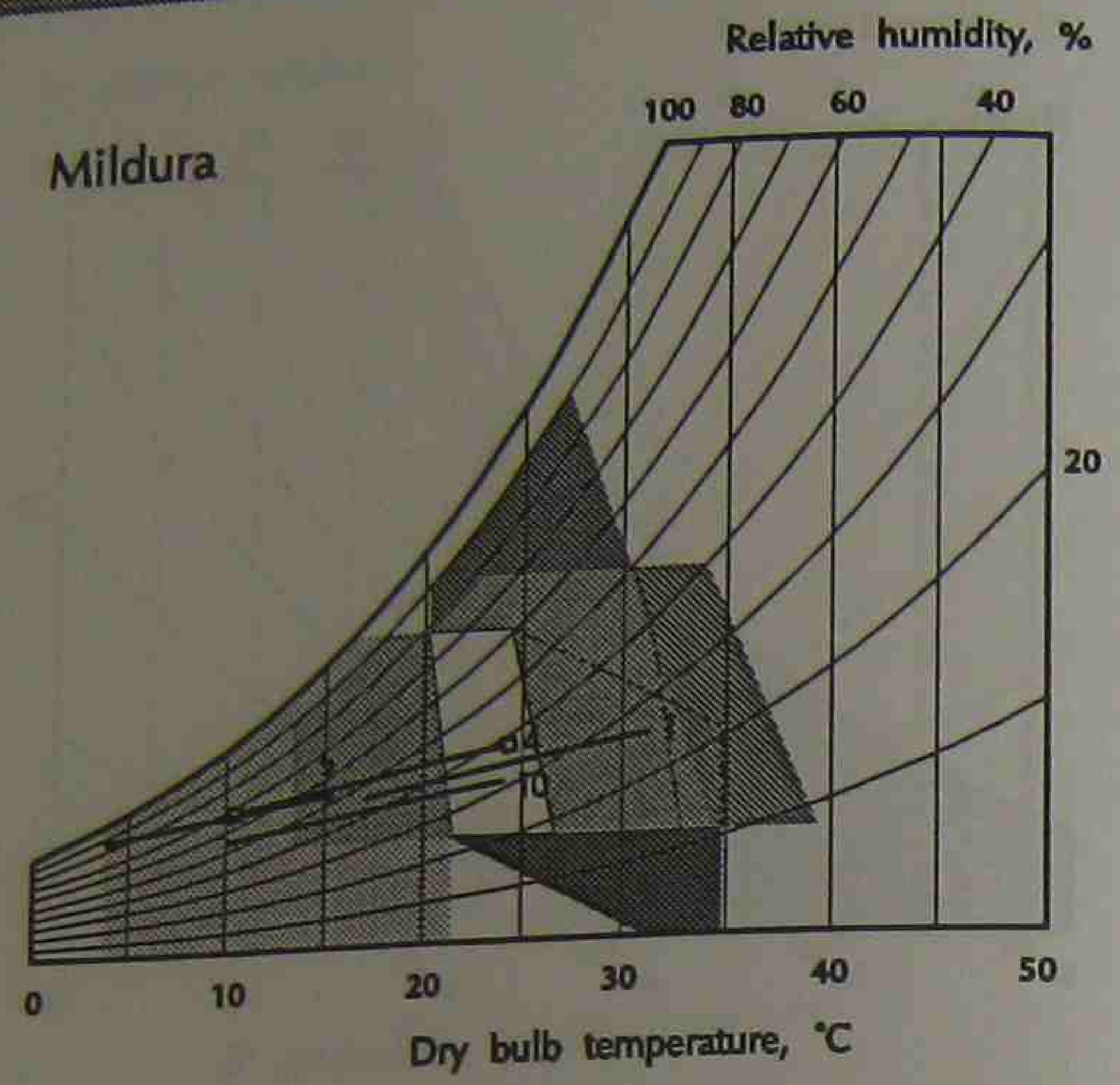


Figure 15 - Psychrometric chart for Mildura.

Comfort maintenance considerations are listed below:

- Heating, and therefore solar gain is only necessary in the middle of winter.
- Provide complete shading of windows at all times except in the middle of winter, possibly with a verandah around the building, or adjustable shading.
- Minimise total glazing.
- Place glazing on the north and south sides only.
- Use a high thermal mass construction type in order to utilise the large diurnal temperature swings.
- Orient the building east-west in subtropical latitudes for effective shading of northern walls and windows.
- Use vegetation such as vines to shade external walls.
- Avoid light coloured reflecting surfaces on the ground near the building.
- Provide a well ventilated or even double roof to minimise heat gain through the ceiling.
- Use water in pools or from misting sprays to provide evaporative cooling.
- Protect the building from hot summer winds with walls or a vegetative shelter belt.
- Consider the use of an internal courtyard containing vegetation and water.
- Consider the use of a low thermal mass sleeping area which will cool down rapidly in the evening.

The psychrometric chart for Alice Springs is shown in Figure 16. Thermal mass is obviously useful in moderating diurnal temperature swings. Evaporative cooling, air movement and night-time ventilation can all be used to moderate the effects of the high outside temperature maximums. Direct solar gain through windows would provide adequate heating in July but the 20% window to floor ratio shown in Figure 16 would lead to overheating in summer. Both the ceiling and walls should be insulated.

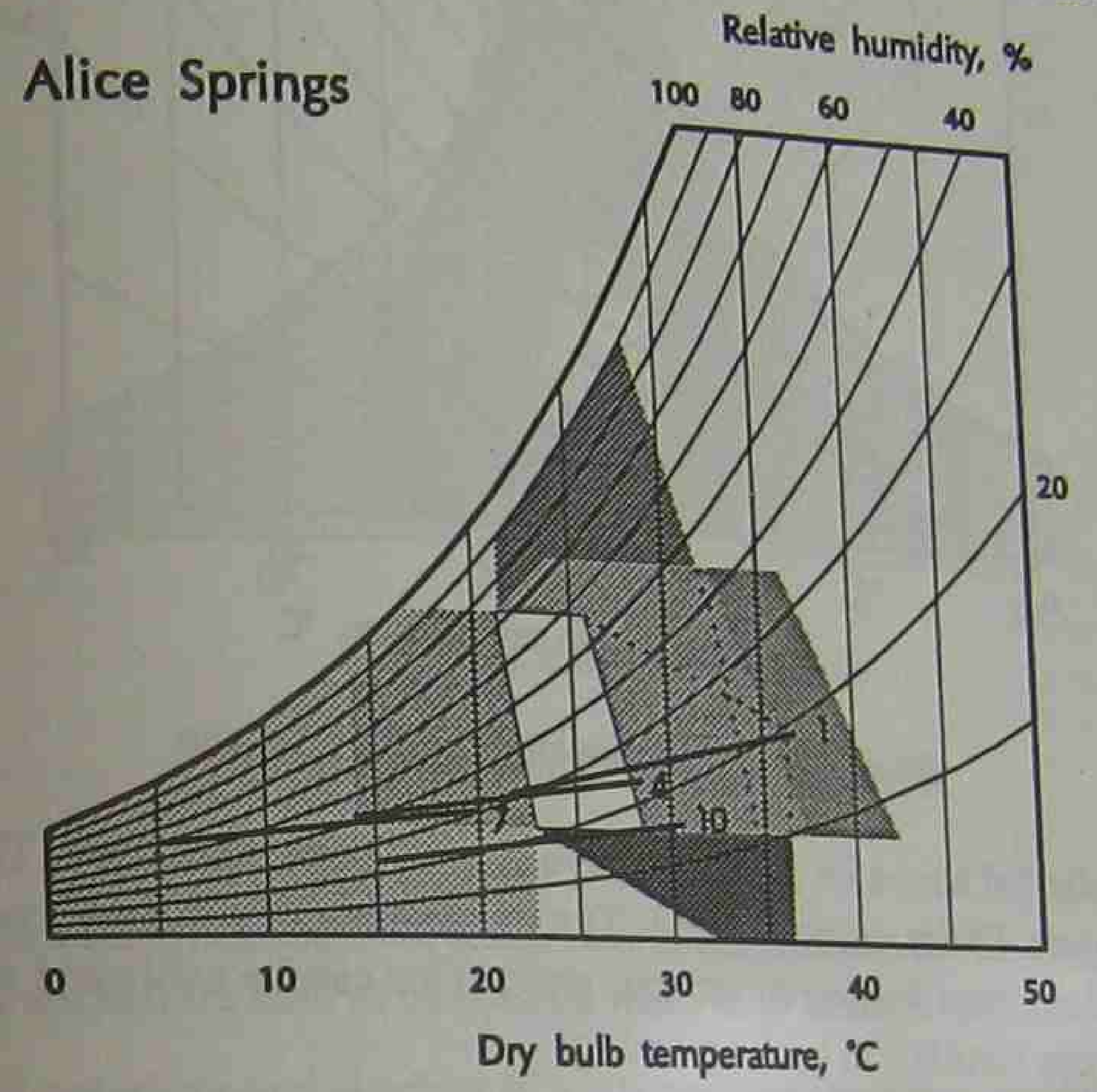


Figure 16 - Psychrometric chart for Alice Springs.

2.10 Subtropical Humid Climate

Subtropical humid climates lie between the coastal temperate and hot humid classifications. Winters are usually clear and sunny with some heating being required. Summers are warm to hot and humid. It is primarily the high humidity which causes discomfort during this time. Cyclones may extend into these regions. Diurnal temperature ranges are not large so the major advantage of thermal mass is in winter if direct solar gain is used for heating.

If a glazed area of 15 - 20% of the total floor area is used to provide winter heating then a concrete slab on ground floor and masonry internal walls give the best results. However some overheating will occur in summer so it is important to design the building for cross ventilation to provide both air movement and to cool down the thermal mass when the outside air temperature is low enough to allow this.

An east-west orientation is still desirable to allow convenient shading of north windows. Because of the lower latitude, and therefore the higher position of the sun in the sky in summer orientation is less critical than for temperate climates. Summer shading is very important with the strategic use of vegetation providing a cheap and effective solution. Bulk insulation should be installed in the ceiling and reflective foil insulation used in walls. Vapour barriers may be necessary if the building is to be air-conditioned.

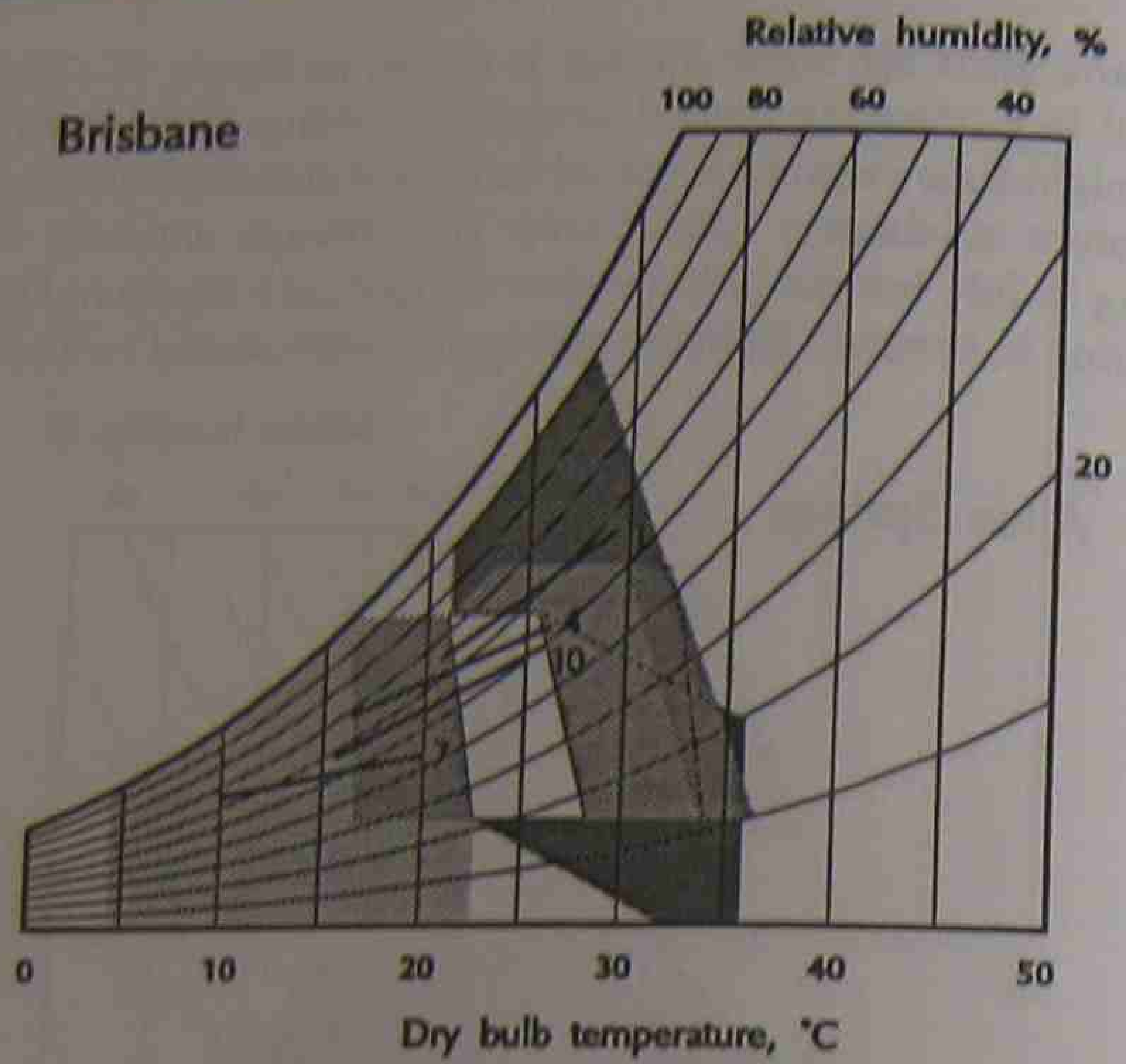


Figure 17 - Psychrometric chart for Brisbane.

The control potential zones for Brisbane have already been discussed. They are brought together in Figure 17 for completeness. The importance of air movement for summer comfort is evident from the psychrometric chart. This can be achieved with fans during the day, and cross ventilation in the evening.

High set houses which make use of summer breezes are common in these areas. It is usually not possible to incorporate much thermal mass into this design so the amount of glazing should be reduced. Verandahs provide good shading for walls and windows, but daylighting to the interior is restricted. Shaded skylights may provide a solution to dim interiors.

2.11 Hot Humid Climate

Locations classified as being in the hot humid zone are subject to high temperatures throughout the year. The daily temperature range is small, particularly in summer when heavy rainfall keeps the humidity high throughout the day. Winter days are warm to hot with mild nights. The seasons are perhaps more accurately described as wet and dry rather than summer and winter. The prevalence of cyclones in summer may place limitations on the type of building construction.

No heating is required so the building should be designed emphasising features that stop it from heating up during the day and allow it to cool down rapidly when outside temperatures fall. Effective strategies are similar to those discussed for subtropical humid zones but without allowances for sun penetration in winter.

Figure 18 shows the psychrometric chart for Darwin. The provision of air movement is the most important strategy. Cooling breezes should be taken advantage of by placing openings so that cross ventilation can occur in the prevailing breeze direction. Ceiling fans are highly recommended. Louvre windows have been suggested in the literature as a means of facilitating ventilation but they are leaky when closed and result in high infiltration of hot air when external temperatures are excessive. Window areas should be kept small but should be able to be opened when cool breezes occur.

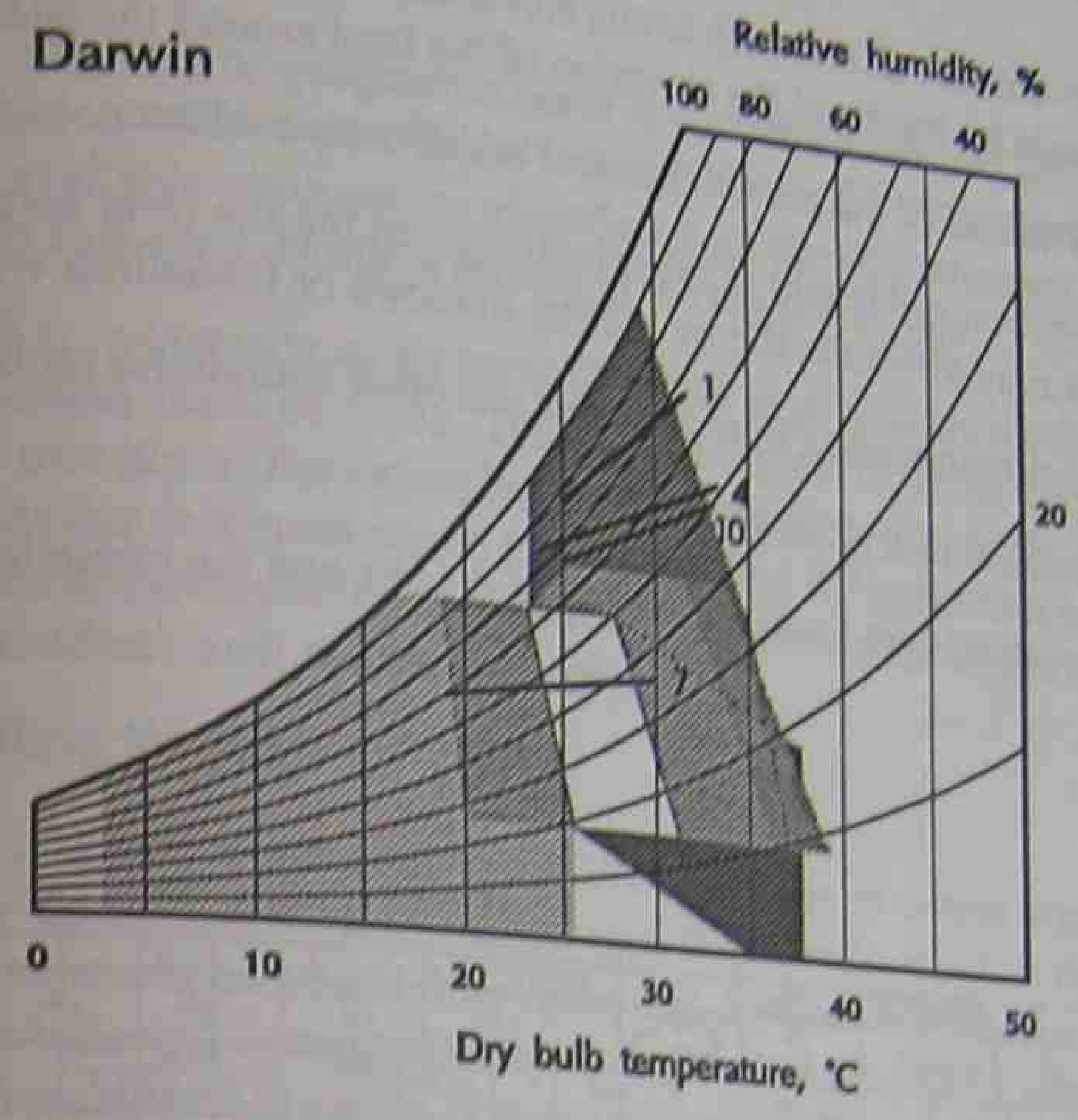


Figure 18 - Psychrometric chart for Darwin.

Light coloured exteriors and shading of walls and windows by vegetation or verandahs should be incorporated into the design. Bulk insulation should be installed in the ceiling below a well ventilated roof cavity. Reflective insulation should be used in the walls. Vapour barriers will be necessary if air-conditioning is used. High set houses designed to catch cool breezes should be of lightweight construction. Low set houses should be built on a concrete slab on the ground. Ground cover and shaded areas should surround the building to reduce reflected sunlight.

3 DESIGN FOR SITE

Having established the broad climatic zone classification of the building location and its features, and having identified the possible strategies for attaining thermal comfort, the next step in the design of the building is to analyse the site. This will enable the designer to decide the best location and orientation of the building and what earth-works, landscaping and planting needs to take place to make the best of what the site offers. The following aspects should be noted:

- ❑ the direction of true north.
- ❑ the slope and drainage of the site.
- ❑ rocky outcrops or areas of swamp or subsidence.
- ❑ the size and location of vegetation such as trees on the site and on neighbouring areas.
- ❑ the direction of views.

- micro-climate effects such as site elevation, shading by mountains, funnelling of winds by trees and the elevation of the land around the site.
- the direction of the prevailing wind in different seasons.
- the location and height of other buildings on the site or in neighbouring areas which may affect the site by casting shadows or funnelling winds.
- the minimum setback from the street and other boundaries required by council.
- the location of any easement.

This information should be shown on a plan of the site and the immediate surrounding area.

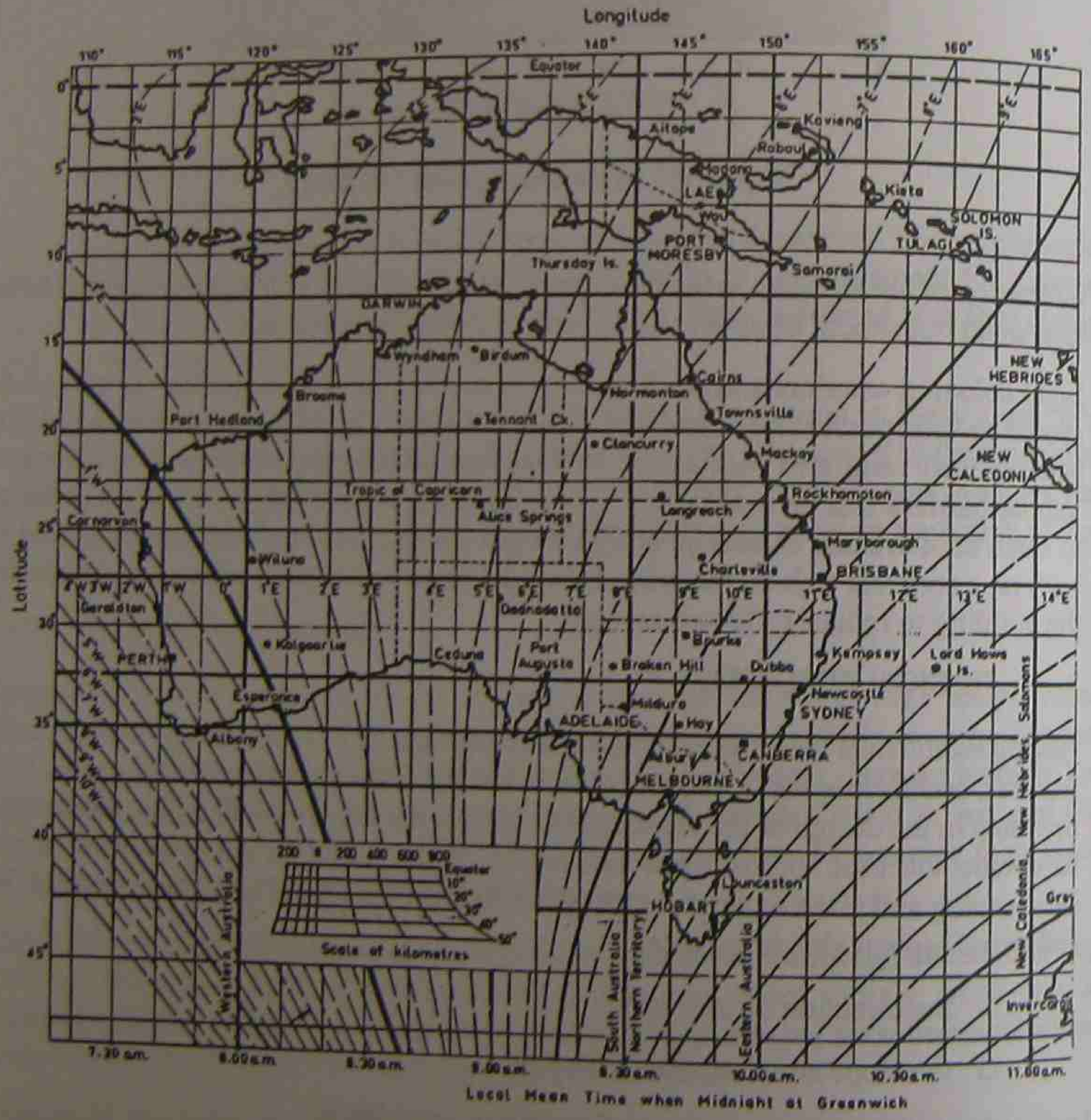


Figure 19 - The variation of magnetic north from true north.
(Source: Phillips, 1975).

3.1 Locating True North

It is important that true or geographic north is correctly identified for the purposes of building orientation with respect to the sun and winds. If a street directory or council survey map is available north can be identified from the grid reference lines which run north-south and east-west. North is usually at the top of the page.

Magnetic north is not usually in the same direction as geographic north so if a compass is used a correction must be made. The map in Figure 19 gives the variation of the compass from true north. For example, the variation from true north in Sydney is 12° East. This means that true north can be found by adding 12° to the west of compass north. There may be local variations in the direction of magnetic north due to iron bearing rock or man made artefacts such as steel or electric cables.

3.2 Prevailing Winds

Summer winds usually come from a different direction to winter winds. Wind in the afternoon may be of a different strength and direction to wind in the morning. The analysis of when winds occur and their speed and direction is important to determine the placement of windows for natural ventilation. Wind roses usually give information on the direction from which the wind comes and the frequency with which it comes from that direction. Information is usually given for 9.00am and 3.00pm. The wind roses may be drawn for both summer and winter or may give information on a monthly basis. Figure 20 shows morning and afternoon wind roses for Brisbane. The outer octagon represents wind coming equally from all directions. It can be seen that in the mornings in winter the wind comes mainly from the south and south-west while in summer there is a slight predominance of wind from the south and south-east. In the afternoons in winter there is slightly more wind coming from the south around to the west, while in summer the wind comes mainly from the north-east and the east. The percentages of calm periods per month given in the inner octagon indicate that afternoon sea breezes are quite reliable in summer.

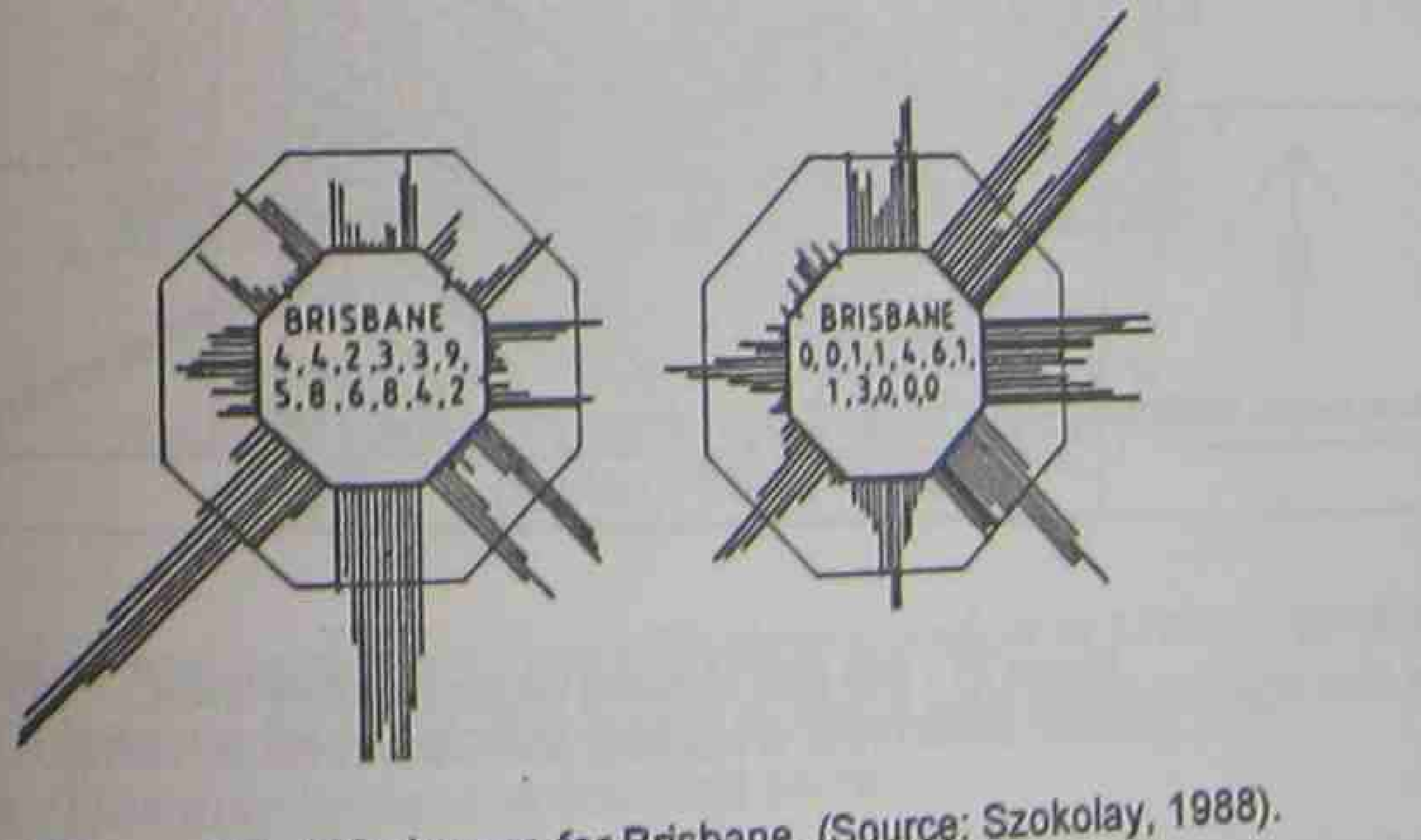
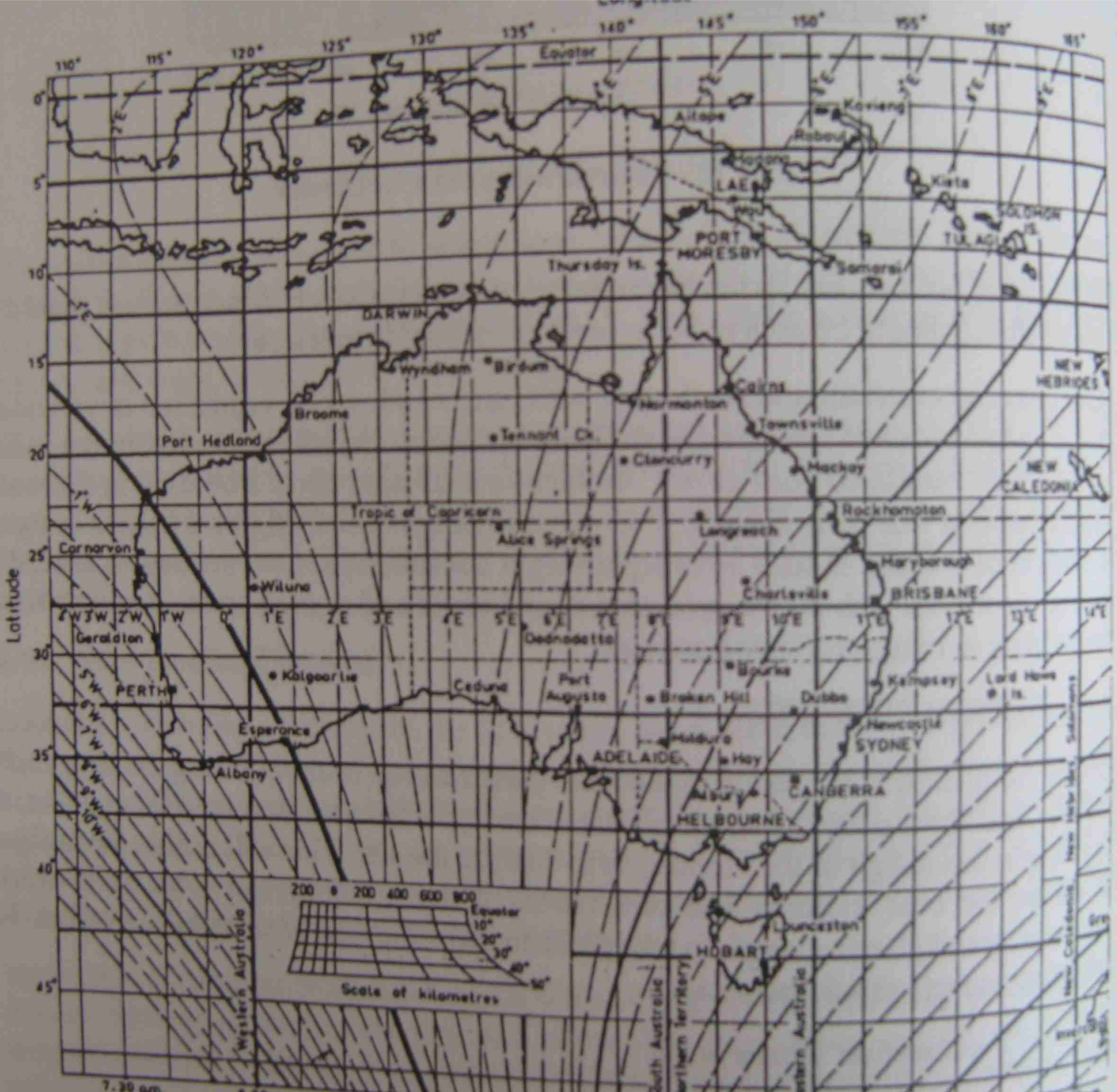


Figure 20 - Wind roses for Brisbane. (Source: Szokolay, 1988).

The information examined for Brisbane would indicate that in the absence of any over-riding local effects, protection of the south side of the building from cold winter winds would be of value. It also suggests that cross ventilation from north-east to south-west would provide a cooling effect in the late afternoon and evening in summer.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Broome
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Cloncurry
Townsville
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PERTH
Ceduna
Port Augusta
Broken Hill
Dubbo
Esperance
Mildura
Newcastle
SYDNEY
Albany
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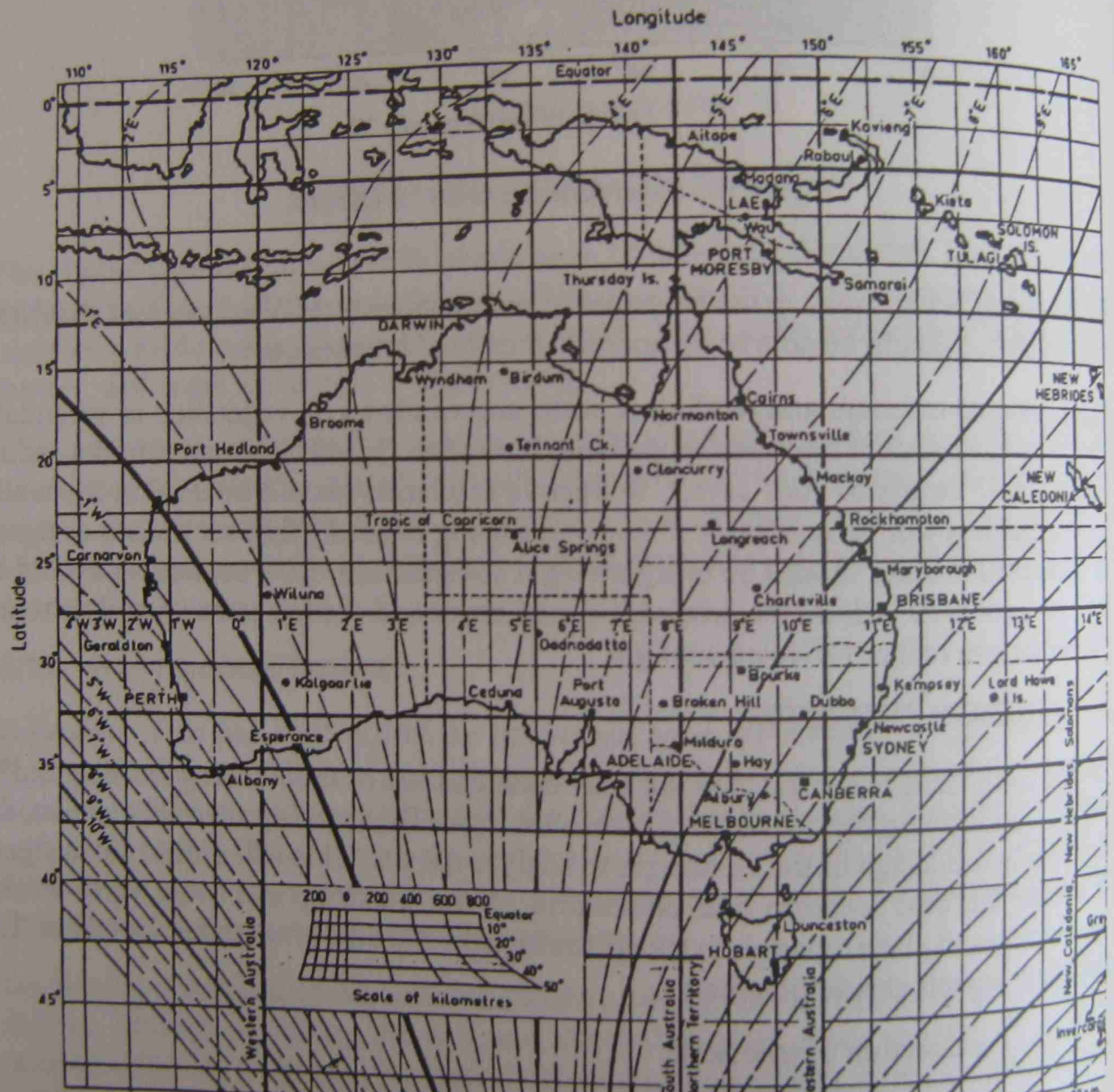

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11.00 a.m.

3.3 Solar Access

Solar access relates to the availability of sunlight at a particular point. If there are structures or trees near the building site then it is necessary to determine if shading takes place and when this occurs. It may be necessary to either set the building back from trees that may cause shading or to remove these trees if direct solar gain to the building is a winter thermal control strategy. High buildings on the northern side of the proposed structure can be a greater problem than trees.

It is desirable to have at least 6 hours of sunlight in winter in temperate climates. A sun path diagram designed for the latitude of the location will enable the azimuth and altitude of the edge of an obstruction to be found at 9am, 12 and 3pm on the 21st of June. These shadows should be marked on a map of the site to help identify the best location for the building on that site. An example of a site plan showing shadow lines is given in Figure 21.

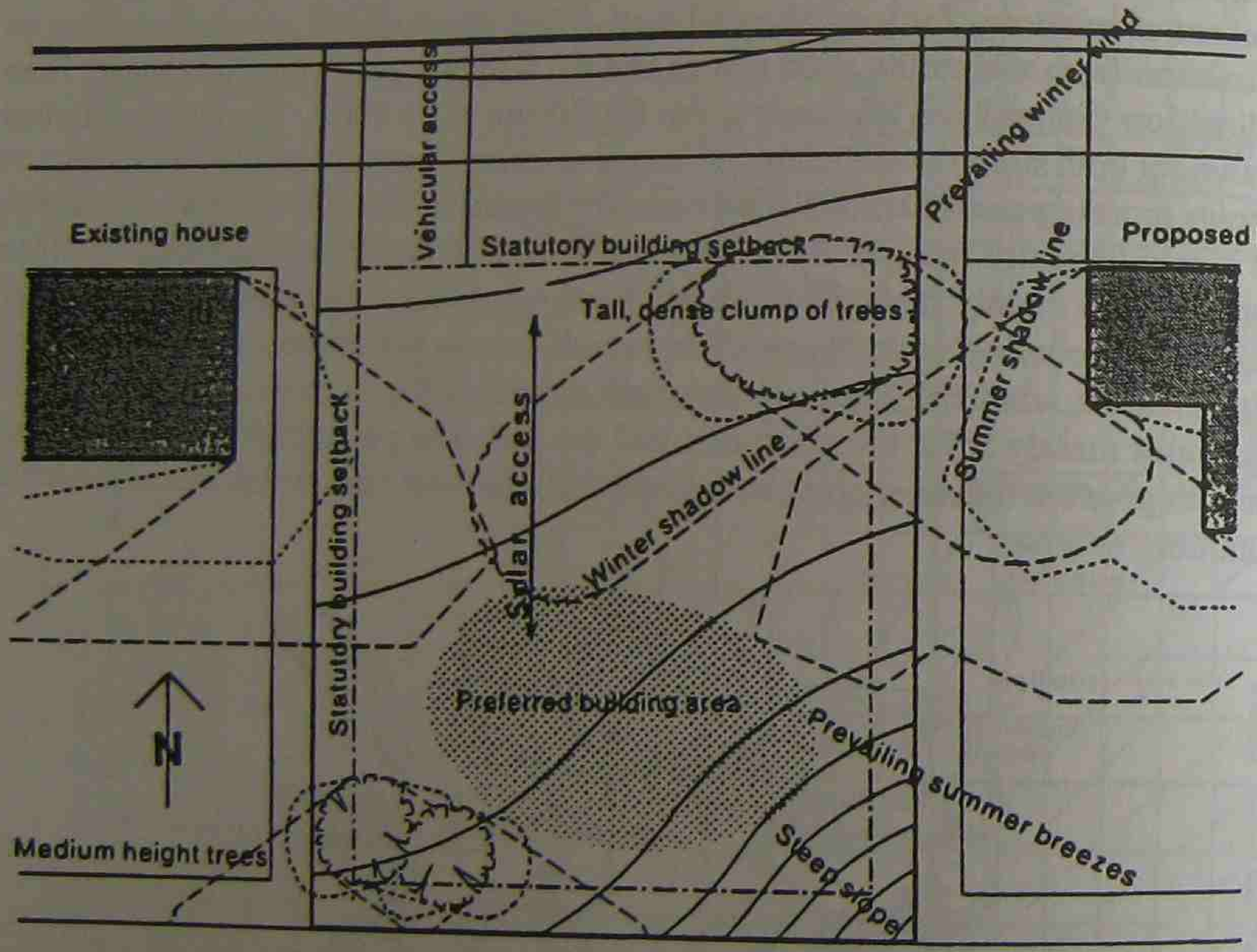


Figure 21 - Site plan showing winter shadow lines.
(Source: Department of Housing and Construction, 1985).

Once the location for the building has been decided upon there may still be some winter shading. Perhaps some summer shading of the west or east walls or windows needs to be considered. Shading can be studied with the aid of a sunpath diagram and a transparent shadow angle protractor. These are both shown in Figure 22.

It is possible to use these tools to find out at what times sunlight will enter the room by following the procedure as outlined by Phillips, 1975:

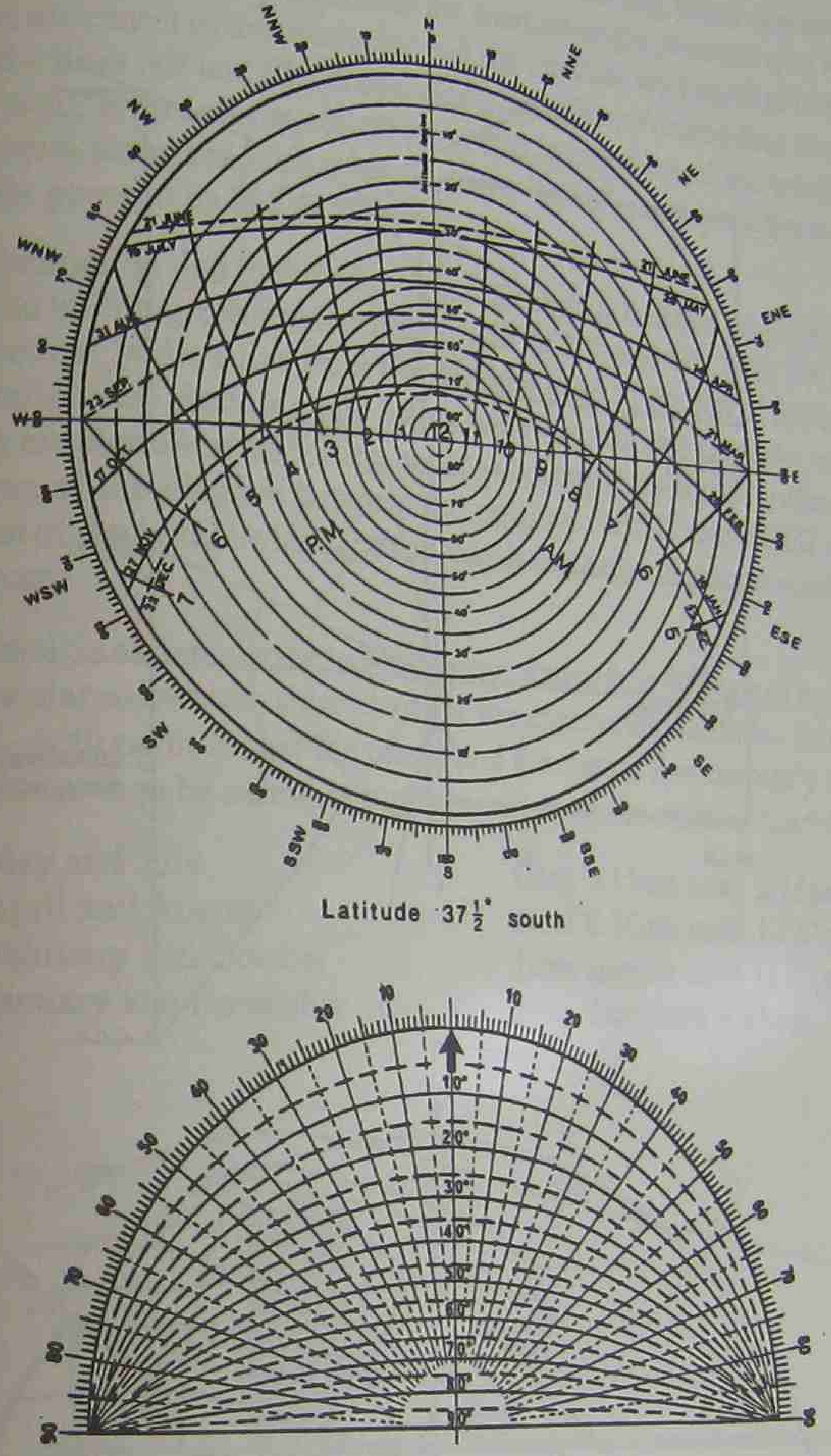


Figure 22 - Sunpath diagram and shadow angle protractor.
(Source: Phillips, 1975).

The plan and section (in Figure 23) show a window in a room, opposite which is an adjoining building. It is desired to find at what times sunlight will enter the room. This may be done as described below.

Lines are drawn from the inner to the outer edges of the jambs of the windows, intersecting at X. These lines make angles of 75° with the centre line of the window. It is evident that the sun cannot enter the room when the horizontal shadow angle exceeds 75°. A line on section from the inner edge of the sill to the edge of the eaves is at an angle of the elevation of 60°. Therefore, when the vertical shadow angle exceeds 60°, no sun will enter the room.

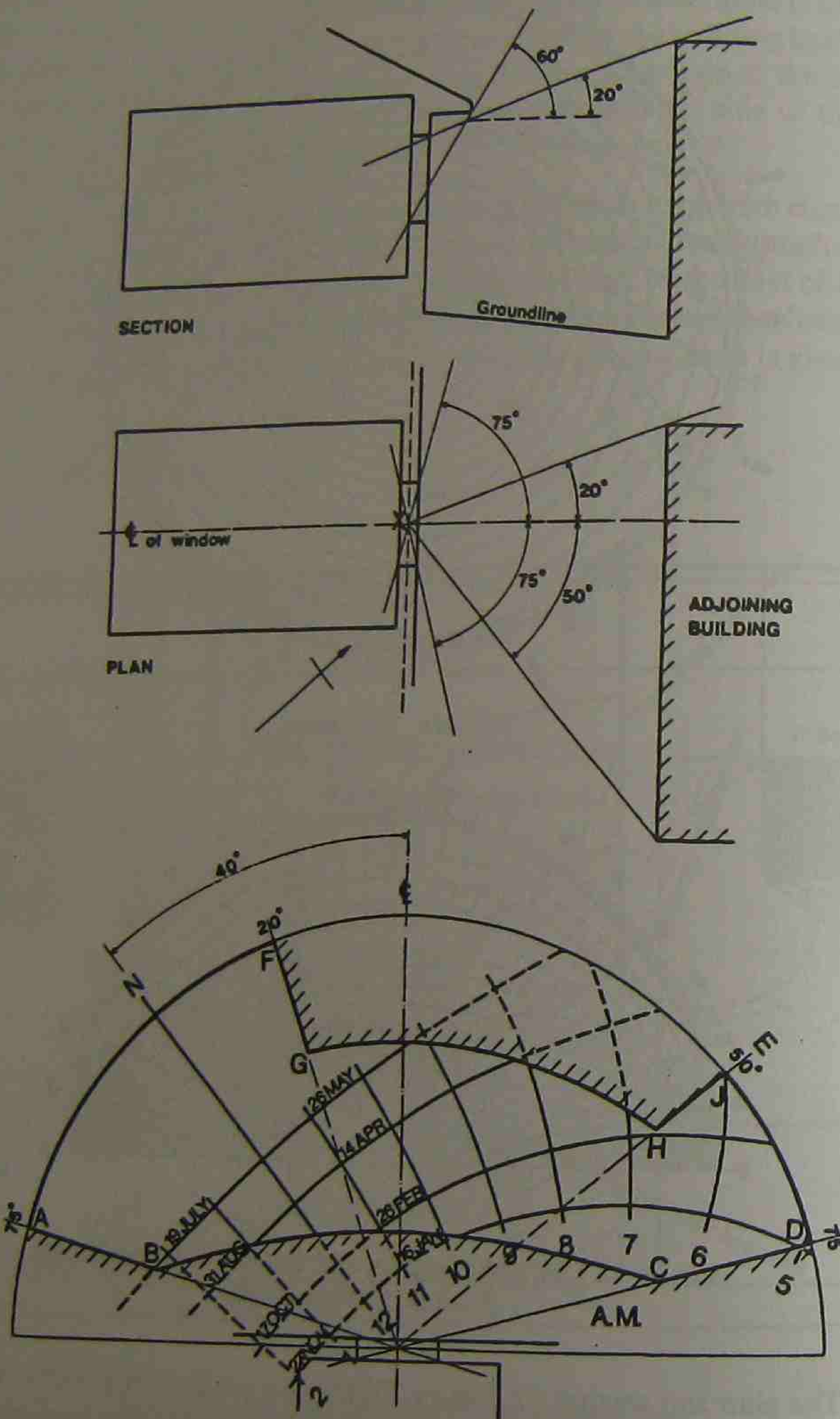


Figure 23 - Determination of times when sunlight penetrates a window. (a) Plan and section of buildings. (b) Diagram of sunlight "cut-off" lines and sun paths for latitude 37.5°S. (Source: Phillips, 1975).

A plan of the window is drawn on a piece of tracing paper represented by the lower diagram. This is placed over the shadow-angle protractor, so that the point X is on the centre of the protractor and the window wall parallel to the base line. Then the lines AB and CD, drawn along the radii corresponding to angles of 75° to the wall, represent the cut-off lines due to the sides of the window. The line BC, drawn along the shadow-angle curve for 60°, represents the cut-off line for sunlight penetration due to the eaves.

The obstruction due to the adjoining buildings is defined on plan by lines from X to the building corners forming angles of 20° and 50° with the centre line of the window, while a line from the window head to the top of the obstruction, at 20°, defines the shadow angle below which no sun can enter the window. These angles are plotted on the tracing paper as before, forming the outline FGHJ. Then the area of the diagram between the outlines ABCD and FGHJ represents the portion of sky within which the sun may lie, in order that some sunlight will enter the room.

If the wall is assumed to be in Melbourne, and to face 40° east of north, the tracing is now placed over the solar chart for the appropriate latitude - in this case 37.5° south - with point X over the centre and the central line correctly oriented to 40° east. It can then be seen that sunlight will enter the room at the following times:

May and July	from 9.15am until 2.15pm
April and August	from 8.10am until 12.55pm
February and October	from sunrise until 11.05am
January and November	from 5am until 9.45am

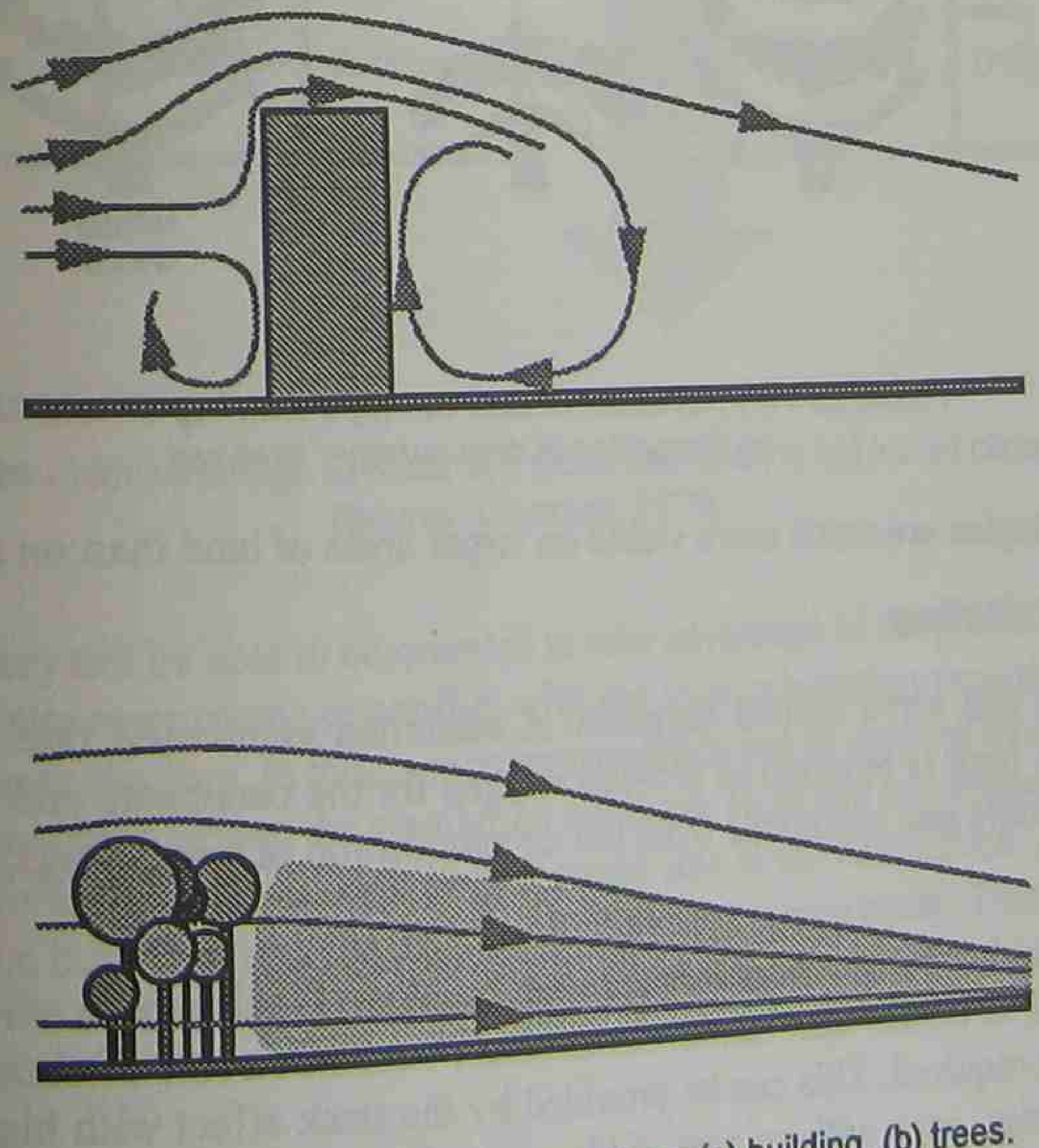


Figure 24 - Air flow around obstructions: (a) building, (b) trees.

3.4 Wind Protection and Funnelling

Trees or shrubs planted in groups can be used as windbreaks to deflect or reduce the severity of prevailing winter winds. The selection of appropriate species is important.

Any solid obstruction in a wind flow path will create an area of turbulence on the leeward side of the object. Large objects will also create areas of turbulence on the windward side near the object, and will create local areas of increased wind speed. Unlike solid objects, open shelter belts of vegetation tend to absorb the energy of the wind and reduce air speeds without the excessive turbulence associated with dense planting. This effect is illustrated in Figure 24.

The area of significantly reduced speed on the leeward side of a wind break extends to a distance of 7 to 10 times the effective height of the windbreak. At a distance of 20 times the height, the wind velocity is reduced by only 20%. The most effective wind protection is provided within a distance of 3 to 7 times the windbreak height.

When designing a wind break care should be taken to deflect cold winter winds rather than damming them. This is shown in Figure 25 (a) and (b). Part (c) of this figure shows how vegetation can be used to funnel summer breezes to provide a cooling effect.

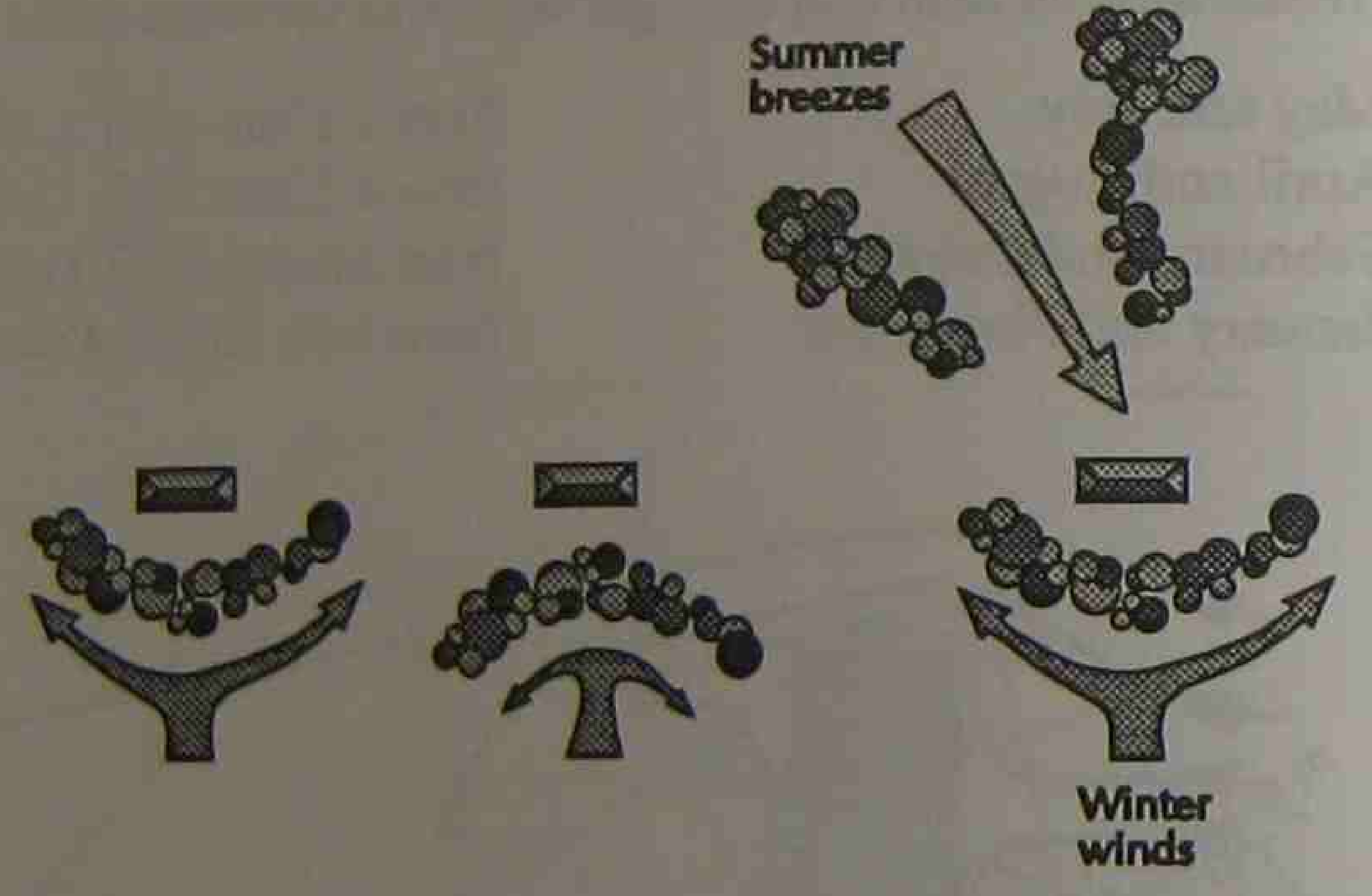


Figure 25 - (a) Deflection of cold air. (b) Damming of cold air.
(c) Funnelling of cool summer breezes.

These strategies are much more viable on larger areas of land than on suburban blocks.

3.5 Ventilation

Ventilation can serve several purposes. A minimum ventilation rate of about one air change per hour is required to provide oxygen for the occupants and to remove water vapour, odours and chemicals from the decomposition of furnishings, surface coatings etc.

The structural cooling of high thermal mass buildings is achievable when the outside air is at least 2°C cooler than inside. A minimum ventilation rate of about 10 air changes per hour is required. This can be provided by the stack effect with high outlet and low inlet openings, each with an area of 5% of the floor area. An adequately sized exhaust fan venting into the ceiling cavity and then to the outside can also accomplish this task.

Air movement to provide body cooling requires a speed of between 1 and 1.5 m/s which is equivalent to at least 100 air changes per hour. Prevailing cool breezes and cross ventilation is required to achieve these air speeds. Alternatively ceiling or wall mounted fans can be used if these breezes are not reliable.

3.5.1 Cross Ventilation

If cool evening breezes are available at the end of a hot day they can be used to cool down the fabric of the building as well as providing the air movement required for greater physical comfort. Openings such as doors and windows should be placed so that air can flow through the building as unimpeded as possible. This makes the positioning of internal partitions critical.

In hot humid climates where winter heating is not required the house can be oriented with its long axis perpendicular to the direction of the prevailing breezes. A long thin building as shown in Figure 26 will ensure that all rooms have cross ventilation. An extraction fan and stove canopy will be necessary to stop kitchen cooking smells from being blown through the building.

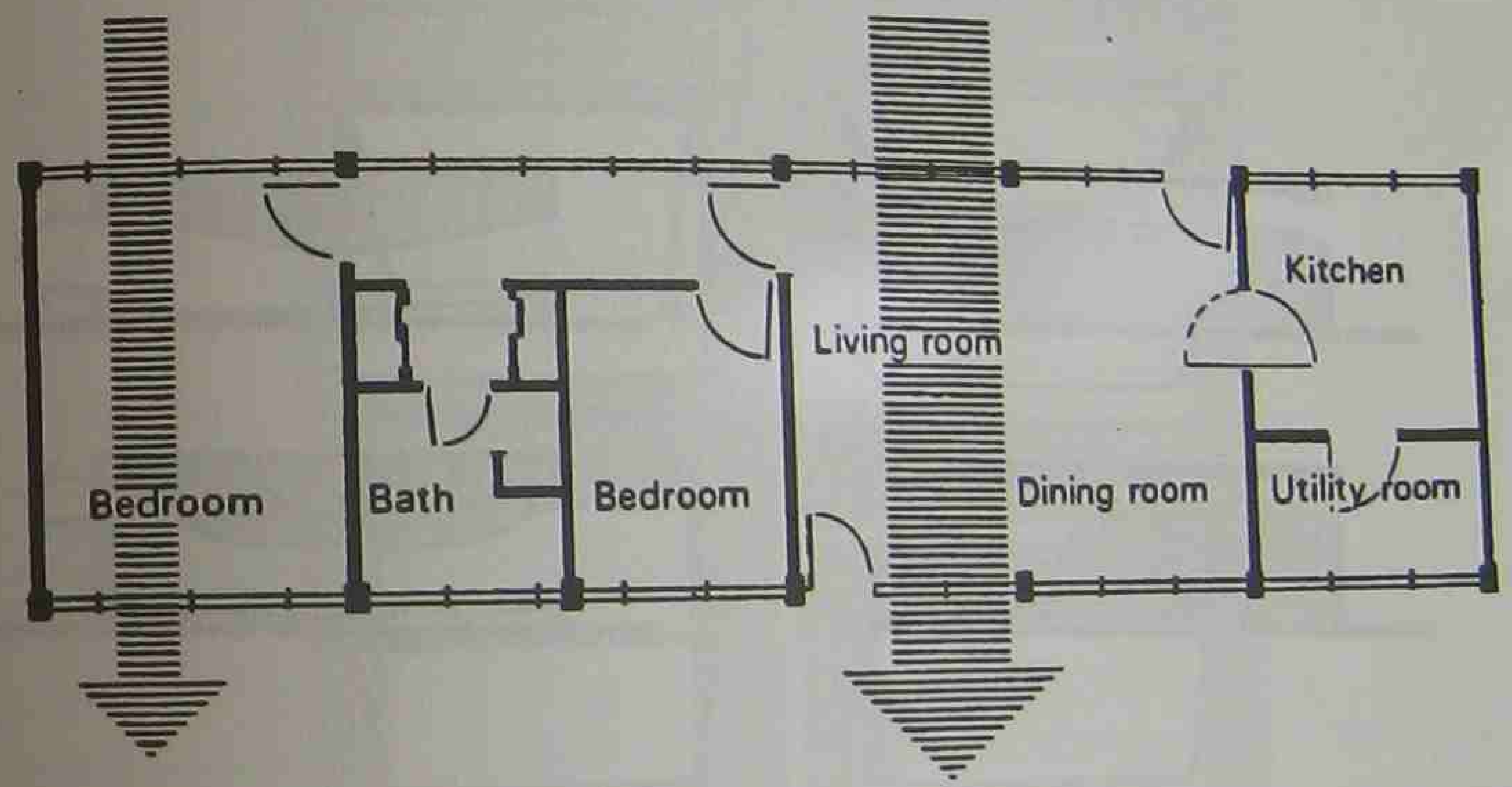


Figure 26 - House design to maximise cross ventilation in hot humid climates.
(Source: Drysdale, 1975).

The building may not be able to be oriented to take advantage of the prevailing summer breezes due to site restrictions or conflict with the solar orientation required for winter heating or summer shading. In this case cross ventilation can be induced by creating high and low pressure areas next to the ventilation openings. High and low pressure zones are created respectively on the windward and leeward side of the obstruction. Air will then flow through the building from the high and to the low pressure zones. This is illustrated in Figure 27.

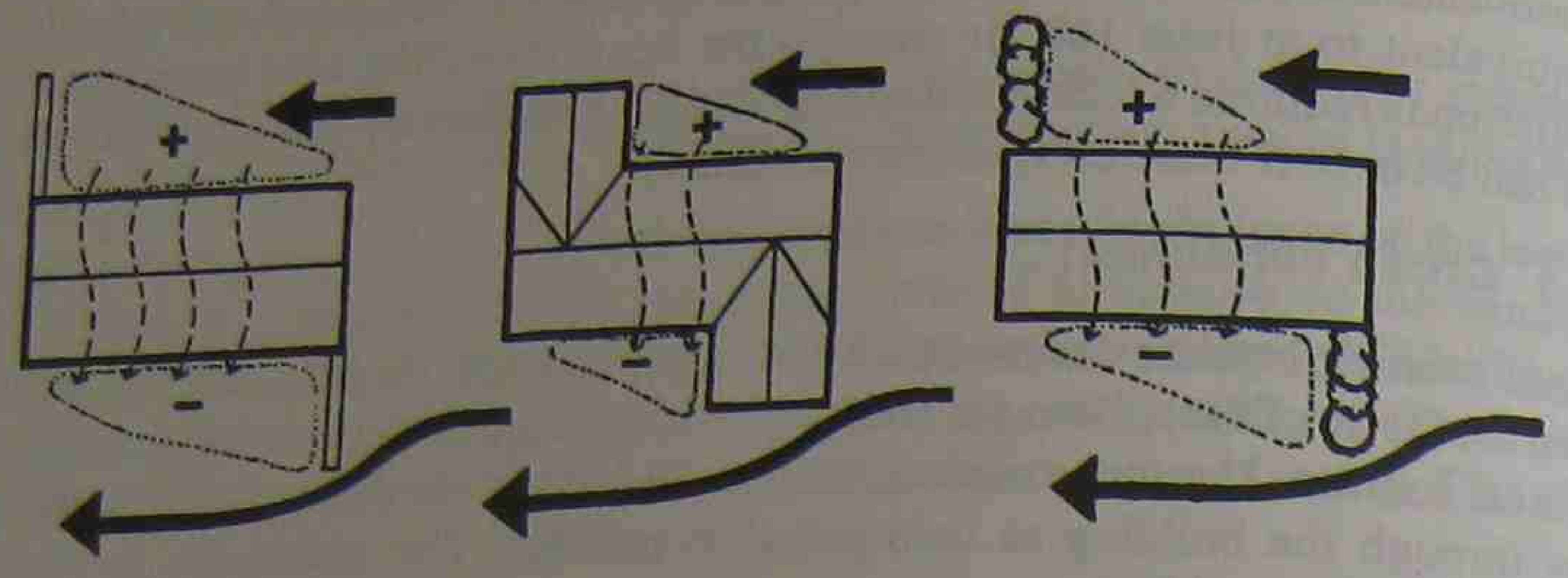


Figure 27 - High and low pressure zones are created by obstructions to wind flow next to the building. (Source: Szokolay, 1991).

The height of the air inlet and outlet influences the air flow distribution pattern in the room. High level cross ventilation does not create much air movement around people. The air inlet should be low to create good air flow low down in the room. The air flow distribution for a number of opening arrangements are shown in Figure 28.

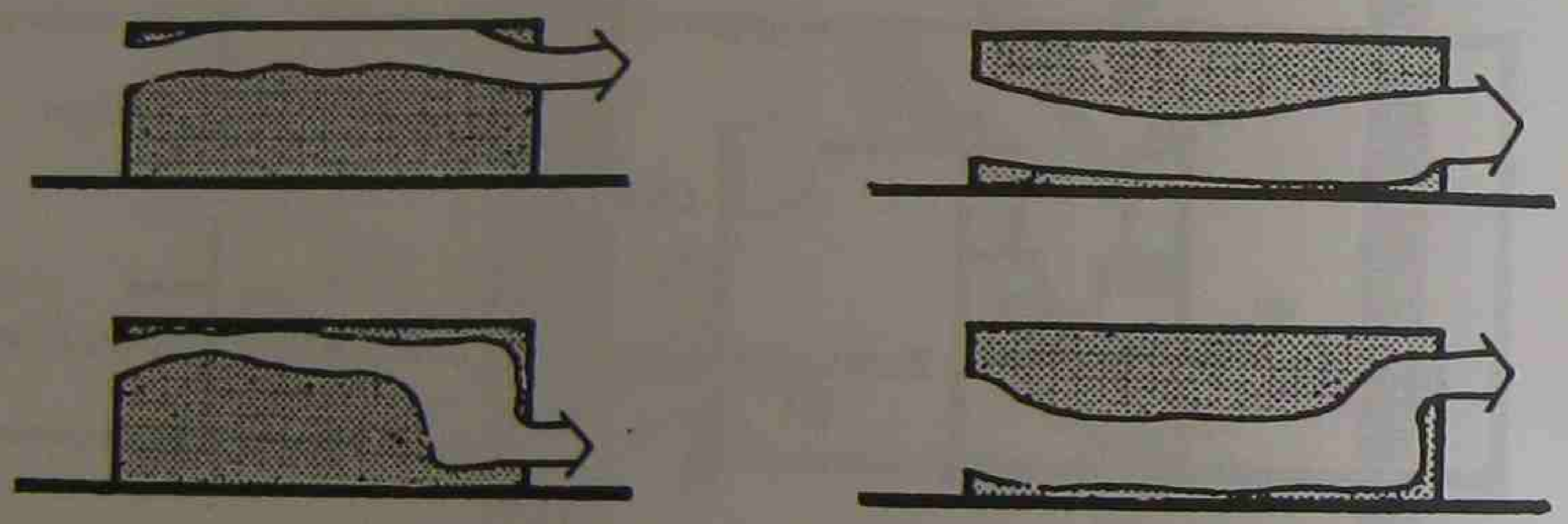


Figure 28 - Cross ventilation air flow distributions for differently positioned openings. (Source: Szokolay, 1980).

In order to get sufficient air flow the area of the openings on each side should be at least 20% of the wall area. Outlets should be about 25% larger than the inlets.

If verandahs are used on the windward side then they should be insulated and left open to make sure that the inlet air is not heated as it passes through.

The type of windows used effects both infiltration and air flow. Aluminium windows are generally manufactured to a greater sealing tolerance than wooden windows because they do not warp and jam as the humidity and temperature changes.

Figure 29 shows a variety of window types. The vertical sliding windows, usually referred to as double hung windows, only allow a maximum of half of the area to be opened. They do however give a choice of high or low level ventilation opening. The high level position can be used in wet weather if it is protected by eaves.

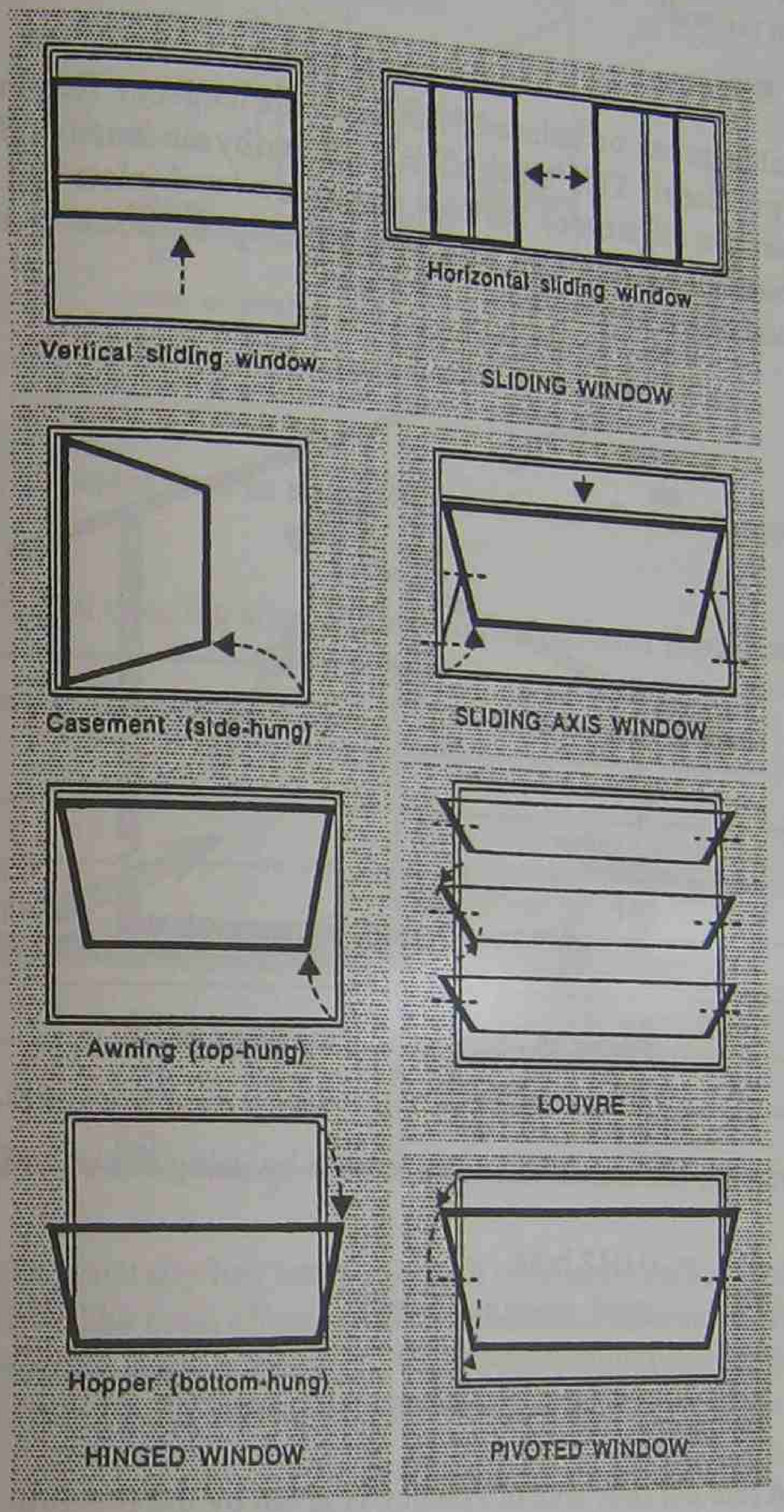


Figure 29 - A range of window types. (Source: CSIRO - Notes on the Science of Building).

Awning or top hung hinged windows can also be left slightly open in rainy weather. There is a limit to how far these windows can be opened which is a disadvantage when trying to capture low speed breezes.

Louvre windows do not seal well and therefore should be used with caution in cool to cold climates. They do however allow virtually unimpeded cross ventilation and can be used successfully in warm humid climates.

Casement or side hung hinged windows, and in particular sliding axis windows which can be opened in either direction are effective in capturing breezes coming from more acute angles to the wall.

3.5.2 Stack Effect

Air flow in buildings can be induced by utilising the tendency for warm air to rise and be displaced by cooler air. This "stack effect" is driven by air density difference (resulting from air temperature difference). Suitably placed low level inlets and high level outlets induce air movement when the air inside the building is warmer than outside. This is shown schematically in Figure 30.

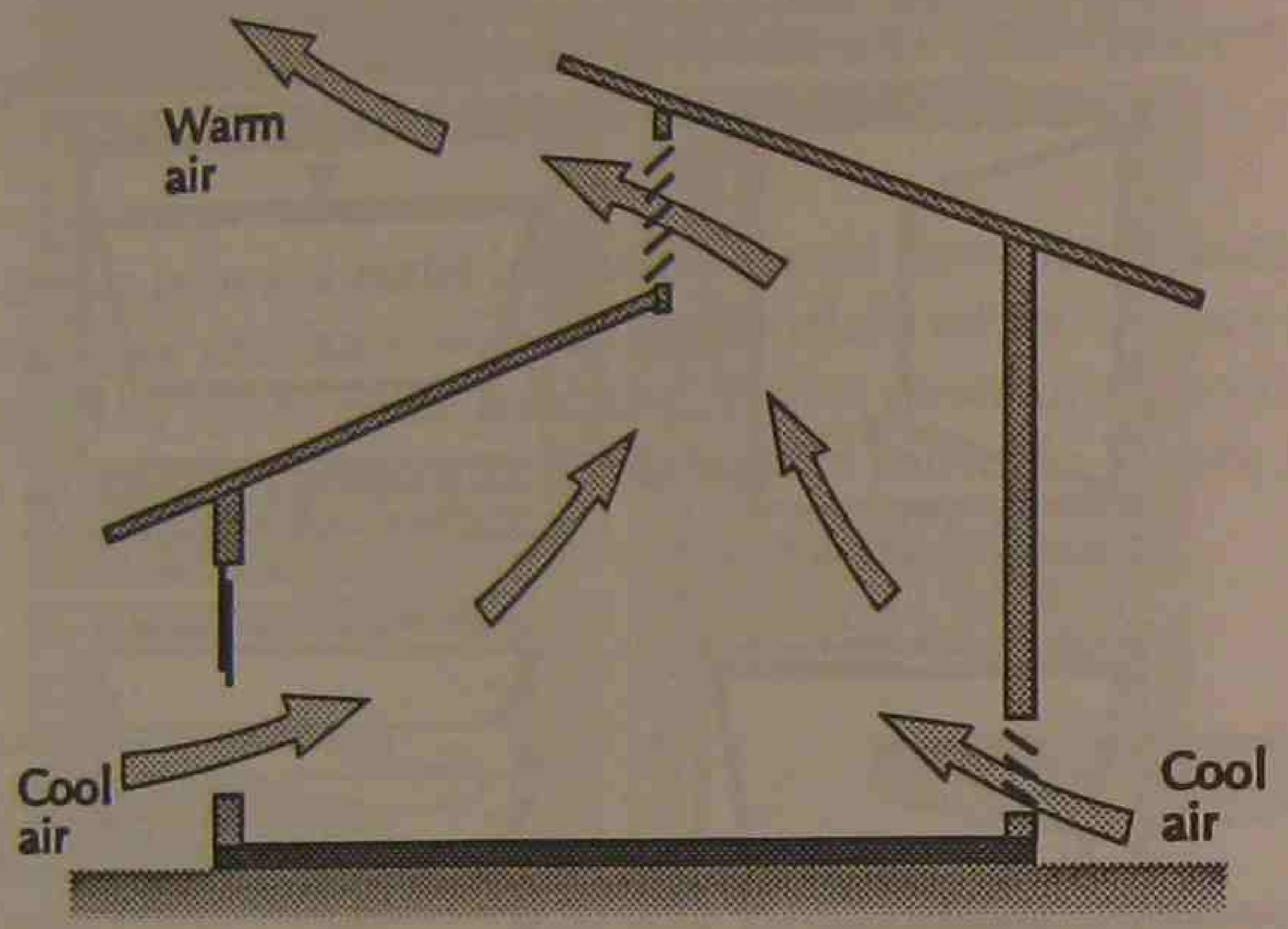


Figure 30 - Schematic of the stack effect.

Stack effect pressure difference can be calculated by using the equation

$$P_s = 0.042.h.\Delta t$$

where P_s - stack pressure (N/m^2)
h - height of stack (m)
Δt - temperature difference ($t_i - t_o$) (^oC)

The ventilation rate per unit area of opening is given by the formula:

$$V = 0.117\,A.h.\Delta t \quad (m^3/sec/m^2)$$

where V - ventilation rate per unit air (m^3/sec)
A - Area of inlet (m^2)
h - height of stack (m)
Δt - temperature difference (^oC)

Figure 31 shows the parameters required for stack effect calculations.

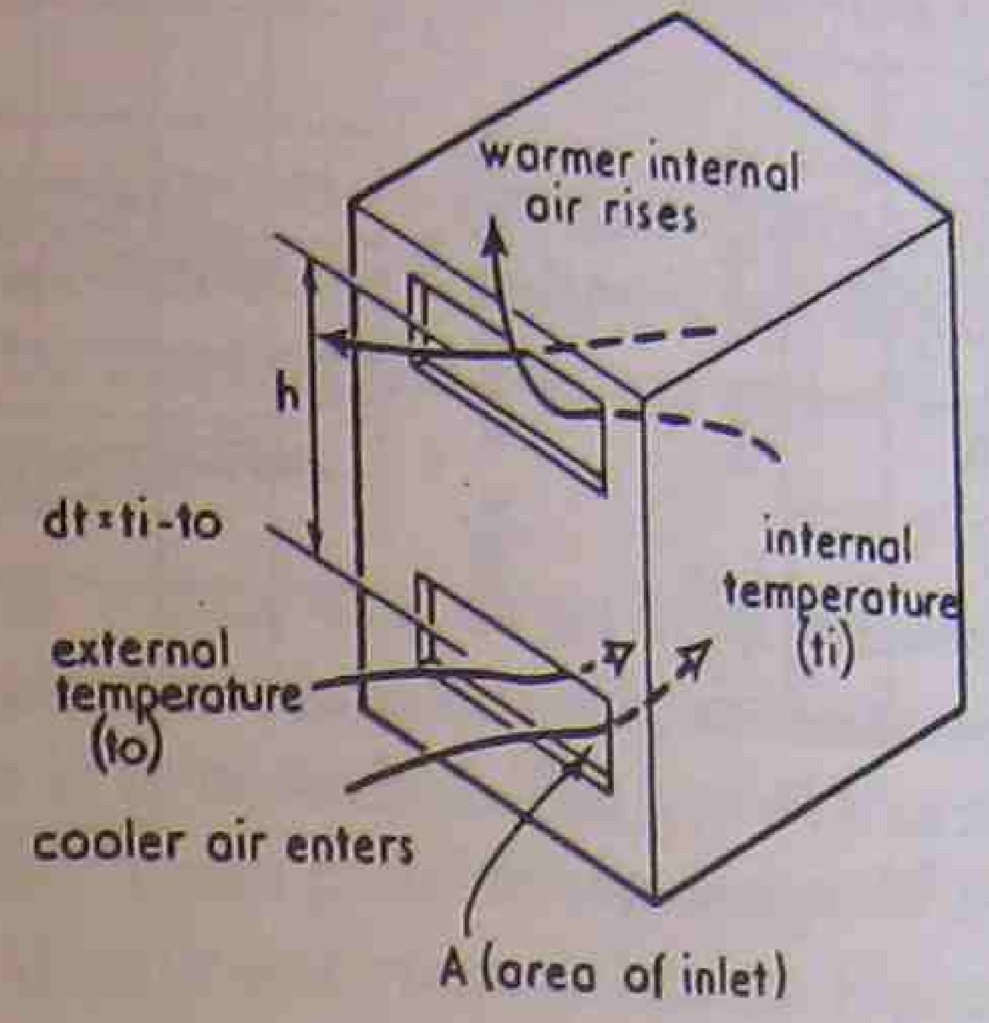


Figure 31 - Variables used for stack effect calculations. (Source: Evans, 1980).

Where inlet and outlet opening sizes differ, a correction factor should be applied to V:

Area outlet/inlet ratio	Correction Factor
5	1.38
4	1.37
3	1.33
2	1.26
1	1.0
0.75	0.84
0.5	0.63

These air flows are generally low compared with wind pressure induced air movement, so the stack effect will be most effective in still conditions. As wind movement increases it will tend to override stack ventilation. Where the design incorporates chimneys to exploit the effect, wind pressures may be less dominating.

3.5.3 Fans

Mechanical fans are useful for removing cooking odours, for removing the build-up of hot air, for cooling down the structural mass of a building at night, or for providing the air movement required for thermal comfort of the occupants in hot weather. Exhaust fans pull air in from outside the building while ceiling and wall mounted fans circulate the air within the building. The use of both exhaust and circulating fans ensures that the "coolth" stored in the structural mass the night before is effectively distributed into the building.

Ceiling mounted fans require ceiling heights of at least 3 m so that the blades are at least 2.2 m above the floor. Wall mounted fans are not as effective over as broad an area as ceiling fans but can be directed to provide personalised comfort. The spatial effectiveness of these two fan types is shown in Figure 32.

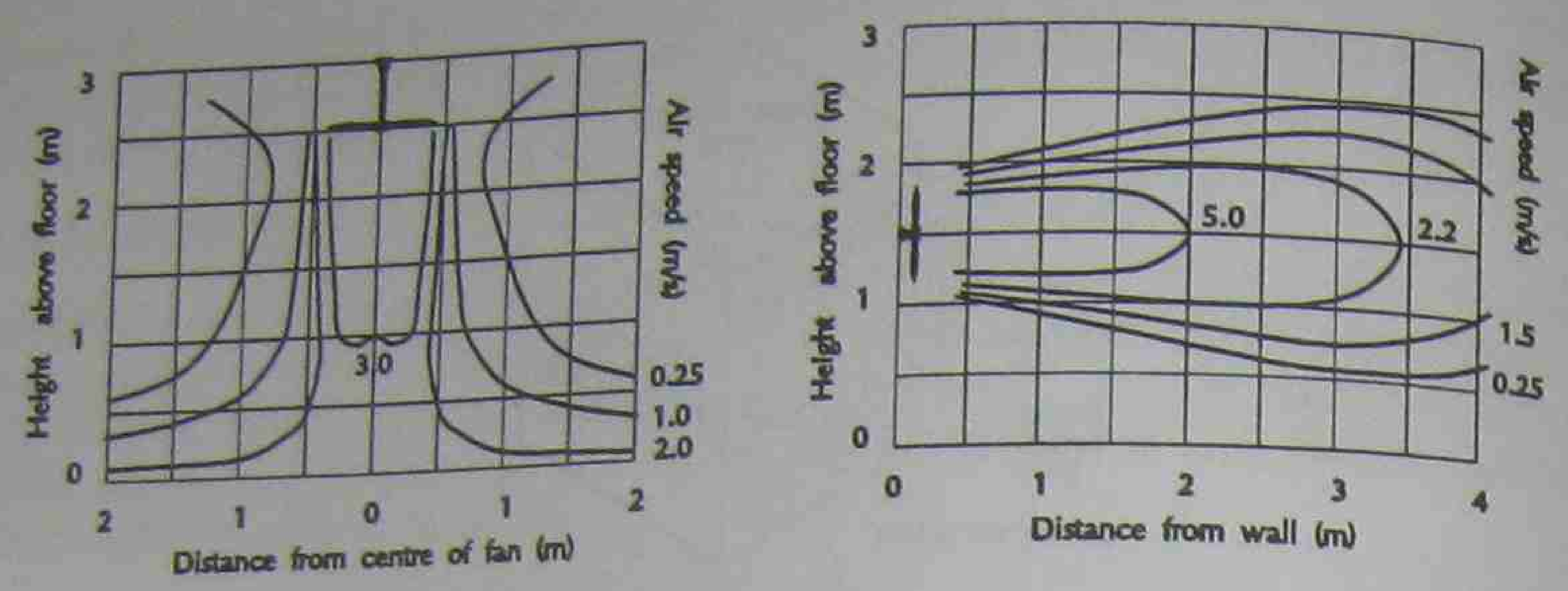


Figure 32 - Air movement caused by fans. (a) Ceiling fan. (b) Wall fan. (After Ballanger, 1992).

3.6 Internal Spatial Zoning

The internal division of a house depends on the number of occupants and their lifestyles. Most houses can be subdivided into living, sleeping, service and connecting zones. Formal internal arrangements may separate the kitchen from the living area making it part of the service zone along with bathrooms, laundry and storage spaces. Informal lifestyles tend to have occupants using the kitchen as part of the living area which often incorporates the lounge, dining and family rooms of the formal house in an open plan arrangement. The "formal" house is well represented in the older housing stock while many modern houses favour the "open plan".

The living zone, which could include a study or studio is used mainly during the day and should be oriented to provide the best advantage for solar access or breezes, depending on the climate and the strategies to be used to attain comfort for the occupants. In temperate regions this orientation would be towards the north, while in hotter parts of Australia it would be in the direction of prevailing breezes.

Bedrooms can afford to be cooler than the rest of the house and can be placed on the south side of the building. An exception might be bedrooms used by children as playrooms during the day. In hotter more humid climates it is important to have cooler conditions in bedrooms at night in order to be able to sleep. Here design to achieve good cross ventilation through the bedrooms is important.

Two storey houses offer a way of making good use of a small site. They can be made narrower than single level buildings having the same floor area. This makes it easier to provide solar access to most rooms and facilitates the provision of cross ventilation. Thermal stratification occurs in these buildings, making the upstairs part hotter than downstairs. In order to get rid of this heat when it is not required, good upstairs ventilation is essential. These buildings usually have the sleeping areas upstairs and the living and services area on the ground floor. This arrangement keeps the living area cooler than it would be in a single level house.

Service areas such as the toilet, laundry and bathroom are not used as often as the living or sleeping area. These wet areas have ventilation requirements that are considerably greater than the rest of the house and are often fitted with permanent vents. Consequently they can be grouped together on the southern or western side of the building. Internal doors from this area should be weather sealed to prevent air infiltration into the rest of the house.

Many modern buildings incorporate a garage or have a carport nearby. If this vehicle space is located on the west end of the building it will help to protect the rest of the house from the afternoon sun by shading the western end of the building or by providing a relative still air space as insulation.

If heating is necessary in winter and direct solar gain through windows needs to be supplemented then a decision needs to be made as to whether the whole house, the living area or just a single room is to be heated. The heated area should be able to be sealed off from the rest of the house. "Open plan" living designs will require more supplementary energy for heating than if only one room is heated. Higher levels of insulation and the use of "air locks" in the entrances of "open plan" houses may offset the apparent increase in heating this type of house.

Buildings in hot humid climates may use a different approach to that suggested above. The overriding design factor for this climate relates to adequate cross ventilation. A long building incorporating a row of single banked rooms with verandahs on all sides and oriented towards cool breezes may provide the best solution.

3.7 Daylighting and Glare

Good access to daylight contributes to the non-thermal comfort of the occupants of a building. Glare, caused by a sharp contrast in light intensity is a source of discomfort. Effective daylighting is a balance of adequate light without glare and without too much solar heat gain when it is not wanted.

Sunlight entering a building comes via three paths:

- ☐ directly from the sun,
- ☐ diffused by the atmosphere and arriving almost isotropically from the sky dome,
- ☐ reflected by the ground or some other object.

Glare can be produced when strong sunlight is incident on a highly reflecting surface such as glass, water, light coloured paving, walls or floor coverings, or even by the top of louvres designed to keep direct sunlight out of the building. Grass or other vegetative ground cover will reduce glare from the ground. Shading the glare producing area with trees or vines can also be effective in reducing these reflections.

Daylight penetration into a building through large windows is effective to a depth of about four metres. Good natural lighting further into the building can be achieved with the use of high-set windows like the ones shown in Figure 30. Alternatively skylights or light tubes can be used provided that glare or excess solar gain in summer and heat loss in winter will not be a problem. In climates where verandahs are used to exclude the sun, and the windows are only large enough to allow effective ventilation, daylighting can be a problem unless the rooms are single banked.

Unit 9

Design and Assessment Tools

1 INTRODUCTION

There are various design and assessment tools available to consultants working in the field of energy efficient building design. They range from rule of thumb type systems, through steady state models to full blown dynamic modelling of multizoned buildings. Some of the simpler systems allow hand calculations, but most use computers.

2 PRE-DESIGN TOOLS

Pre-design tools may be used broadly within predefined climatic zones. They are of value for making "ball park" decisions for designers unfamiliar with thermal considerations of buildings in general or with designing for a particular climatic zone. Australian examples are TECTO , SOLAREXPERT and MAHONEY TABLES.

Expert systems are computer programs which attempt to capture the experience of experts in a particular field. They deal with "rules of thumb" which allow strategic decisions to be made in the absence of the type of detailed information required for full simulations of performance. Only two programs which offer limited "expert system" type advice on predesign, TECTO and the computerised Mahoney tables in ARCHIPAK have been commercially available in Australia. TECTO has been withdrawn from sale. Figure 1 shows a page from the design manual compiled using the results of program TECTO. The use of Mahoney tables is limited to tropical areas.

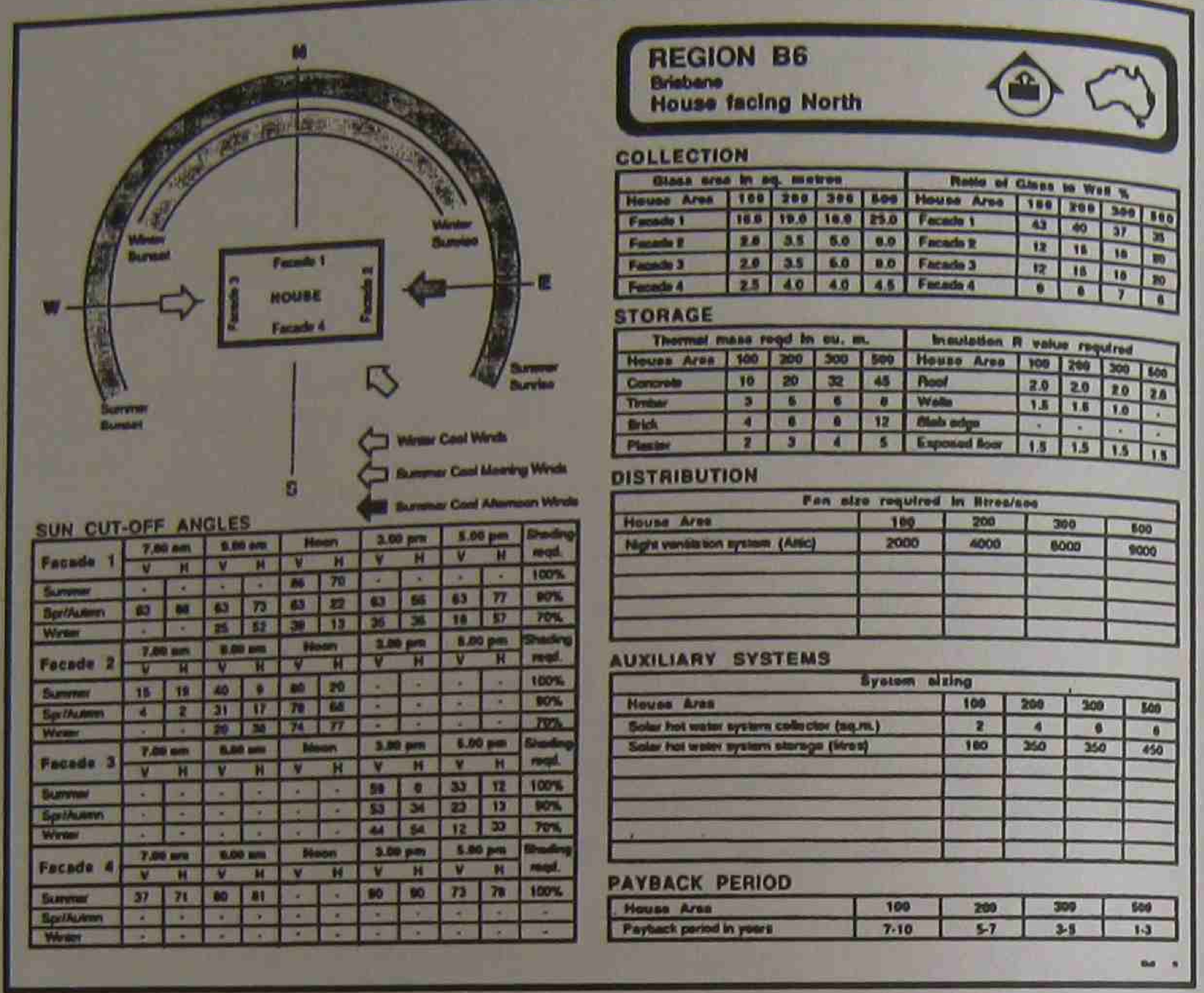
SOLAREXPERT is a prototype expert system to aid passive solar designers dealing with domestic buildings. It presents knowledge in a structured way which was obtained mainly from "The Passive Solar Energy Book" by Mazria, 1979, an American text, with some Australian modifications to the "rules of thumb" given for North American conditions. It uses an icon driven graphics interface to select geographic location, and to input the building floor plan, simple zoning within the building, sunlight obstructions to the building, and building lot shape and dimensions. A significant drawback to most uses of SOLAREXPERT is that it can only be used on a Sun workstation running UNIX with a licensed version of Quintus Prolog.

3 HOME ENERGY RATING SYSTEMS (HERS)

Most home energy rating systems are based on many simulations using sophisticated thermal modelling tools. They can then be applied to a limited set of building types within particular climatic zones.

Home energy rating schemes seek to compare energy consumption rates of houses which may be different in design, construction materials and techniques, of different solar orientation and fitted with a variety of different heating, cooling, lighting and hot water systems and other energy consuming appliances. Many HERS address only a subset of the above mentioned energy consumption such as the thermal efficiency of the building envelope, or the energy efficiency of heating, cooling, lighting and domestic appliances in an existing home.

It is important to rate buildings at the design stage so that the owner, builder or designer can get early feedback which can be incorporated into a more energy efficient design.



REGION B6
Brisbane
House facing North

COLLECTION

Glass area in sq. metres					Ratio of Glass to Wall %				
House Area	100	200	300	500	House Area	100	200	300	500
Facade 1	16.0	19.0	16.0	25.0	Facade 1	43	40	37	35
Facade 2	2.0	3.5	6.0	8.0	Facade 2	12	15	18	20
Facade 3	2.0	3.5	6.0	8.0	Facade 3	12	15	18	20
Facade 4	2.5	4.0	4.0	4.5	Facade 4	6	6	7	8

STORAGE

Thermal mass reqd in cu. m.					Insulation R value required				
House Area	100	200	300	500	House Area	100	200	300	500
Concrete	10	20	32	45	Roof	2.0	2.0	2.0	2.0
Timber	3	5	6	8	Walls	1.5	1.5	1.0	-
Brick	4	6	8	12	Slab edge	-	-	-	-
Plaster	2	3	4	5	Exposed floor	1.5	1.5	1.5	1.5

DISTRIBUTION

Fan size required in litres/sec				
House Area	100	200	300	500
Night ventilation system (Attic)	2000	4000	6000	9000

AUXILIARY SYSTEMS

System sizing				
House Area	100	200	300	500
Solar hot water system collector (sq.m.)	2	4	6	6
Solar hot water system storage (litres)	180	350	350	450

PAYBACK PERIOD

House Area	100	200	300	500
Payback period in years	7-10	5-7	3-5	1-3

SUN CUT-OFF ANGLES

Facade 1	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd.
	V	H	V	H	V	H	V	H	V	H	
Summer	-	-	-	-	86	70	-	-	-	-	100%
Spr/Autumn	63	88	63	73	63	22	63	66	63	77	90%
Winter	-	-	25	52	39	13	36	36	18	57	70%

Facade 2	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd.
	V	H	V	H	V	H	V	H	V	H	
Summer	15	19	40	9	80	20	-	-	-	-	100%
Spr/Autumn	4	2	31	17	78	68	-	-	-	-	90%
Winter	-	-	29	38	74	77	-	-	-	-	70%

Facade 3	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd.
	V	H	V	H	V	H	V	H	V	H	
Summer	-	-	-	-	-	-	58	0	33	12	100%
Spr/Autumn	-	-	-	-	-	-	53	34	23	13	90%
Winter	-	-	-	-	-	-	44	54	12	33	70%

Facade 4	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd.
	V	H	V	H	V	H	V	H	V	H	
Summer	37	71	80	81	-	-	90	90	73	78	100%
Spr/Autumn	-	-	-	-	-	-	-	-	-	-	-
Winter	-	-	-	-	-	-	-	-	-	-	-

Figure 1 - A typical page from the TECTO derived manual, "Low energy building in Australia". (Source: Baverstock and Paolino, 1986).

3.1 GMI Five Star Design Rating

The Five Star Design Rating program (FSDR) was released in 1985 by the Glass, Mass and Insulation Council of Australia (GMI). The GMI manual presents detailed guide lines on the design and construction of affordable energy efficient homes while the Five Star Design award is the result of a certification procedure which aims to assist builders to market energy efficient home designs which pass a certain standard. It is not a rating system as such because there is only a single award, (a design either passes or fails) unlike the appliance energy "star" rating system where the number of "stars" represents efficiency. The FSDR has been adopted in Tasmania, South Australia, Victoria and NSW. The present status of the FSDR is "dormant".

The design evaluation criteria are applied to five distinct climatic regions typified by the climates of Adelaide, Hobart, Melbourne, Sydney and Wagga. Within each climatic zone, four different construction types are considered:

- ❑ concrete slab floor with framed external walls, various levels of internal masonry
- ❑ concrete slab floor with full masonry walls
- ❑ timber floor with framed external walls, various levels of internal masonry
- ❑ timber floor with full masonry walls

Computer simulations were performed with the program ZSTEP3 (now incorporated into CHEETAH) by the CSIRO Division of Building Research.

As a result a series of graphs were drawn for each construction type which are used to determine if the degree of summer discomfort in the building is less than 180 degree hours at 6°C above the preferred temperature for each locality. A typical appraisal graph is shown in Figure 2. This evaluation is based on the level of northern glazing given as a percentage of the floor area of rooms with north facing windows, in relation to the internal thermal mass of those rooms.

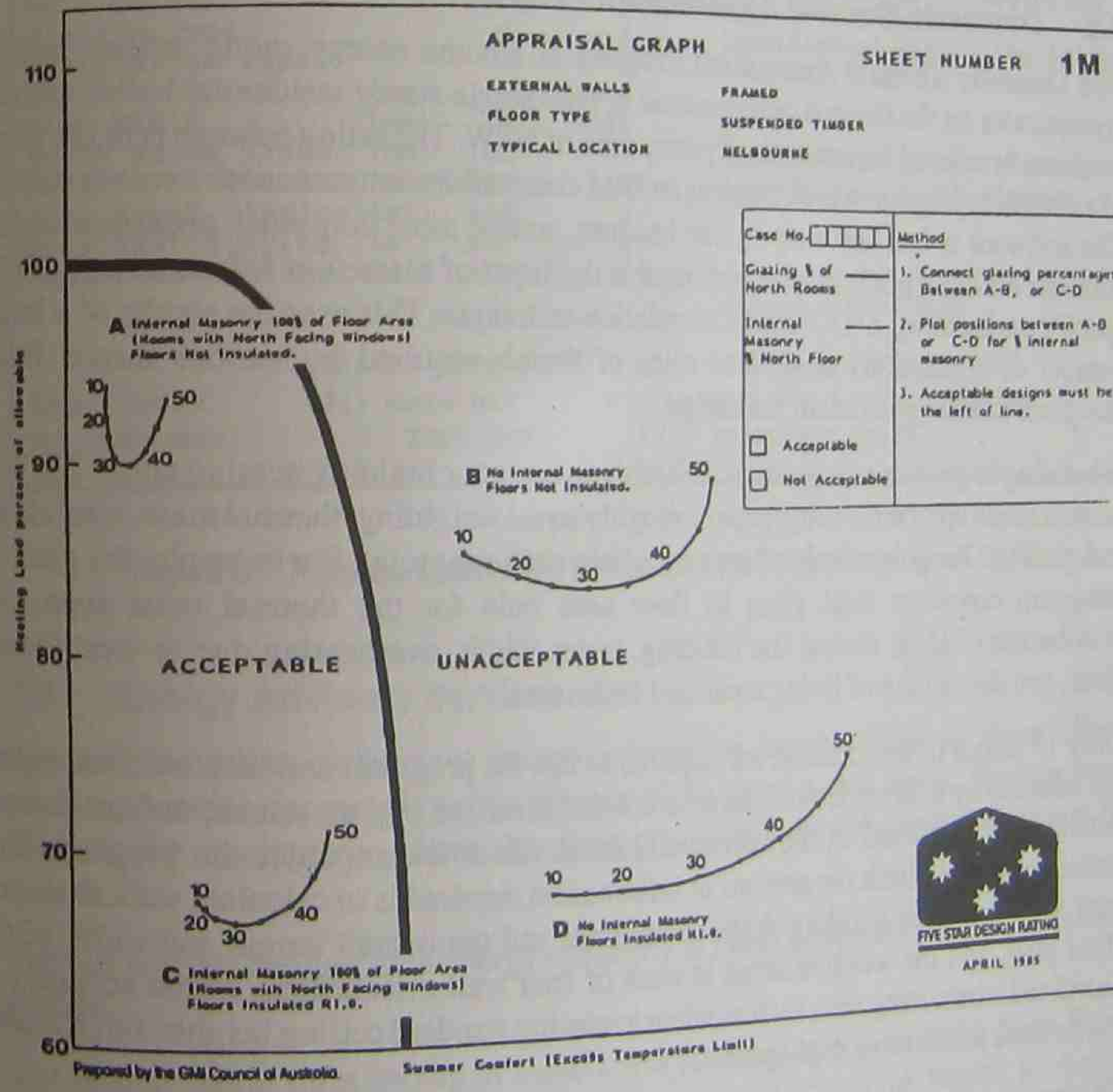
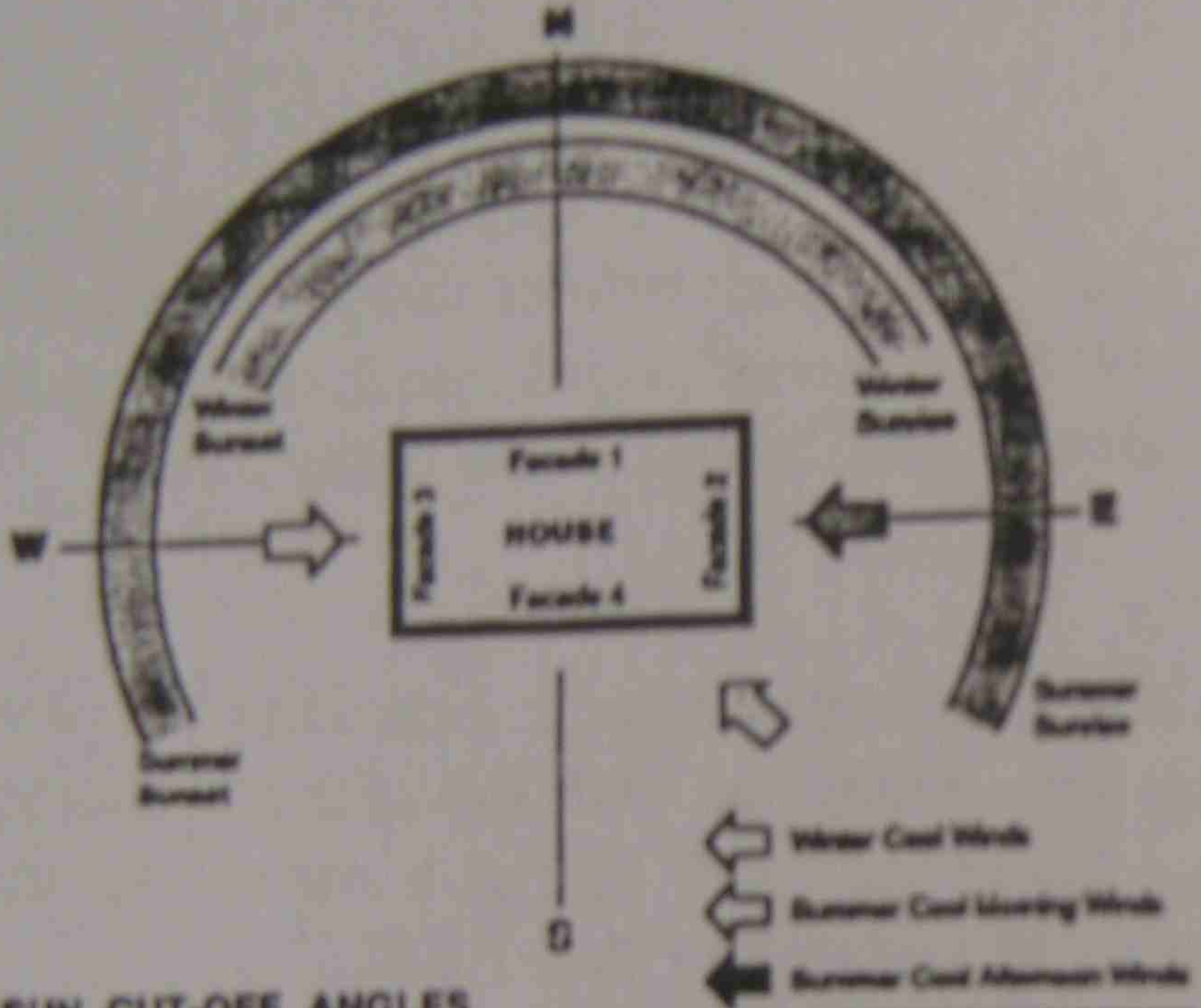


Figure 2 - FSDR appraisal graph for determining if a particular design is acceptable for a Melbourne type climatic zone. (Source: GMIC, 1985).



REGION B6

Brisbane

House facing North

COLLECTION

Glass area in sq. metres					Ratio of Glass to Wall %				
House Area	100	200	300	500	House Area	100	200	300	500
Facade 1	16.8	19.8	16.8	25.0	Facade 1	43	40	37	35
Facade 2	2.8	3.5	5.0	6.0	Facade 2	12	15	18	20
Facade 3	2.8	3.5	5.0	6.0	Facade 3	12	15	18	20
Facade 4	2.5	4.0	4.0	4.5	Facade 4	9	8	7	8

STORAGE

Thermal mass reqd in cu. m.					Insulation R value required				
House Area	100	200	300	500	House Area	100	200	300	500
Concrete	10	20	30	45	Roof	2.5	2.5	2.5	2.5
Timber	3	5	6	8	Walls	1.5	1.5	1.5	-
Brick	4	6	8	12	Slab edge	-	-	-	-
Plaster	2	3	4	5	Exposed floor	1.5	1.5	1.5	1.5

DISTRIBUTION

Fan size required in litres/sec				
House Area	100	200	300	500
Night ventilation system (Attic)	2000	4000	6000	9000

AUXILIARY SYSTEMS

System sizing				
House Area	100	200	300	500
Solar hot water system collector (sq.m.)	2	4	6	8
Solar hot water system storage (litres)	180	300	300	370

PAYBACK PERIOD

House Area	100	200	300	500
Payback period in years	7-10	5-7	3-5	1-2

SUN CUT-OFF ANGLES

Facade 1	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd
	V	H	V	H	V	H	V	H	V	H	
Summer	-	-	-	-	86	70	-	-	-	-	100%
Spr/Autumn	63	66	63	73	63	22	63	56	63	77	90%
Winter	-	-	25	52	38	13	25	36	16	57	70%

Facade 2	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd
	V	H	V	H	V	H	V	H	V	H	
Summer	15	19	40	9	60	20	-	-	-	-	100%
Spr/Autumn	4	2	31	17	78	68	-	-	-	-	90%
Winter	-	-	20	36	74	77	-	-	-	-	70%

Facade 3	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd
	V	H	V	H	V	H	V	H	V	H	
Summer	-	-	-	-	-	-	58	6	33	12	100%
Spr/Autumn	-	-	-	-	-	-	53	34	23	13	90%
Winter	-	-	-	-	-	-	44	54	12	33	70%

Facade 4	7.00 am		9.00 am		Noon		3.00 pm		5.00 pm		Shading reqd
	V	H	V	H	V	H	V	H	V	H	
Summer	37	71	80	61	-	-	90	90	73	79	100%
Spr/Autumn	-	-	-	-	-	-	-	-	-	-	-
Winter	-	-	-	-	-	-	-	-	-	-	-

As well, the house must satisfy each of the following:

- ☐ ceiling insulated to Australian Standard AS2627 - Part 1.
- ☐ external walls to be insulated to at least R1.0
- ☐ window to have internal covering with R ≥ 0.2
- ☐ door between living and sleeping zones and the outside to be weather stripped
- ☐ the largest living zone must have some north facing glass
- ☐ all north, east and west facing windows to have internal or external shading devices with SC ≤ 0.3
- ☐ the area of east, west and south glass not to exceed 15% of total floor area
- ☐ the area of east and west glass not to exceed 10% of the floor area of the rooms which contain them
- ☐ the area of west glass not to exceed 2% of total floor area
- ☐ upper floor of multi-storey houses to have no east or west glass

3.2 Domestic Thermal Assessment Program (DTAP)

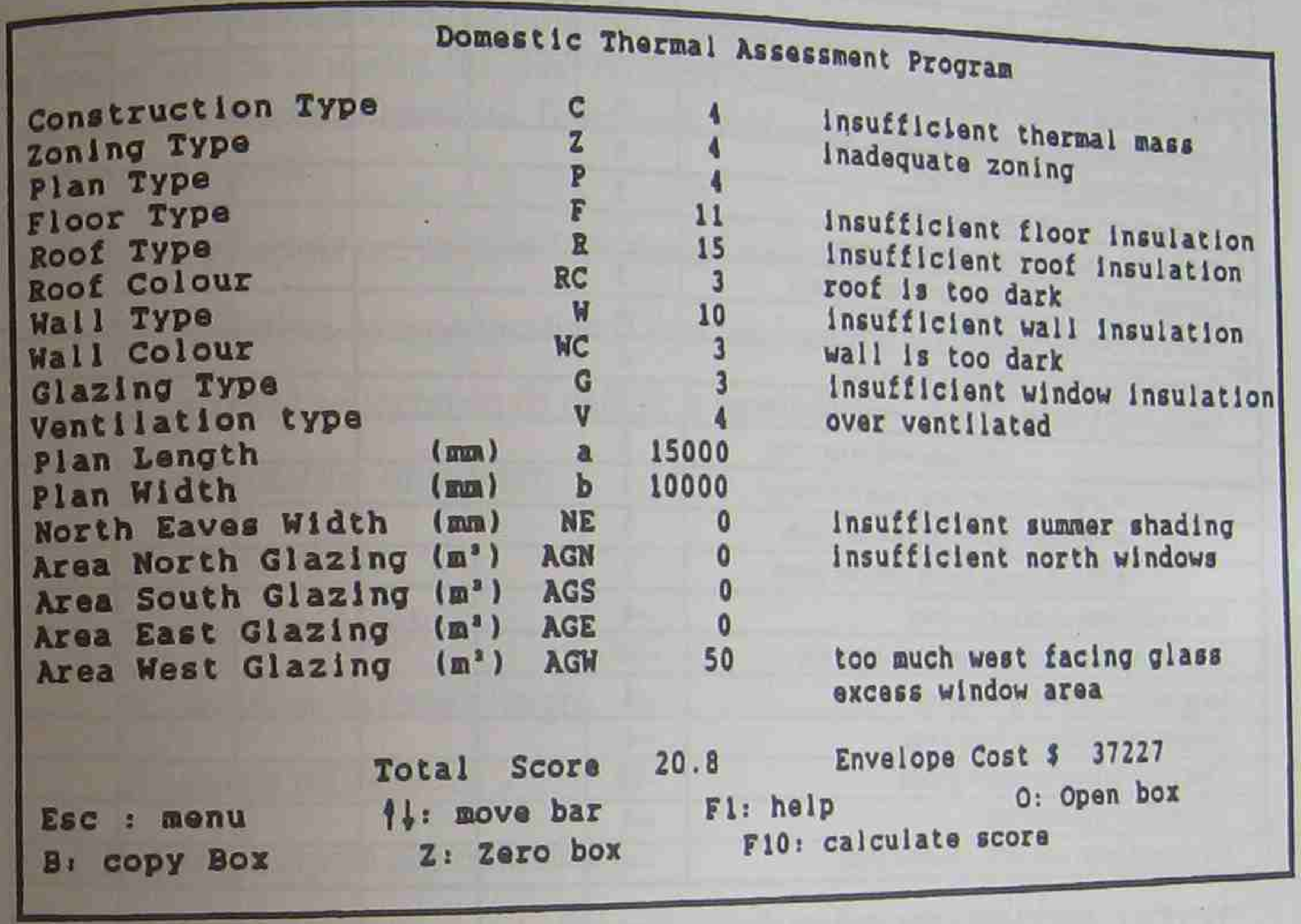
The Domestic Thermal Assessment Program is a home energy rating scheme which concentrates on the thermal performance of new single storey residential buildings and has been developed for use in the Sydney area of NSW. The rating scheme is in the form of a computer program which requires an IBM compatible computer with a colour screen. The software is fast and easy to use because, unlike most computer programs which simulate building performance and require the input of masses of information to fully specify the building, DTAP uses a correlation technique. This uses the results of a large number of simulations as well as rules of thumb acquired by various means from designers of energy efficient buildings.

A building is given a rating out of 100 with a very poor building scoring about 20. The score is made up of three subgroups of roughly equal weighting: thermal mass, insulation, and glazing. There is a further break up within each subgroup. For example, the glazing subgroup considers total glass to floor area ratio for the thermal mass type, the distribution of glass around the building, eaves width, overheating due to west facing glass, and the zoning of living areas and bedrooms.

Only 17 pieces of information are required to run the program, and most of these inputs are selected by number from a list on a context sensitive pop up screen, or from a more detailed list contained in the software manual which accompanies the program. One technique used to limit the amount of information required is to calculate wall, floor and roof areas from the building shape group code and the overall length and width of the floor plan, and the window areas in each of four wall orientations. Some accuracy is sacrificed when doing this, such as when assuming standard ceiling heights, but it makes the process much more manageable.

The input and output takes place on a single screen. Inputs are : construction type (ranges from full brick with slab on ground to stud walls with timber floor), internal zoning, plan shape and (2) dimensions, floor type (11 options), roof type (15 options) and colour, wall type (10 options) and colour, glazing type, air (draught) tightness, eaves width, and glazing areas of each (of 4) wall orientations. As well as the thermal rating score the program provides feedback on any inputs that are considered to be thermally inadequate.

Changing any one entry will not dramatically affect the overall performance. Large changes in performance will only occur as a result of several changes in design. Consequently it is possible to include some aspects of design which may not be considered desirable but can be compensated for by paying careful attention to other design aspects. The approximate cost of the building envelope is also calculated. This is based on local costs and must be updated periodically. A typical input/output screen is shown in Figure 3.



```
                    Domestic Thermal Assessment Program

Construction Type                 C       4     insufficient thermal mass
Zoning Type                       Z       4     inadequate zoning
Plan Type                         P       4
Floor Type                        F      11     insufficient floor insulation
Roof Type                         R      15     insufficient roof insulation
Roof Colour                      RC       3     roof is too dark
Wall Type                         W      10     insufficient wall insulation
Wall Colour                      WC       3     wall is too dark
Glazing Type                      G       3     insufficient window insulation
Ventilation type                  V       4     over ventilated
Plan Length         (mm)          a   15000
Plan Width          (mm)          b   10000
North Eaves Width   (mm)         NE       0     insufficient summer shading
Area North Glazing  (m²)        AGN       0     insufficient north windows
Area South Glazing  (m²)        AGS       0
Area East Glazing   (m²)        AGE       0
Area West Glazing   (m²)        AGW      50     too much west facing glass
                                                excess window area

                    Total  Score   20.8         Envelope Cost $  37227
Esc : menu          ↑↓: move bar       F1: help            O: Open box
B: copy Box           Z: Zero box        F10: calculate score
```

Figure 3 - A typical input/output screen from the correlation program DTAP.

3.3 Energy Advisory Services

Several Australian states have energy information centres. Some of these offer an advisory service for people in the process of designing a new home. The assessment tends to be qualitative, where the plans are brought in and discussed, rather than quantitative.

Various leaflets dealing with energy efficiency in house design are available from these centres.

The design rating form shown in Table 1 was produced by the Victorian Solar Energy Council and distributed by Energy Victoria to enable new home buyers to compare potential purchases from a solar efficient design perspective.

		HOUSES INSPECTED				
DIRECTIONS: Give each house a design rating up to its maximum value, then total the scores (adding or subtracting as the case may be) for each house and compare designs.	Design rating	1	2	3	4	5
* Insulation in ceiling (other than foil)	13					
* Insulation in walls (other than foil)	7					
☐ Reflective foil insulation under roof	4					
● Reflective insulation in walls	3					
* Living areas mainly in north side	10					
● Utility rooms mainly on south or west sides	3					
* Windows to living areas protected from summer sun	8					
☐ Concrete slab floor	8					
● 50/50 concrete/timber floor	2					
● Brick, block or stone walls inside	6					
* Windows and internal doors placed to give quick cross-ventilation on cool summer nights	5					
* Weathershields to external doors	4					
☐ Draftseals to windows of living areas	2					
● Draftseals to internal doors of toilet, laundry	2					
☐ Damper/draft control device for open fireplace	3					
☐ Doors to close off heated areas	4					
☐ Curtains/Blinds have pelmets or top cover	4					
TREES AND SHRUBS: ☐ Shade windows in summer	4					
● Shade walls in summer	2					
● Shade outdoor living areas in summer	2					
● Provide break to cold winter winds	2					
● Provide break to hot summer winds	2					
Shade living area windows in winter	–6					
Unshaded east or west windows to living areas	–10					
Large east or west facing windows	–6					
Skylights over kitchen or living areas	–6					
Glass roofs to living or sleeping areas	–10					
Timber floor to living areas	–4					
Permanent open wall vents in heated areas	–4					
TOTAL DESIGN RATING						

* Essential
☐ Important
● Desirable

Houses with a rating below 55 are not Solar Efficient Designs.

Table 1 - Home Buyers Checklist - "The Solar Angle".
(Source: Victorian Solar Energy Council).

4 COMPUTER TOOLS FOR CALCULATING INDIVIDUAL ASPECTS OF SOLAR BUILDING DESIGN

A number of tools exist which are useful for calculating certain aspects of a solar efficient design, without providing a full thermal analysis. Some of the functions of these tools include calculating :

- sun shading by adjacent buildings and trees
- solar energy falling on surfaces of arbitrary slope and orientation

- solar energy penetration through windows
- effect of sun shading devices
- heat loss coefficients, or U-values of building elements
- cost benefit analysis of insulation and thermal mass .

Examples of these kinds of tools are the software programs RAD, SOLPOS, UVAL and RADTEMP.

A separate users manual is included in this teaching package for these programs.

4.1 Program RAD

Program RAD calculates daily radiation totals on planes of arbitrary tilt and orientation. An option which is useful for solar efficient building design is the calculation of daily irradiation of vertical surfaces fitted with horizontal sun breaks such as walls with overhanging eaves.

The following inputs are required for shaded walls or windows:

- radiation data or location if data has been entered previously
- ground reflectance (if default is unsuitable)
- orientation of surface
- eaves width
- window height
- window to eaves height
- eaves reflectance .

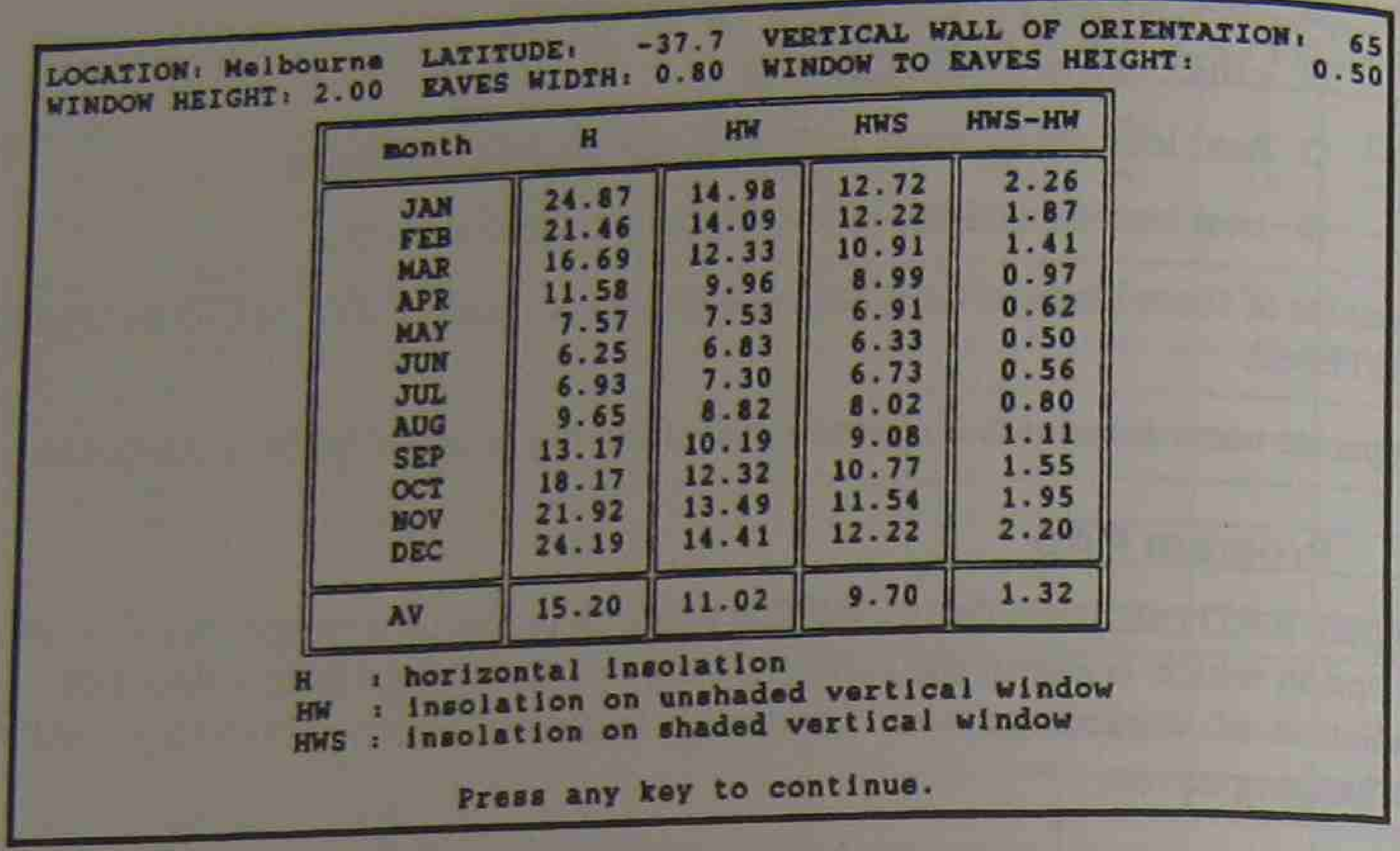
The following outputs are obtained:

- daily radiation totals for each month on the horizontal plane
- daily radiation totals for each month on the arbitrary plane
- daily radiation totals for each month on the arbitrary vertical plane as modified by a horizontal shading device
- the non-reflective surface option will also display sunrise and sunset times for the earth as well as for the plane .

All data can be displayed:

- displayed in table form
- displayed as a histogram
- displayed as a polygon
- printed or saved for use in other programs .

Figures 4 and 5 show typical output screens for RAD.



```
LOCATION: Melbourne  LATITUDE:    -37.7  VERTICAL WALL OF ORIENTATION:  65
WINDOW HEIGHT: 2.00  EAVES WIDTH: 0.80   WINDOW TO EAVES HEIGHT:      0.50

              month        H        HW       HWS    HWS-HW

               JAN      24.87    14.98    12.72     2.26
               FEB      21.46    14.09    12.22     1.87
               MAR      16.69    12.33    10.91     1.41
               APR      11.58     9.96     8.99     0.97
               MAY       7.57     7.53     6.91     0.62
               JUN       6.25     6.83     6.33     0.50
               JUL       6.93     7.30     6.73     0.56
               AUG       9.65     8.82     8.02     0.80
               SEP      13.17    10.19     9.08     1.11
               OCT      18.17    12.32    10.77     1.55
               NOV      21.92    13.49    11.54     1.95
               DEC      24.19    14.41    12.22     2.20

               AV       15.20    11.02     9.70     1.32

           H   : horizontal insolation
           HW  : insolation on unshaded vertical window
           HWS : insolation on shaded vertical window

                    Press any key to continue.
```

Figure 4 - Tabulated output screen from program RAD.

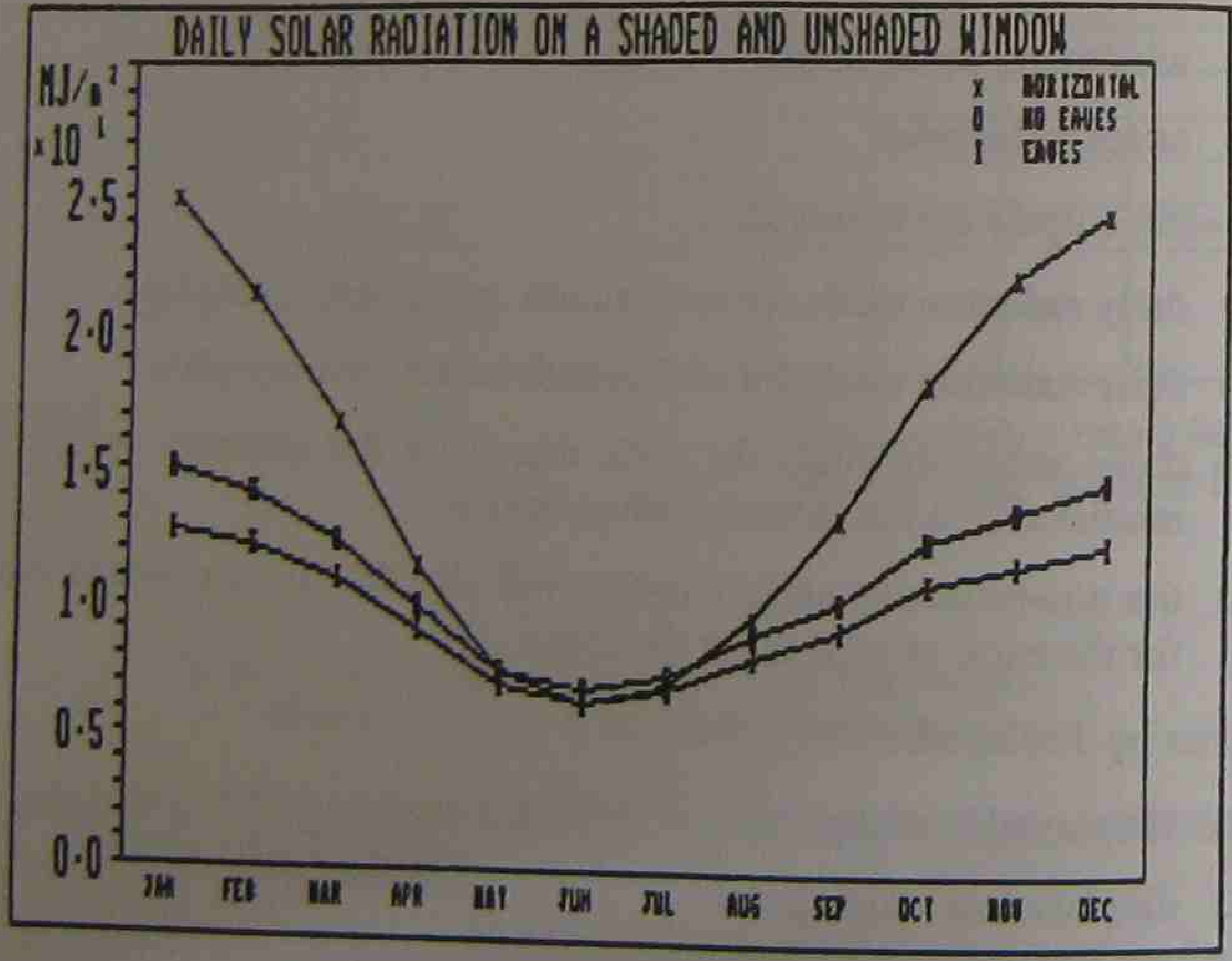
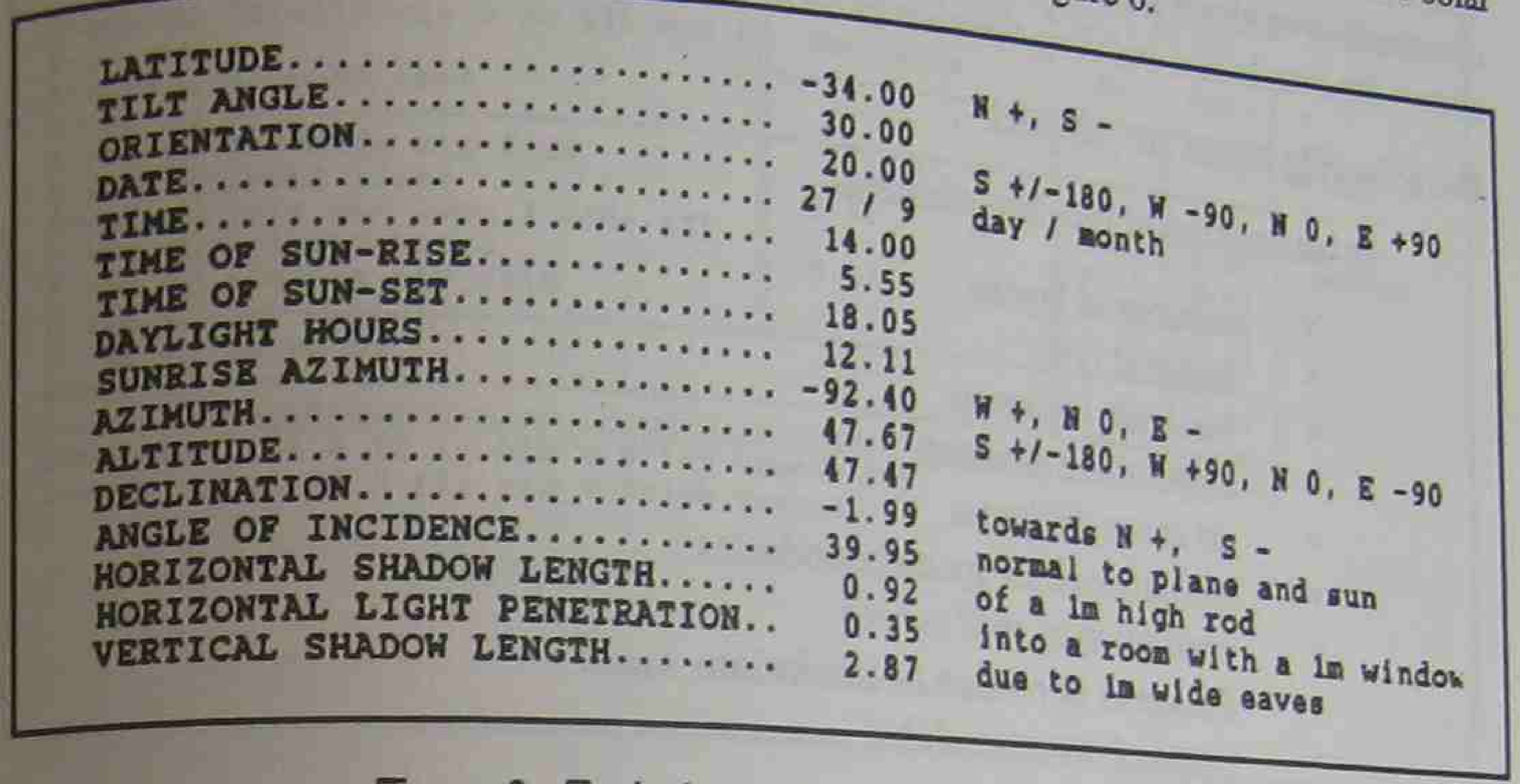


Figure 5 - Graphical output screen from program RAD.

4.2 Program SOLPOS

Program SOLPOS calculates geometric data relating to the position of the sun in the sky and its position relative to building surfaces. The calculation of the penetration of sunlight into a building and the shadow length of eaves are of particular use to the solar building designer. A typical output screen is shown in Figure 6.



```
LATITUDE.....................  -34.00
TILT ANGLE...................   30.00   N +, S -
ORIENTATION..................   20.00
DATE.........................  27 / 9   S +/-180, W -90, N 0, E +90
TIME.........................   14.00   day / month
TIME OF SUN-RISE.............    5.55
TIME OF SUN-SET..............   18.05
DAYLIGHT HOURS...............   12.11
SUNRISE AZIMUTH..............  -92.40
AZIMUTH......................   47.67   W +, N 0, E -
ALTITUDE.....................   47.47   S +/-180, W +90, N 0, E -90
DECLINATION..................   -1.99
ANGLE OF INCIDENCE...........   39.95   towards N +,  S -
HORIZONTAL SHADOW LENGTH.....    0.92   normal to plane and sun
HORIZONTAL LIGHT PENETRATION..   0.35   of a 1m high rod
VERTICAL SHADOW LENGTH.......    2.87   into a room with a 1m window
                                        due to 1m wide eaves
```

Figure 6 - Typical output screen for program SOLPOS.

The following data must be entered into the program:

- ❑ latitude
- ❑ tilt angle of the illuminated plane
- ❑ orientation of the plane
- ❑ date
- ❑ time

The following calculations are made:

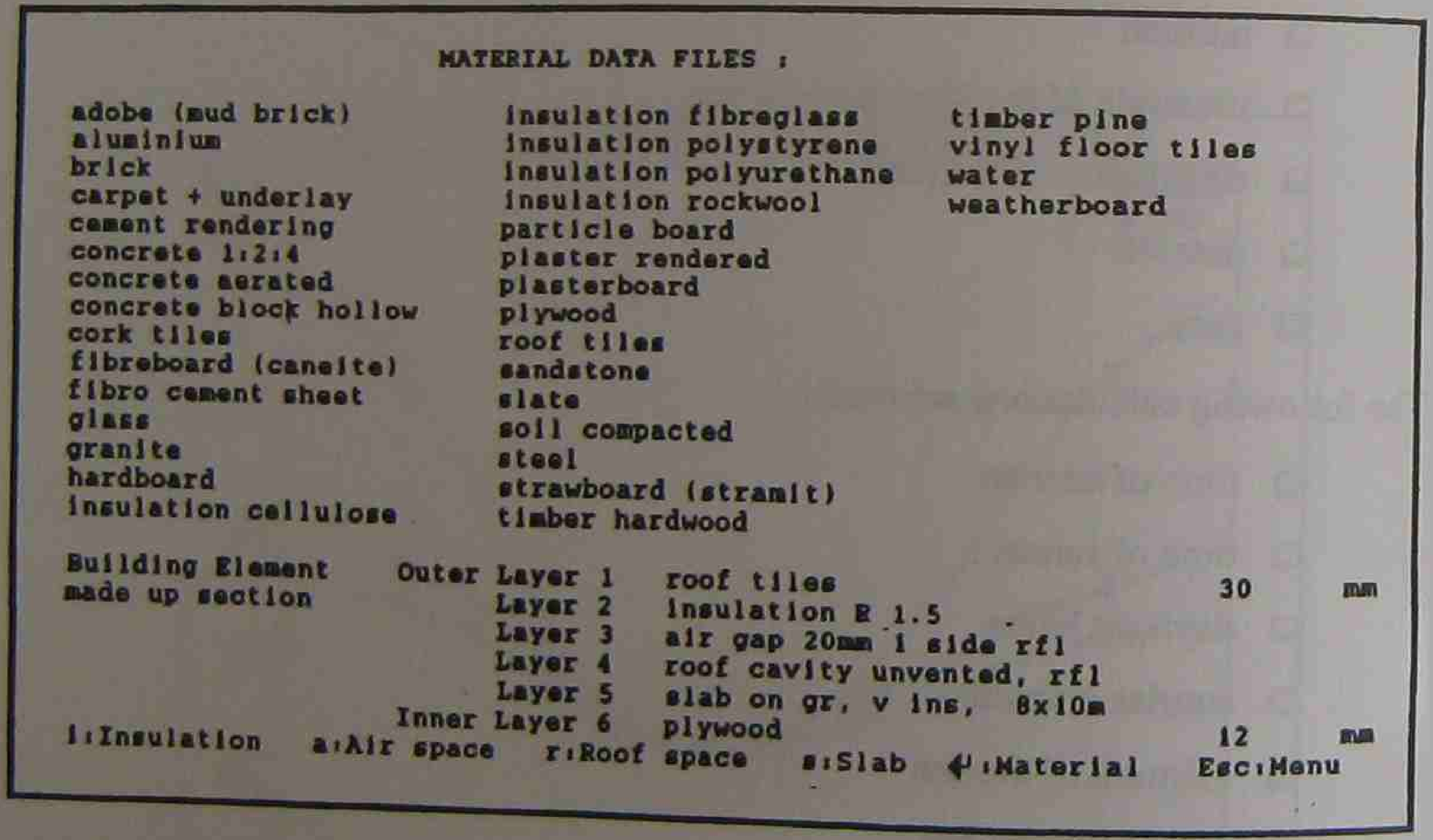
- ❑ time of sunrise
- ❑ time of sunset
- ❑ daylight hours
- ❑ sunrise azimuth
- ❑ azimuth of the sun
- ❑ altitude of the sun
- ❑ declination
- ❑ angle of incidence of the sun on the specified plane
- ❑ horizontal shadow length
- ❑ horizontal light penetration into a room
- ❑ vertical shadow length of eaves down a wall

4.3 Program UVAL

Program UVAL calculates summer and winter heat loss coefficients, or U-values for building elements. The program accesses files of properties of building materials to construct files of data for building elements. Figure 7 shows an input screen for the construction of these new building elements. Figure 8 shows a pop up screen which allows the details of a building element to be examined.

The following inputs are required:

- ☐ description of building elements
  - number of layers
  - material type
  - material thickness
  - slope of the element
  - air space thickness
  - emittance of air space boundaries
  - ventilation of roof spaces
  - thickness or r-value of insulation
  - shape of concrete slab
- ☐ description of new materials if not contained in data file

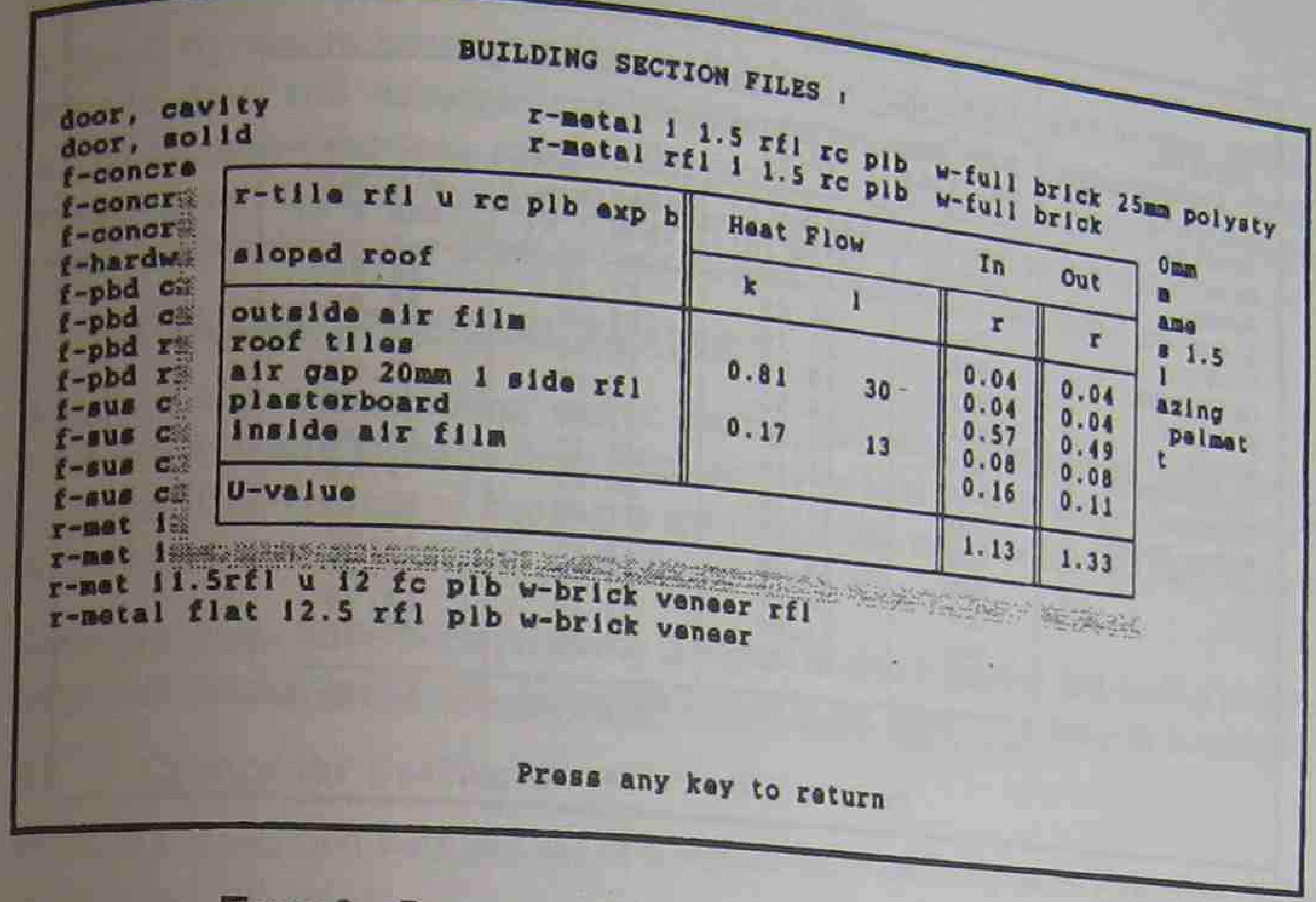


```
                          MATERIAL DATA FILES :

adobe (mud brick)          insulation fibreglass     timber pine
aluminium                  insulation polystyrene    vinyl floor tiles
brick                      insulation polyurethane   water
carpet + underlay          insulation rockwool       weatherboard
cement rendering           particle board
concrete 1:2:4             plaster rendered
concrete aerated           plasterboard
concrete block hollow      plywood
cork tiles                 roof tiles
fibreboard (caneite)       sandstone
fibro cement sheet         slate
glass                      soil compacted
granite                    steel
hardboard                  strawboard (stramit)
insulation cellulose       timber hardwood

Building Element     Outer Layer 1   roof tiles                          30      mm
made up section            Layer 2   insulation R 1.5
                           Layer 3   air gap 20mm 1 side rfl
                           Layer 4   roof cavity unvented, rfl
                           Layer 5   slab on gr, v ins,  8x10m
                     Inner Layer 6   plywood                             12      mm
i:Insulation   a:Air space   r:Roof space   s:Slab   ↵:Material   Esc:Menu
```

Figure 7 - Input screen used to "construct" a new building element in program UVAL.

The following outputs are obtained:

- ☐ summer and winter heat loss coefficients
- ☐ description of make up and properties of building elements contained in the data file



```
                        BUILDING SECTION FILES :
door, cavity
door, solid                  r-metal i 1.5 rfl rc plb  w-full brick 25mm polysty
f-concre                     r-metal rfl i 1.5 rc plb  w-full brick
f-concr  r-tile rfl u rc plb exp b | Heat Flow                 |
f-concr                            |                 In    Out | 0mm
f-hardw  sloped roof               |  k       l                | m
f-pbd c                            |                  r     r  | ame
f-pbd c  outside air film          |                           | s 1.5
f-pbd r  roof tiles                |                 0.04  0.04| l
f-pbd r  air gap 20mm 1 side rfl   | 0.81     30     0.04  0.04| azing
f-sus c  plasterboard              |                 0.57  0.49|  palmat
f-sus c  inside air film           | 0.17     13     0.08  0.08| t
f-sus c                            |                 0.16  0.11|
f-sus c  U-value                   |                           |
r-met i                                              1.13  1.33
r-met i
r-met i1.5rfl u i2 fc plb w-brick veneer rfl
r-metal flat i2.5 rfl plb w-brick veneer


                        Press any key to return
```

Figure 8 - Pop up screen showing the k, r, and U-value details of a building element in the program UVAL.

4.4 Program RADTEMP

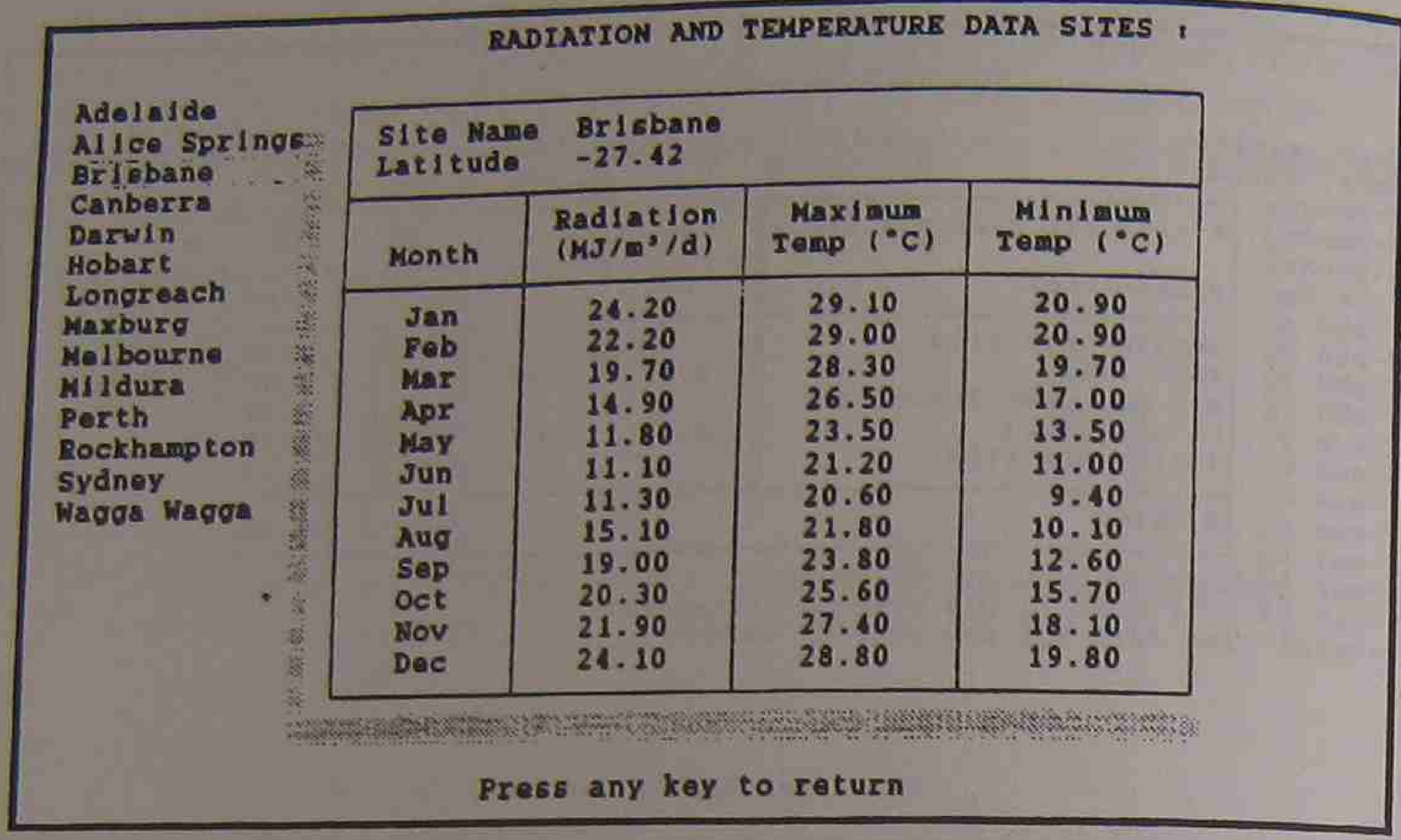
RADTEMP is a radiation and temperature data file handling program. Data can be displayed, added to, deleted or exported to other programs. Hourly data is synthesised from average daily totals for each month. Figure 9 shows the average monthly data held for one location. Figure 10 shows average hourly temperatures synthesised for the first half of a day.

The following information must be entered into the program:

- ☐ location name
- ☐ if new data is to be entered
  - location name and latitude
  - average daily global horizontal radiation and temperature data for each month.

The following outputs can be obtained:

- ☐ monthly radiation data
- ☐ monthly temperature data
- ☐ synthesised hourly data



RADIATION AND TEMPERATURE DATA SITES :

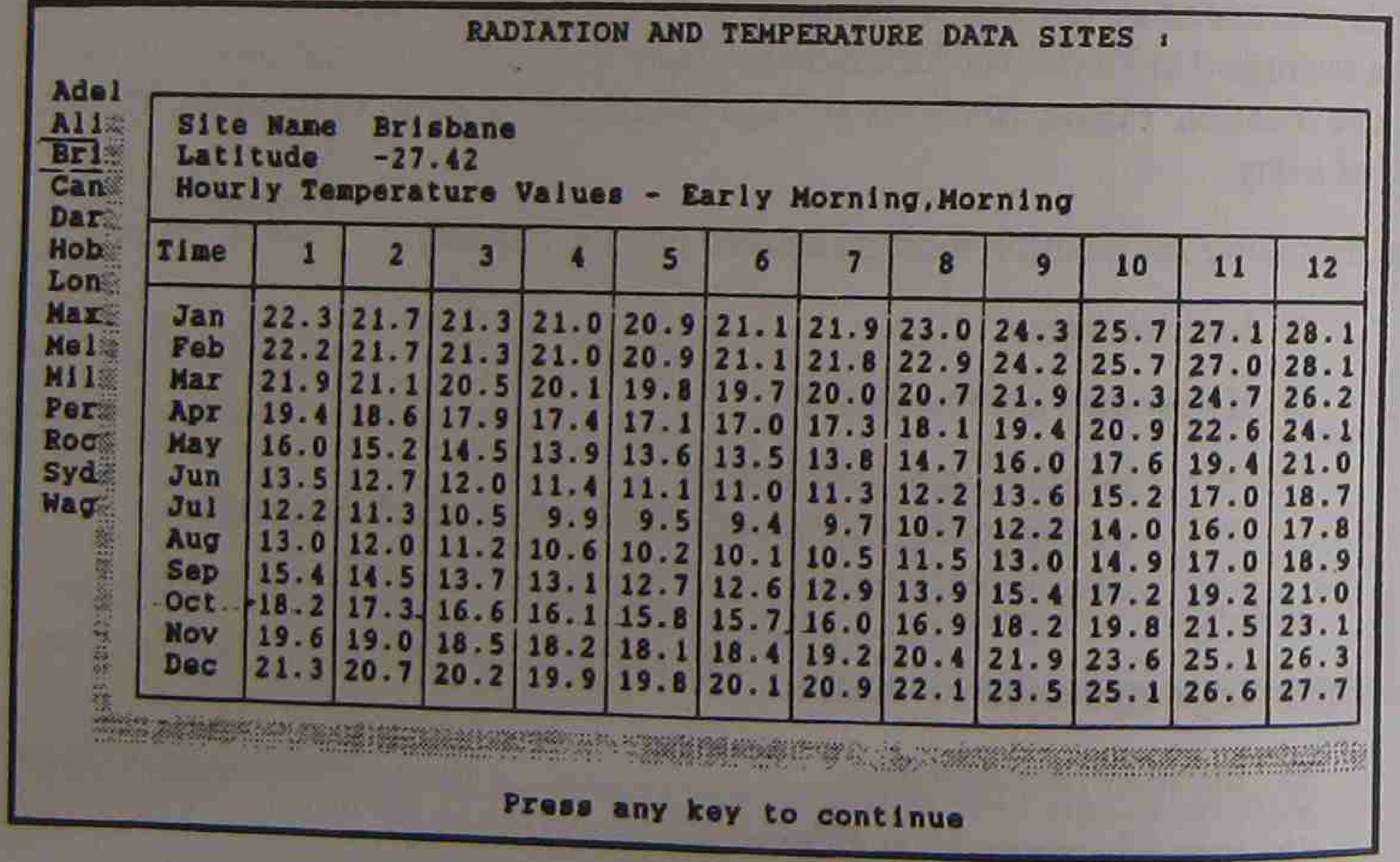
Adelaide
Alice Springs
Brisbane
Canberra
Darwin
Hobart
Longreach
Maxburg
Melbourne
Mildura
Perth
Rockhampton
Sydney
Wagga Wagga

Site Name Brisbane
Latitude -27.42

Month	Radiation (MJ/m³/d)	Maximum Temp (°C)	Minimum Temp (°C)
Jan	24.20	29.10	20.90
Feb	22.20	29.00	20.90
Mar	19.70	28.30	19.70
Apr	14.90	26.50	17.00
May	11.80	23.50	13.50
Jun	11.10	21.20	11.00
Jul	11.30	20.60	9.40
Aug	15.10	21.80	10.10
Sep	19.00	23.80	12.60
Oct	20.30	25.60	15.70
Nov	21.90	27.40	18.10
Dec	24.10	28.80	19.80

Press any key to return

Figure 9 - Average monthly data held for each location in the program RADTEMP.



RADIATION AND TEMPERATURE DATA SITES :

Adel
All
Bri
Can
Dar
Hob
Lon
Max
Mel
Mil
Per
Roc
Syd
Wag

Site Name Brisbane
Latitude -27.42
Hourly Temperature Values - Early Morning,Morning

Time	1	2	3	4	5	6	7	8	9	10	11	12
Jan	22.3	21.7	21.3	21.0	20.9	21.1	21.9	23.0	24.3	25.7	27.1	28.1
Feb	22.2	21.7	21.3	21.0	20.9	21.1	21.8	22.9	24.2	25.7	27.0	28.1
Mar	21.9	21.1	20.5	20.1	19.8	19.7	20.0	20.7	21.9	23.3	24.7	26.2
Apr	19.4	18.6	17.9	17.4	17.1	17.0	17.3	18.1	19.4	20.9	22.6	24.1
May	16.0	15.2	14.5	13.9	13.6	13.5	13.8	14.7	16.0	17.6	19.4	21.0
Jun	13.5	12.7	12.0	11.4	11.1	11.0	11.3	12.2	13.6	15.2	17.0	18.7
Jul	12.2	11.3	10.5	9.9	9.5	9.4	9.7	10.7	12.2	14.0	16.0	17.8
Aug	13.0	12.0	11.2	10.6	10.2	10.1	10.5	11.5	13.0	14.9	17.0	18.9
Sep	15.4	14.5	13.7	13.1	12.7	12.6	12.9	13.9	15.4	17.2	19.2	21.0
Oct	18.2	17.3	16.6	16.1	15.8	15.7	16.0	16.9	18.2	19.8	21.5	23.1
Nov	19.6	19.0	18.5	18.2	18.1	18.4	19.2	20.4	21.9	23.6	25.1	26.3
Dec	21.3	20.7	20.2	19.9	19.8	20.1	20.9	22.1	23.5	25.1	26.6	27.7

Press any key to continue

Figure 10 - Average hourly temperatures for a typical location synthesised from average daily data for each month by the program RADTEMP.

5 STEADY STATE THERMAL ANALYSIS

A month by month heating and/or cooling load is calculated using average monthly climatic data and accurate specifications of the building envelope and energy usage/occupant behaviour pattern. The energy audit is based on keeping the building within a given thermal comfort zone. The building is analysed as a single zone. This is covered in much greater detail in Unit 5 which is devoted to this topic.

6 DYNAMIC THERMAL ANALYSIS

A daily or monthly heating and/or cooling load may be calculated using real or synthesised hourly climatic data. Alternatively an hour by hour temperature profile is produced if no heating or cooling is specified. Some models allow the building to be divided into zones which may be analysed separately.

Some programs have been primarily designed to specify heating and cooling plant for large commercial buildings. These are generally not suitable for domestic buildings.

6.1 Computer Software

Problems associated with the use of computer software for dynamic thermal modelling include the following:

- ☐ A lot of the software is not commercially available.
- ☐ Much of the software was developed on mainframe computers and is either not available on PC's or the PC version is very difficult to use. This arises because of the limited data input facility inherited from the embedded mainframe core program language, usually FORTRAN.
- ☐ A lot of the software developed specifically for use in PC's is unsophisticated and not very user friendly. Lack of sufficient error trapping can be a major cause of frustration if programs "bomb out" regularly. "Bugs" which have not been ironed out or inadequate documentation of idiosyncrasies can waste a lot of time.
- ☐ Data input is often clumsy and time consuming. It is often difficult to make quick changes or to examine "what if" type cases.
- ☐ Data bases for climatic variables, materials or building elements are often fixed and can not be added to. This restricts the type and geographic location of the buildings which can be analysed.
- ☐ The building may be restricted in shape, size or to a single level.
- ☐ Documentation, if it exists may be inadequate.
- ☐ Assumptions made in the model may not be stated.
- ☐ Limitations of the model may not be stated.
- ☐ The source of the algorithms used may not be referenced.

The software most widely used seems to be TRNSYS from the USA, CHEETAH from the CSIRO and based on ZSTEP, TEMPER and BUNYIP from the CSIRO, CAMEL from the Department of Housing and Construction, and HARMON from the Queensland University Architecture Department. CAMEL and BUNYIP are primarily concerned with providing heating and cooling plant sizing information. TRANSYS was developed primarily to be able to model active solar buildings.

This leaves only CHEETAH, HARMON and TEMPER as readily available local products useful for dynamic thermal analysis of domestic buildings. All three give thermal performance based on real or synthesised hourly climatic data.

6.2 Program CHEETAH

This is probably the best known and most widely used thermal prediction software in Australia. It is available for IBM compatible machines but they must be fitted with a maths co-processor or the program will not run. The response factor method is used as the basis for calculations.

- The program can take quite a while to run if multizoned buildings are modelled for a whole year. A building may have up to 10 zones. Each zone may have up to 20 buildings sections.
- It uses real climatic data from only one particular year for any one of the seven locations. This data can not be changed or added to by the user.
- The building material data file can not be changed or added to. Building sections can be constructed by the user, but only a limited set can be used by any one simulation, e.g., only 4 different kinds of roof are available. This makes recalculation with new building sections time consuming.
- Heat losses or gains are strongly dependent on the direction of heat flow, however the program treats heat flow through roofs and floors as being the same in either direction.
- Shading devices for walls and windows can be modelled but the program assumes that the device is placed directly above or next to the window.
- Only buildings with walls that meet at right angles can be modelled.
- Areas of building sections must be calculated beforehand.
- The program would be more user friendly if it did not use a different way of entering information at almost every stage. However, error trapping seems to work without "bombing" the program. It is reasonably easy to use if the number of building zones is restricted.
- Output is provided in table or graph form. This can be viewed on screen or printed. Figures 11, 12, and 13 illustrate the three forms of graphic output available from CHEETAH.
- The manual provided is comprehensive. Built-in help screens are available while running the program.

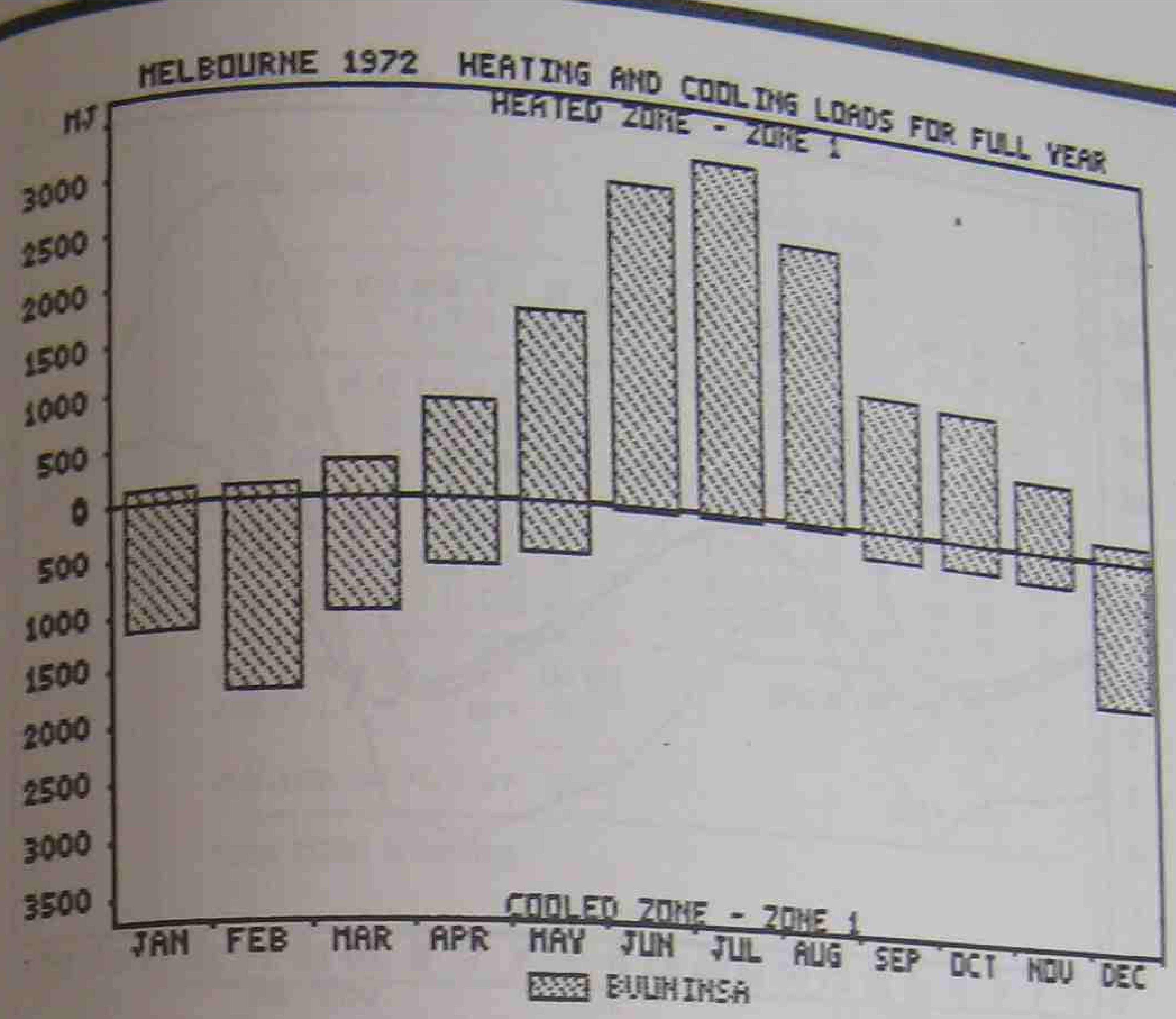


Figure 11 - Monthly heating and cooling energy requirements for a full year. Output from program CHEETAH.

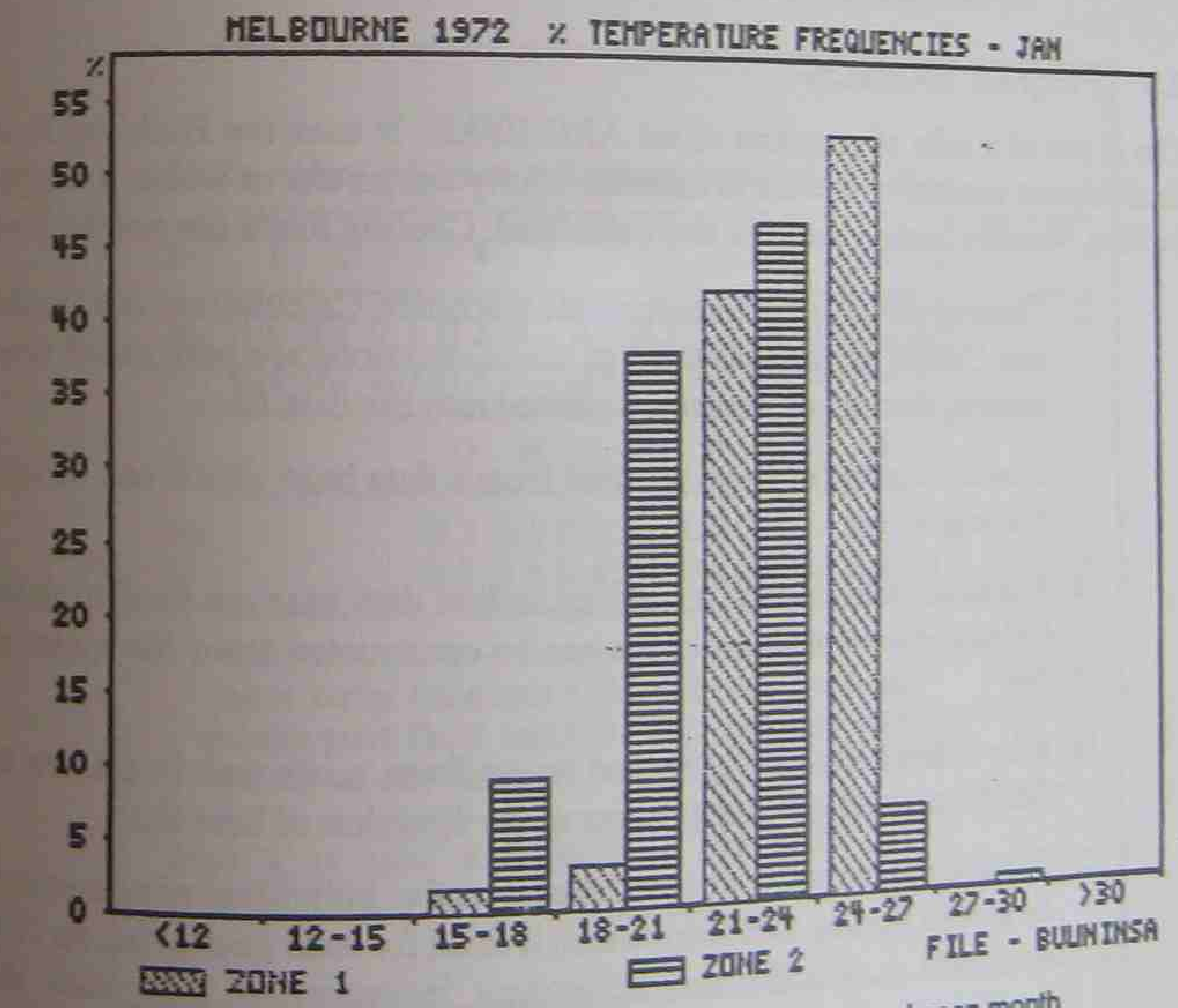


Figure 12 - Temperature frequency distribution for a chosen month. Output from program CHEETAH.

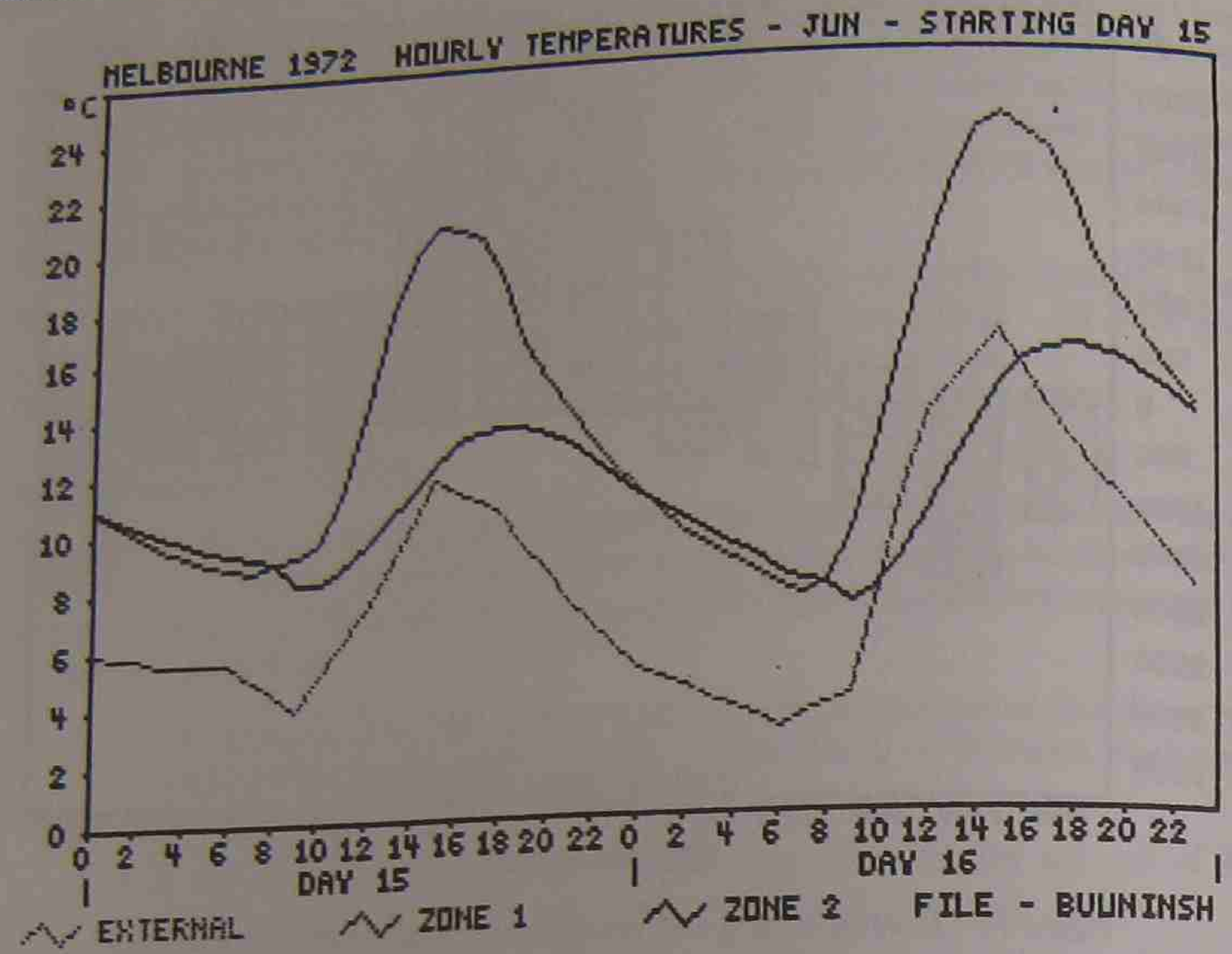
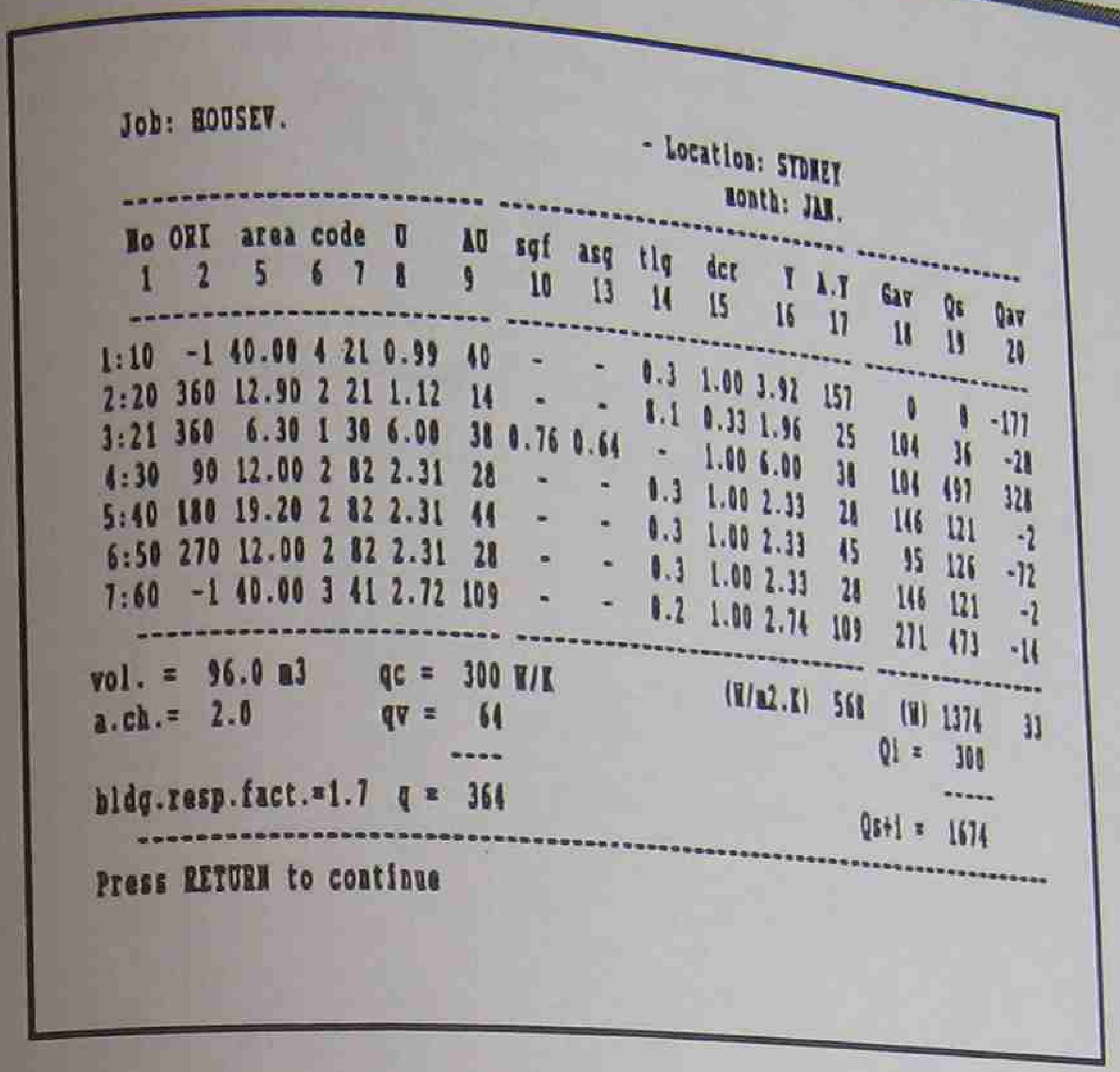


Figure 13 - Hourly temperatures over two days for two zones within a building compared to the external ambient temperature. Output from program CHEETAH.

6.3 Program HARMON

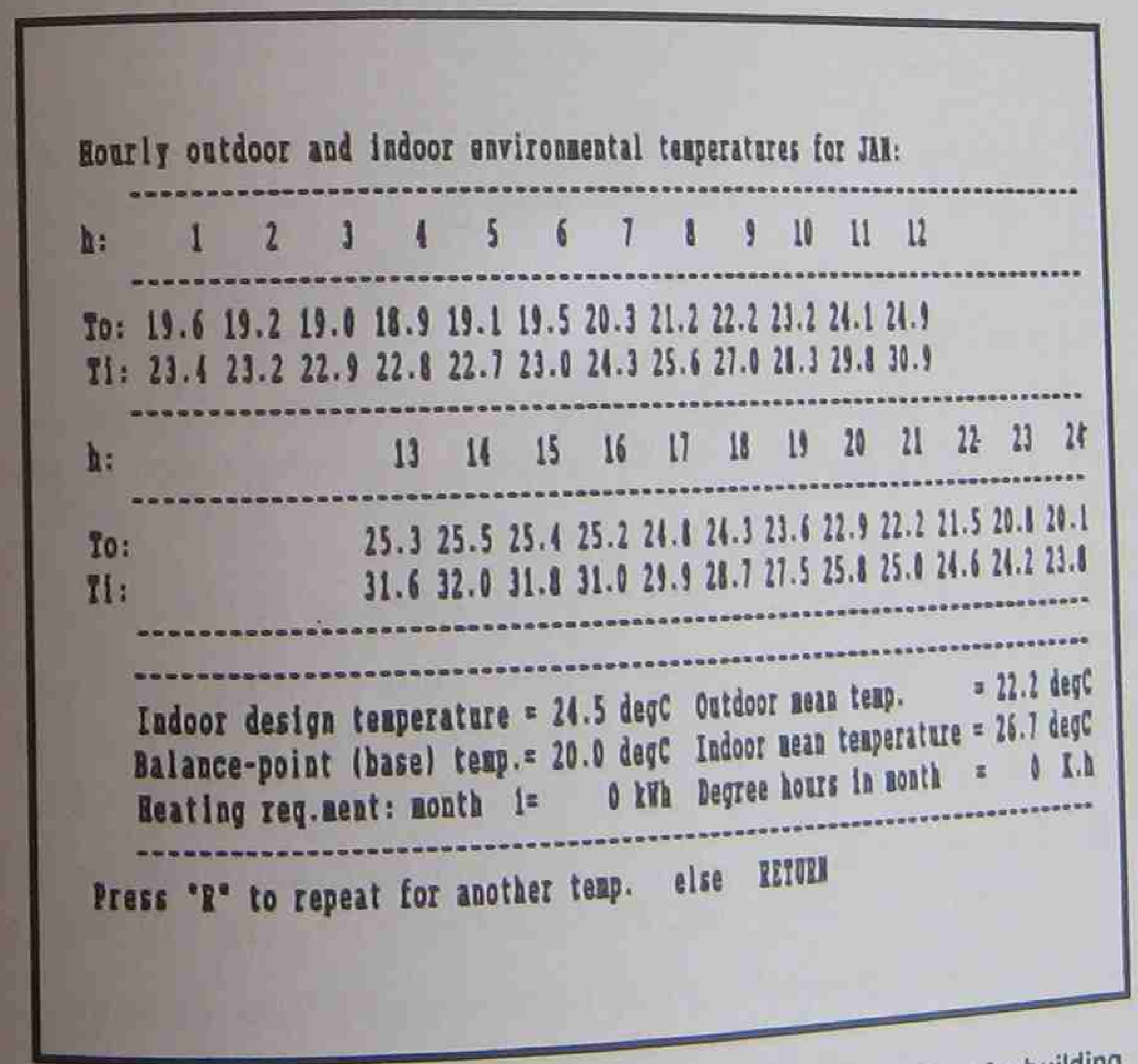
This is part of a suite of programs called ARCHIPAK. It uses the Building Research Establishment admittance method to calculate hourly temperatures within a single zone building. Monthly heating loads are also calculated. Cooling loads are not dealt with.

- ☐ The program runs on IBM compatible machines. Calculations are much faster than CHEETAH because some of the calculations are performed when the building element properties are entered into the data files.
- ☐ Monthly climatic averages are used from a data base which can be added to or changed.
- ☐ A material data base and a building section data base are used to define the building. New building sections can be constructed from the material data file.
- ☐ Like CHEETAH, heat gains and losses from roofs and floors are treated (incorrectly) as being independent of the direction of heat flow.
- ☐ Shading devices can not be modelled directly. Individual windows can only be given a shading coefficient which is fixed for each year's run, so 12 yearly runs with a pre-calculated adjustment incorporated into each shading coefficient corresponding to each month must be made to obtain a year's data. Angle of incidence effects for beam components of radiation on windows are not allowed for. Shading effects of eaves on walls are not considered.



```
Job: HOUSEV.
                                                   - Location: SYDNEY
                                                        month: JAN.
---------------------------- ---------------------------- ---------------
No ORI  area code  U     AU  sgf  asg  tlg  dcr    Y  A.Y   Gav   Qs   Qav
 1  2    5   6  7  8      9   10   13   14   15   16   17    18   19    20
---------------------------- ---------------------------- ---------------
1:10  -1 40.00 4 21 0.99  40    -    -  0.3 1.00 3.92  157     0    0  -177
2:20 360 12.90 2 21 1.12  14    -    -  0.1 0.33 1.96   25   104   36   -28
3:21 360  6.30 1 30 6.00  38 0.76 0.64    - 1.00 6.00   38   104  497   328
4:30  90 12.00 2 82 2.31  28    -    -  0.3 1.00 2.33   28   146  121    -2
5:40 180 19.20 2 82 2.31  44    -    -  0.3 1.00 2.33   45    95  126   -72
6:50 270 12.00 2 82 2.31  28    -    -  0.3 1.00 2.33   28   146  121    -2
7:60  -1 40.00 3 41 2.72 109    -    -  0.2 1.00 2.74  109   271  473   -14
---------------------------- ---------------------------- ---------------
vol. =  96.0 m3     qc =  300 W/K              (W/m2.K)  568  (W) 1374    33
a.ch.=  2.0         qv =   64                                Ql =  300
                          ----                                    -----
bldg.resp.fact.=1.7  q =  364                               Qs+l = 1674
--------------------------------------------------------------------------
Press RETURN to continue
```

Table 2 - Input data for program HARMON can be altered by entering the "co-ordinates" of the required change.



```
Hourly outdoor and indoor environmental temperatures for JAN:
  ---------------------------------------------------------------
h:     1    2    3    4    5    6    7    8    9   10   11   12
  ---------------------------------------------------------------
To: 19.6 19.2 19.0 18.9 19.1 19.5 20.3 21.2 22.2 23.2 24.1 24.9
Ti: 23.4 23.2 22.9 22.8 22.7 23.0 24.3 25.6 27.0 28.3 29.8 30.9
  ---------------------------------------------------------------
h:                13   14   15   16   17   18   19   20   21   22   23   24
  ---------------------------------------------------------------
To:             25.3 25.5 25.4 25.2 24.8 24.3 23.6 22.9 22.2 21.5 20.8 20.1
Ti:             31.6 32.0 31.8 31.0 29.9 28.7 27.5 25.8 25.0 24.6 24.2 23.8
  ---------------------------------------------------------------
  ---------------------------------------------------------------
  Indoor design temperature = 24.5 degC  Outdoor mean temp.      = 22.2 degC
  Balance-point (base) temp.= 20.0 degC  Indoor mean temperature = 26.7 degC
  Heating req.ment: month  1=     0 kWh  Degree hours in month   =    0 K.h
  ---------------------------------------------------------------
Press "R" to repeat for another temp.   else  RETURN
```

Table 3 - Average hourly temperatures inside and outside of a building for one month as calculated by program HARMON.

- Error trapping is not always adequate and can cause the program to crash. Data input can be tricky until the method is mastered. Table 2 shows the input data required for program HARMON. Dimensions of most building elements can be entered without the necessity of area calculations.
- Output is in table form which can be directed to a printer but only at the beginning of each new run. A typical monthly output in table form is shown in Table 3. A graph of the internal and external temperature profile can be displayed on the screen but can not be printed. This is shown in Figure 14.
- A short manual is provided with the software.

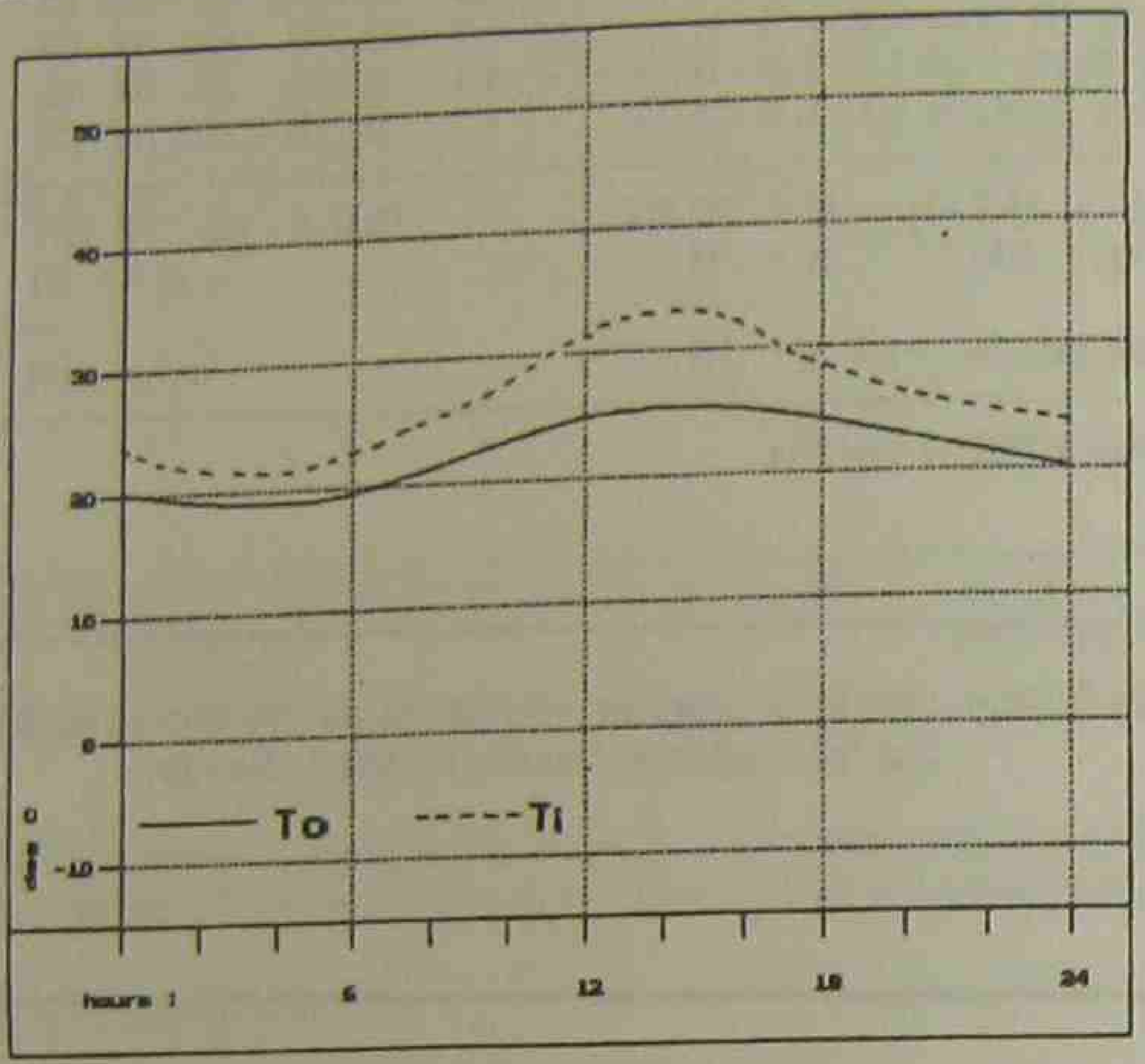


Figure 14. Graphic screen illustrating the average hourly temperatures inside and outside a building for one month as calculated by program HARMON.

6.4 Program TEMPER

Like CHEETAH, TEMPER has been derived from a mainframe program. The user interface is clumsy and not user friendly. It uses a finite difference technique for its calculations.

- TEMPER takes longer to run than CHEETAH or HARMON.
- A multizoned building can be modelled. Only 10 heat paths are allowed from each zone. This means that a house modelled as a single zone can have only four walls with either one window or door in each wall.
- Data entry is tedious and cumbersome. Recalculations with new building sections is time consuming. The lack of error trapping is frustrating.
- Areas of building sections must be calculated before run-time.
- The climatic data given in the manual varies markedly from that used in CHEETAH and HARMON.
- A user manual is provided with the software.

Steady State Thermal Analysis

1 INTRODUCTION

The thermal performance of buildings can be modelled in a number of different ways, usually depending on what information is required. Perhaps the most important information needed to compare different designs is the amount of energy required to keep a building within a particular comfort range. Other information might include the hourly temperatures in a building where no heating or cooling is used.

For the purpose of these notes, the term 'steady state' will be used to indicate the condition where heat gains and losses occur with no energy stored in the material of the actual building. Clearly, this assumption only approaches actual conditions when considering long term performance such as the heating or cooling load over say, a month. The term "dynamic" is used when referring to models which take into account the thermal capacity of building materials in order to calculate hourly temperature changes in a building.

Both steady state and dynamic models need to consider all the energy gains and losses of the building. The temperature difference between the inside and the outside of the building produces gains or losses due to heat flow through the building shell (determined by the U-values) and through the infiltration or ventilation of air. Internal heat gains will be derived from the body heat of occupants of the building and from their activities, such as the operation of appliances. Sunlight penetration through windows will contribute to the heating of the building as will sunlight on the roof and walls.

Two steady state methodologies are presented in this unit. The first, known as the Heating Degree day method, requires the calculation of conduction and infiltration gains and losses while only estimating the contribution of solar gain and occupant behaviour. The second method is much more precise in considering indirect solar gain due to wall and roof colour, direct solar gain through windows, and the heating effect of occupants and appliances. Common to both methods is a calculation of heat flow to and from the building due to temperature difference.

2 HEAT TRANSFER DUE TO TEMPERATURE DIFFERENCE

2.1 Conduction Heat Flows Through Building Elements

A building is made up of many sections through which heat will flow. These heat paths are all in parallel (Figure 1).

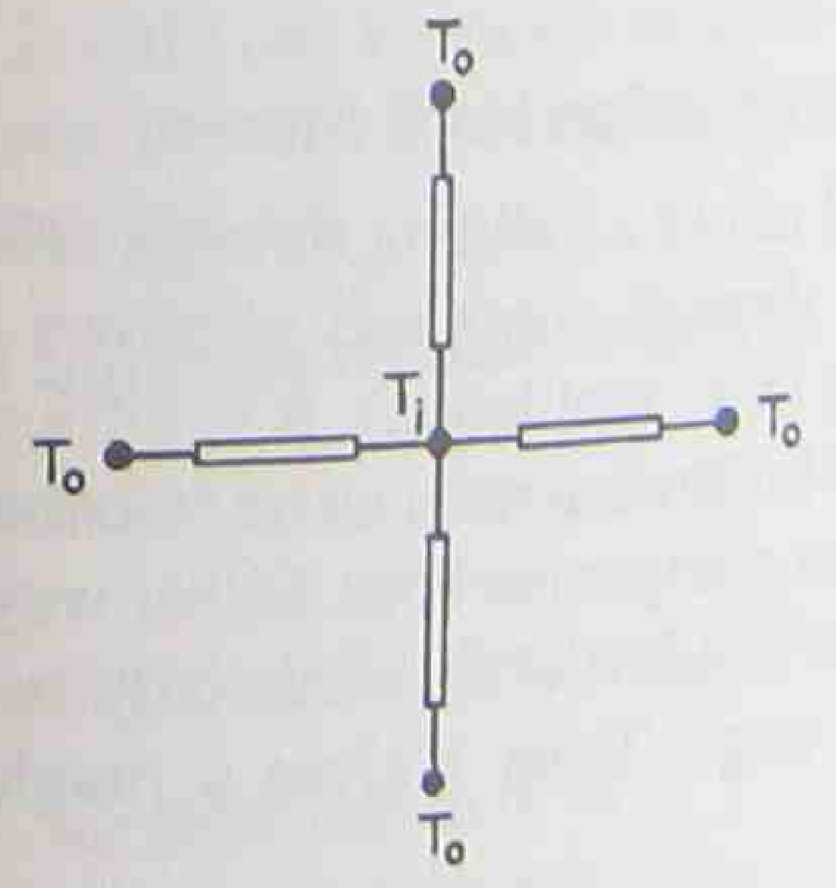


Figure 1 - Heat paths are in parallel for a building.

The total heat flow for a temperature difference ΔT due to conduction is:

$$P_{CT} = \Sigma P_C = \Sigma U A \Delta T$$

where $\Sigma U A$ - the sum of all products of element area and U value.

The average total heat loss per month is:

$$Q_C = \Sigma U A (T_i - T_a) \times N \times 0.0864$$

where Q_C - has units MJ
T_i - is the average internal temperature
T_a - is the average monthly air temperature
N - is the number of days in the month

The top part of Figure 2 outlines the steps required to calculate the conduction heat transfer through the building envelope.

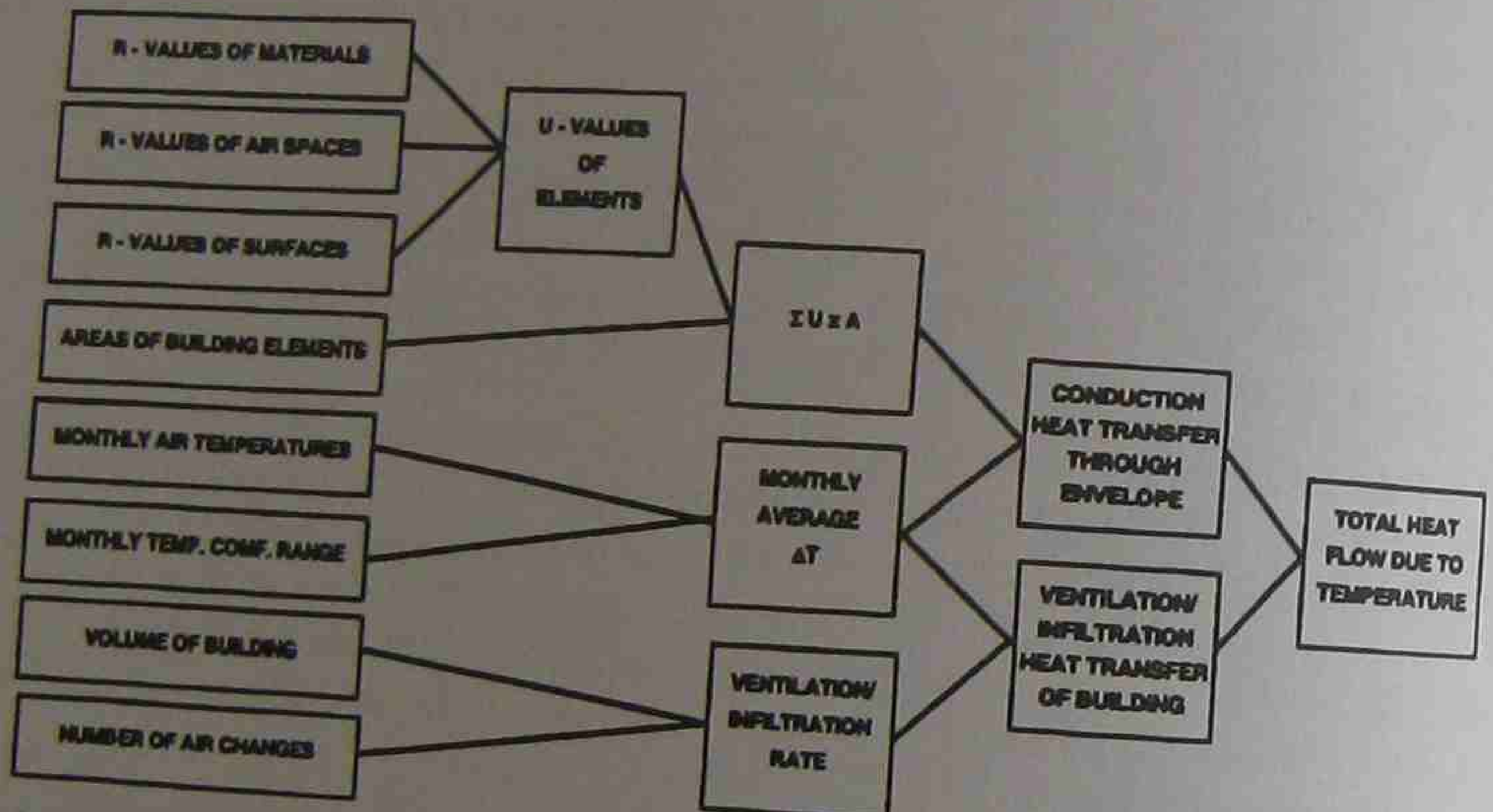


Figure 2 - Heat transfer through the building envelope due to air temperature effects.

2.2 Ventilation and Infiltration Heat Flows

Air can be moved into and out of a building through cracks and spaces in the building construction (infiltration), through doors and windows which can be opened and via mechanical means such as fans (ventilation). It is difficult to calculate the heat lost or gained via infiltration. The infiltration rate can be calculated in terms of air flow as litres per second or in terms of air changes per hour. Either way has problems as the degree of air tightness of a particular window or door can only be guessed at, especially when a building is at the design stage. Table 1 gives a rough guide for heat flows due to infiltration:

Type of building	AC/h
Well sealed building Tight sealed aluminium windows Weather stripping around external doors No open fire places Slab on ground or wall to wall carpet on wooden floor	0.5
Aluminium windows, average sealing No open fireplaces Weather stripping at bottom of external doors	1.0
Timber windows, average sealing No open fireplaces Weather stripping at bottom of external doors	1.5
Double hung or sliding timber windows No open fire places	2.0
Poorly sealed building Open fireplace	5 - 10

Table 1 - Air changes per hour.

Most building regulations require a minimum of one air change per hour for habitable rooms, 4 air changes per hour for the kitchen, 10 for the laundry and bathroom while they are in use and 3 for the toilet. To calculate the monthly heat loss in MJ the following equation is used:

$$Q_v = AC \times V \times (T_i - T_a) \times N \times 0.0286$$

where AC - number of air changes per hour
V - volume of the vented space in m^3

The bottom part of Figure 2 outlines the steps required to calculate the infiltration heat transfer.

Ventilation is used to expel polluted air or to expel hot air which is then replaced with air from outside giving a cooling effect. Quite significant ventilation rates can be achieved with open windows if cross ventilation is used, i.e., the air comes in through one window and leaves through another. With wind speeds as low as 0.4 m/s, 20 air changes per hour are possible with cross ventilation. This can be achieved if the effective window openings per side are at least 8% of the floor area. Where only one window is opened the ventilation rate is only one twentieth as great as for cross ventilation. Cross ventilation is affected by impediments to flow, such as corners formed by walls, corridors, direction of wind into the opening, etc.

The formulae for one sided and cross ventilation air flow rates are respectively:

$$F_{one\ sided} = 0.025\ v\ A$$

and

$$F_{cross} = 0.47\ v\ A \text{ (for windows of equal size)}$$

where F - air flow rate in m^3/s
v - wind speeds in m/s
A - window area in m^2

For cross ventilation, doubling the outlet side increases the ventilation by 25%. The exit window should be at least as large as the entrance window.

Ventilation through open windows or through fans to the outside is only of benefit when the building has overheated and the outside temperature has dropped below that of the inside. This will usually occur in summer in the late afternoon and at night. Significant cooling can be achieved this way, especially if there is a reasonable diurnal temperature swing and the building incorporates substantial thermal mass.

The heat transfer through the building envelope due to air temperature effects is the sum of Q_c and Q_v.

The calculations of Q_c and Q_v both require values of temperature difference, $(T_i - T_a)$. They can be combined to give the total monthly heat loss as:

$$Q_c + Q_v = (\Sigma UA \times 0.0864 + AC \times V \times 0.0286) \times N \times (T_i - T_a) \quad \text{MJ}$$

3 HEAT GAINS FROM OCCUPANTS AND APPLIANCES

Internal heat gains can make a significant contribution to the temperature of the building. For an average family of two adults and two children the average heat output for a range of activities from sleeping to housework might be 110W per person. This must be multiplied by the number of people at home and the amount of time spent inside.

Example:	2 people for 20 hours	=	4400 Wh/d
	2 people for 10 hours	=	2200 Wh/d
			6600 Wh/d

This would need to be adjusted for weekends and holidays and converted to MJ/month.

Apart from the energy used for domestic hot water, all other electrical or gas appliances will have all the energy supplied to them eventually being converted to heat energy, and thus contributing to the heating of the building. This energy can be calculated by summing the energy used by each appliance.

Example: 3 x 60W lights used for 4 hours each night give:

3 x 60 x 4 x 30 = 21.6 kWh/month

This must be multiplied by 3.6 to convert to MJ/month

Perhaps a simpler method would be to calculate the energy used per month from electricity and gas bills.

Example: An all electric home may use 24 kWh/d in total, 40% being used for hot water. If cooking consumes 10% and half of this heat is vented outside with a range hood then the total heating effect of the appliances per month would be:

(50% + 1/2 of 10%) x 24 x 30 = 396 kWh/month

In summary, Figure 3 outlines the steps required to calculate the heat gain via occupants and appliances.

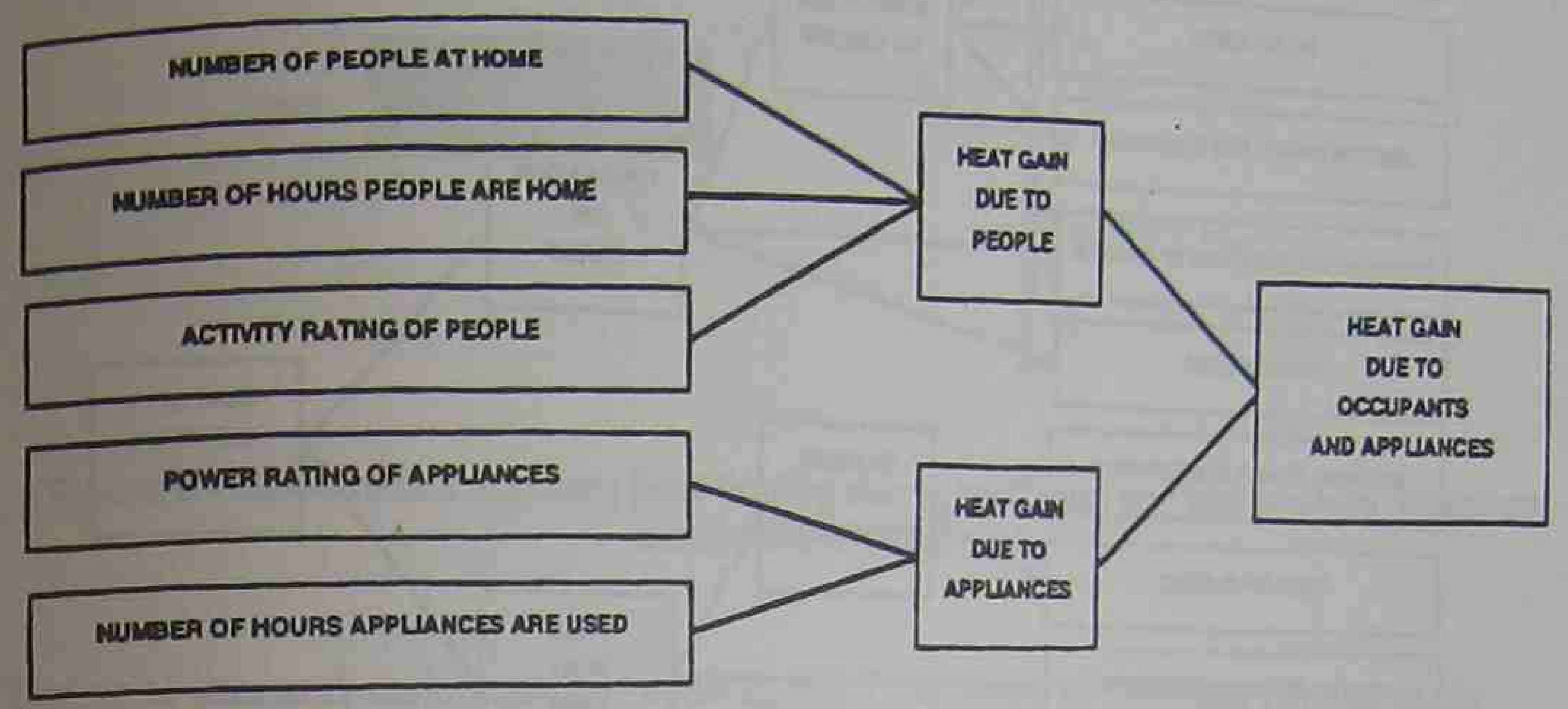


Figure 3 - Heat gain via occupants and appliances.

4 SOLAR GAINS THROUGH WINDOWS

The sunlight penetration through windows will vary from month to month. This is due to the combined effect of the variable radiation on a vertical plane and on the variable shading due to changing height of the sun's path in the sky. Unit 5 deals with this subject in greater detail.

The average daily irradiation on a shaded plane containing the window, H_s must be calculated from H_o, the average daily irradiation for a particular month on a horizontal plane, the width of the eaves or other shading devices, the height of the window and the distance from the top of the window to the eaves. This can be done with a computer program such as RAD.

The actual glass area is found as the product of the window area and the fraction of the window which is transparent. Multiplying this by H_s gives the daily irradiation on the transparent part of the window.

The type of glazing and internal blinds or curtains are compared to a standard 3mm glass pane by means of the shading coefficient.

For normal incident beam radiation the fraction transmitted by the standard glass, the solar heat gain factor, is 0.88. This figure must be derated to allow for the higher reflectance losses at larger angles of incidence. For diffuse radiation or a 60° angle of incidence for beam irradiance the transmittance of the standard glass is reduced to 0.76. The actual solar heat gain is the product of this solar heat gain factor (for standard glass) and the shading coefficient.

The daily solar heat gain through the glass is then the angle of incidence corrected solar heat gain times the daily irradiation on the transparent part of the window.

Figure 4 outlines the steps required to calculate the heat gain via solar radiation through a glazing element.

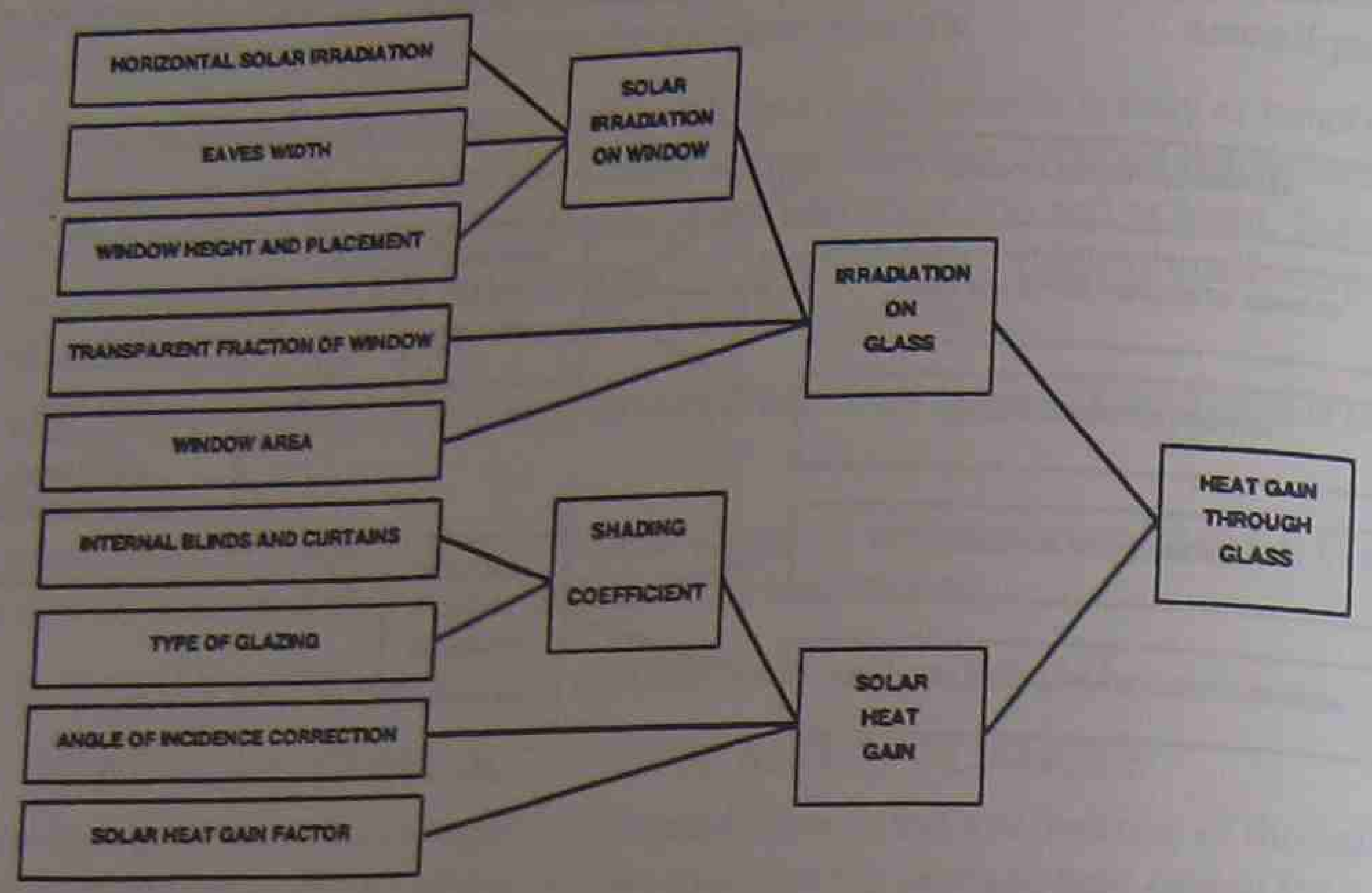


Figure 4 - Heat gain via solar radiation through a glazing element.

5 SOLAR GAIN VIA NON - TRANSPARENT ELEMENTS

Any sunlight falling on the opaque building elements such as the roof, walls and doors will heat the surface to a temperature somewhat above the ambient air temperature. Some of the heat generated will flow into the building. The amount of energy absorbed by the surface depends on the solar irradiance as well as the absorptance of the surface. The proportion of this energy which enters the building depends on the thermal resistance of the outside air film (R_o) which retards heat flow out and the thermal resistance into the building (R_z) where,

$$R_o + R_z = \frac{1}{U} \qquad (1)$$

If the outside air film resistance is low due to windy conditions then less heat will flow into the building. Similarly, if the building element has a high thermal resistance, (ie low U-value) then the amount of heat transferred inside will be reduced. White roofs and light coloured walls will also reduce the heating effects by minimizing absorptance.

Consider the situation where the temperature inside a building is T_i, and the temperature outside is T_a. Sunlight falls on the wall causing it to reach an equilibrium temperature, T_s which is always greater than T_a (Figure 5).

For the sake of the direction given by the arrows in Figure 5 assume that there is a net heat flow rate per unit area into the building (q_i) although the internal temperature is greater than the outside temperature. This situation will occur when the heat gain into the building due to solar radiation being absorbed at the surface (q_s) is greater than the heat lost to the outside due to the temperature difference effects alone.

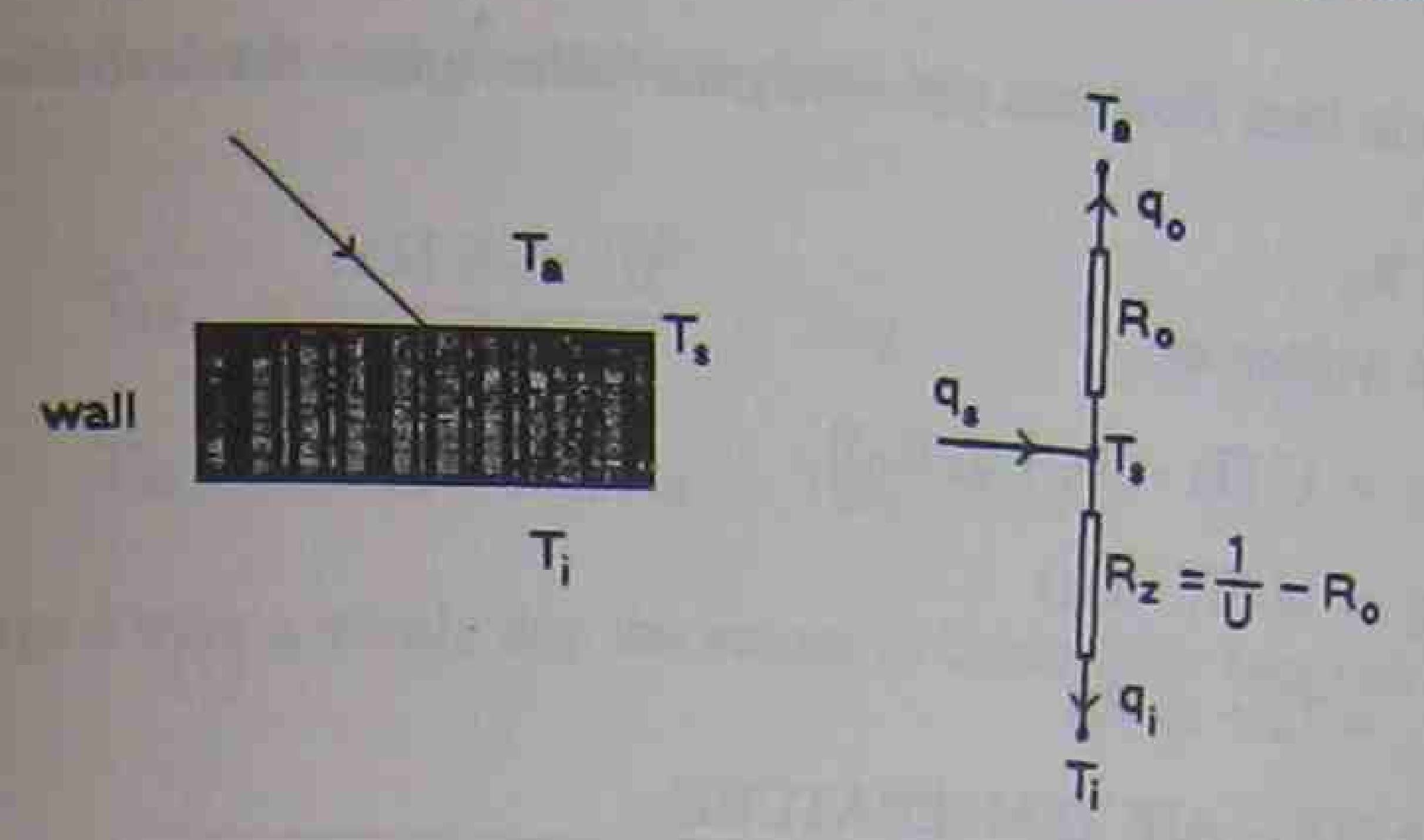


Figure 5 - Schematics showing heat flowing due to solar gain and temperature difference across the building shell.

The total thermal resistance between T_i and T_o is given in equation (1) above, so

$$R_z = \frac{1}{U} - R_o \qquad (2)$$

The heat flowing through R_o is:

$$q_o = \frac{T_s - T_o}{R_o}$$

and the heat flowing through R_z is:

$$q_i = \frac{T_s - T_i}{R_z}$$

Now $$q_s = q_o + q_i \qquad (3)$$

So $$q_s = \frac{T_s - T_o}{R_o} + \frac{T_s - T_i}{R_z}$$

Substituting for R_z from equation (2) and transforming gives:

$$\frac{T_s - T_o}{R_o} = q_s (1 - U R_o) + U (T_i - T_o) \qquad (4)$$

Transforming equation (3) gives:

$$q_i = q_s - q_o$$

so $$q_i = q_s - \frac{T_s - T_o}{R_o} \qquad (5)$$

Substituting equation (4) into equation (5) gives the total heat flow into the building:

$$q_i = q_s U R_o - U (T_i - T_o) \qquad (6)$$

So the contribution to heat flow rate per unit area (W/m^2) into the building due to the sun alone is:

$$q_s U R_o$$

Equation (6) can be written as:

$$q_i = U [T_i - (T_o + q_s R_o)]$$

$$\text{or } q_i = U (T_i - T_{sa})$$

$$\text{where} \quad T_{sa} = T_o + q_s R_o \qquad (7)$$

and is known as the SOL - AIR TEMPERATURE.

The solar radiation absorbed at the surface is given by:

$$q_s = \alpha G - E \qquad (8)$$

where α - absorptance of the surface
G - irradiance on the surface (W/m^2)
E - thermal emitted power from the surface to the ground and sky (W/m^2)

The quantity $q_s R_o$ is sometimes known as the **solar excess temperature** (T_{sx}) where:

$$T_{sx} = q_s R_o = (\alpha G - E) R_o$$

The **sol-air temperature** is then given by:

$$T_{sa} = T_o + T_{sx}$$

ie SOL-AIR TEMP = OUTSIDE TEMP + SOLAR EXCESS TEMP

So the **sol-air temperature** is a fictitious temperature greater than the outside ambient air temperature which produces a heat flow to or from a building element equivalent to the sum of that produced by the solar gain of the surface and that produced by the normal temperature difference between the inside and outside.

The value of E in equation (8) depends on the difference between the ambient air temperature and the actual temperature of the surface or space which is absorbing the radiation. Walls are usually regarded as radiating to the ambient air temperature so the value of E used is zero. Roofs, however, radiate largely to the sky which usually will have a temperature lower than the air temperature.

Instead of using the sol-air temperature concept the rate of solar heat gain per unit area can be calculated directly as:

$$q_s = U (\alpha G - E) R_o$$

If daily totals of irradiation, (H) are used instead of irradiance (G) then the daily total energy gain due to absorbed solar radiation over the area of the building element is:

$$Q_s = U A (T_{sx})$$

---

where the **solar excess temperature** is given by:

$$T_{sx} = \frac{\alpha H R_o \times 10^3}{24 \times 3.6} - T_{sky}$$

$$\text{i.e.} \quad T_{sx} = 11.57 \alpha H R_o - T_{sky}$$

When averaged over a whole day the values in Table 2 for T_{sky} can be used.

Building Element	T_{sky} (°C)
flat roof	3
22.5° roof	2
45° roof	1
wall	0

Table 2 - Sky temperatures to be used when calculating the solar excess temperature.

Solar **absorptances** for common building materials are given in Table 3.

Surface		Absorptance
Brick, red, unglazed		0.68
red, glazed		0.77
cream		0.36
white, glazed		0.26
Concrete		0.65
Galvanised iron,	old	0.75
	new	0.30
Granite		0.55
Fibro-cement,	old	0.75
	new	0.45
Paint, aluminium		0.18
black		0.90
cream		0.30
green		0.50
red		0.74

Table 3 - Solar absorptances for common building materials.

Air film resistance has already been discussed in Unit 4. A reasonable value for R_o is $0.04\ m^2K/W$, which corresponds to a wind speed of 3.5 m/s.

Figures 6 and 7 outline the steps required to calculate the heat gain via solar radiation on a wall and roof respectively.

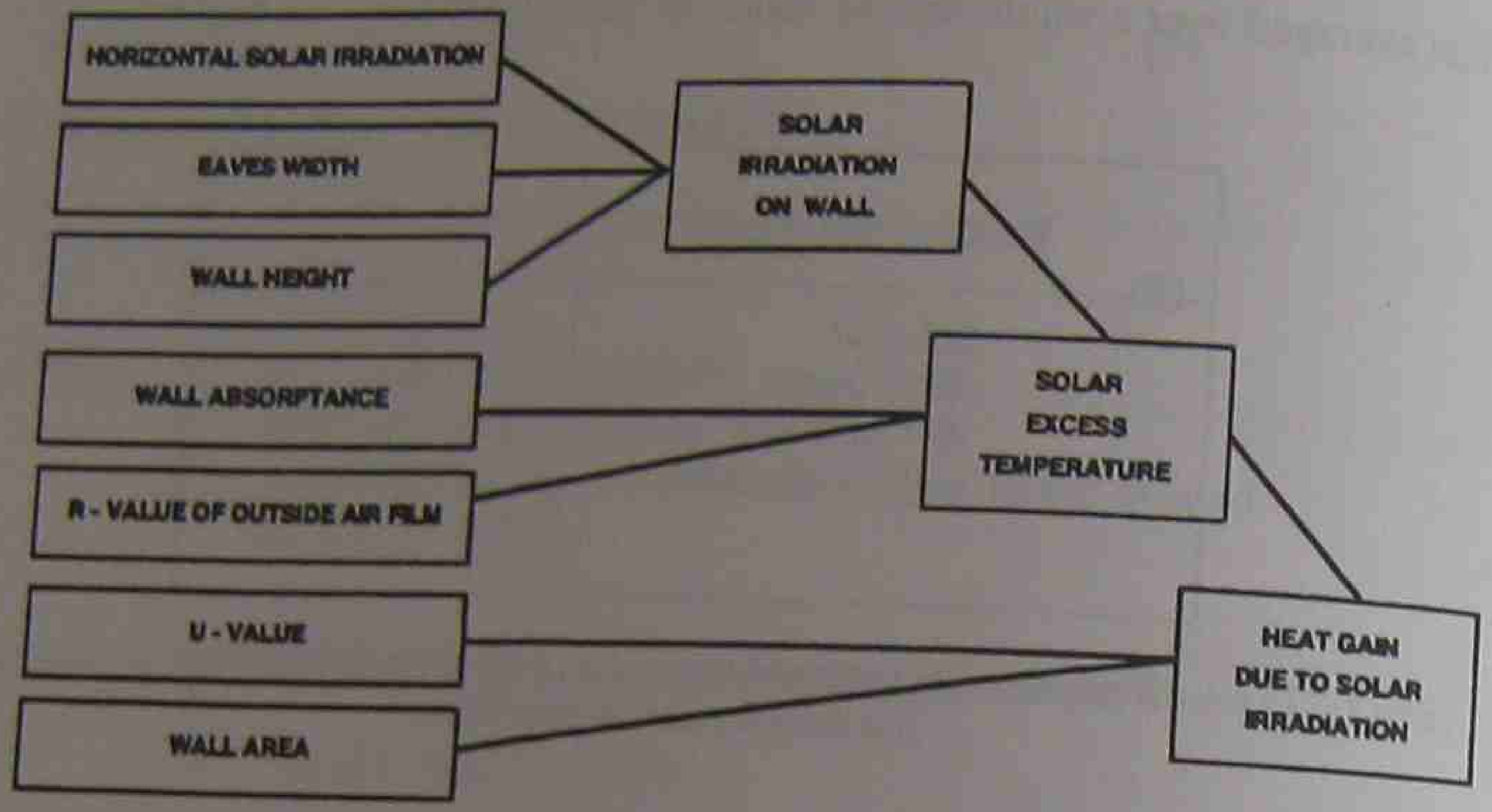


Figure 6 - Heat gain via solar radiation on a wall.

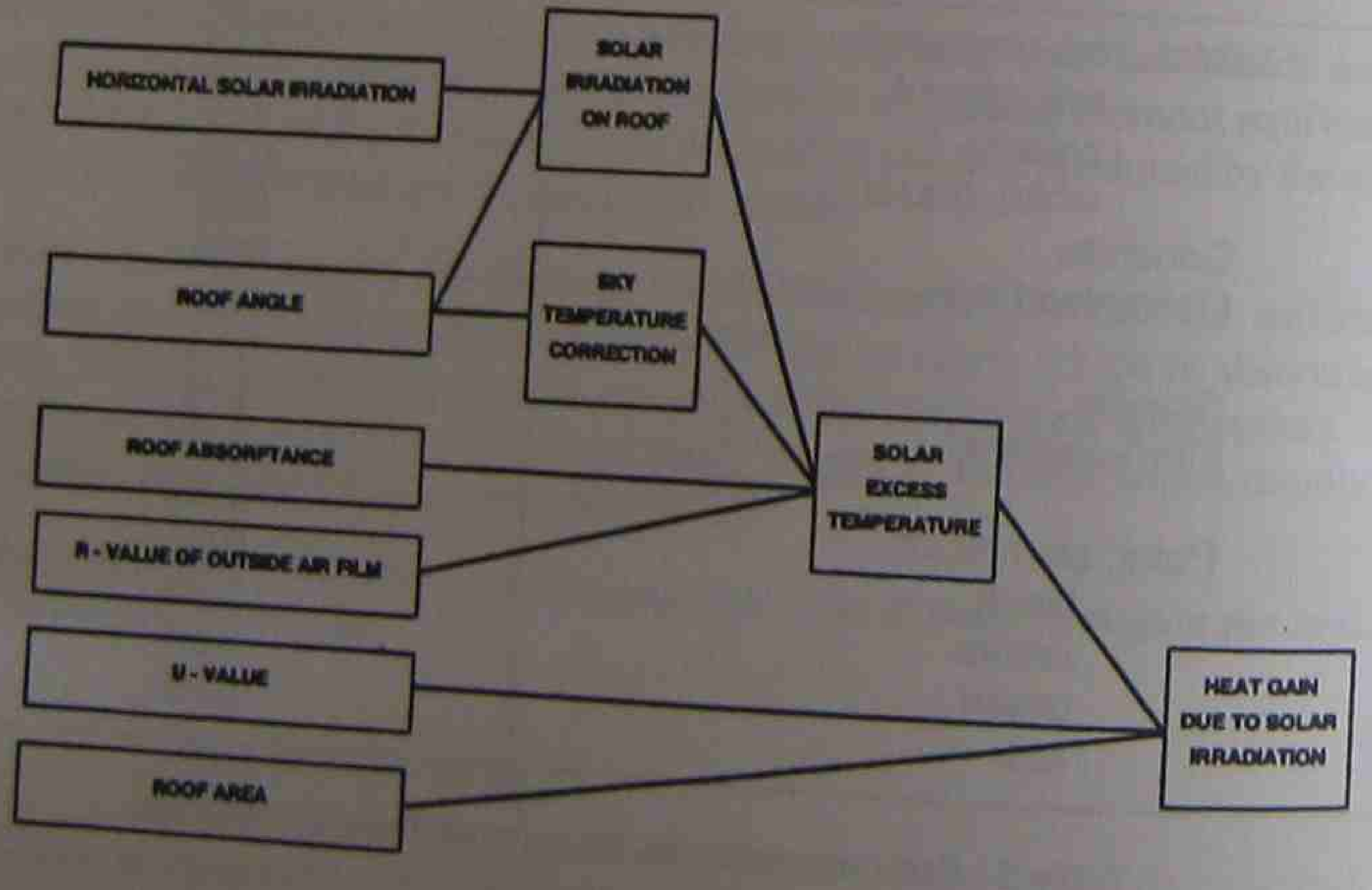


Figure 7 - Heat gain via solar radiation on a roof.

6 STEADY STATE HEAT TRANSFER CALCULATIONS

The instantaneous rate of heat loss of a building is:

$$P_{Tot} = P_{temp\ diff} + P_{glaze} + P_{walls} + P_{roof} + P_{people} + P_{appl} + P_{aux}$$

where $P_{temp\ diff}$ - heat transfer due to temperature difference ie. due to conduction and ventilation
P_{glaze} - solar gain through glazing
P_{walls} - solar gain through walls
P_{roof} - solar gain through roof
P_{people} - body heat from people
P_{appl} - heat generated by appliance
P_{aux} - heat or coolth generated by heating or cooling plant

A positive value of P indicates a heat loss while a negative value indicates heat gain.

$P_{temp\ diff}$ can be positive (eg. Winter) or negative (eg. Summer).

P_{glaze}, P_{walls}, P_{people} and P_{appl} will always represent gains, so they will always be negative.

P_{roof} will generally be a gain (negative). However, a low solar gain due to low radiation intensity and low surface absorptance, and a high surface emittance and a low sky temperature may cause the radiation to the sky to exceed the solar gain. This would make P_{roof} positive.

P_{aux} will be positive for a heater and negative for air conditioning (cooling).

If the internal room surfaces are all at the same temperature as the air temperature inside the building, a positive value of P_{Tot} will decrease the air temperature, while a negative value will increase its temperature. The temperature of internal room surfaces will also decrease and increase respectively. In practice the thermal mass of the building will absorb and re-emit heat when the air temperatures are higher or lower respectively. This process is shown diagrammatically in Figure 8.

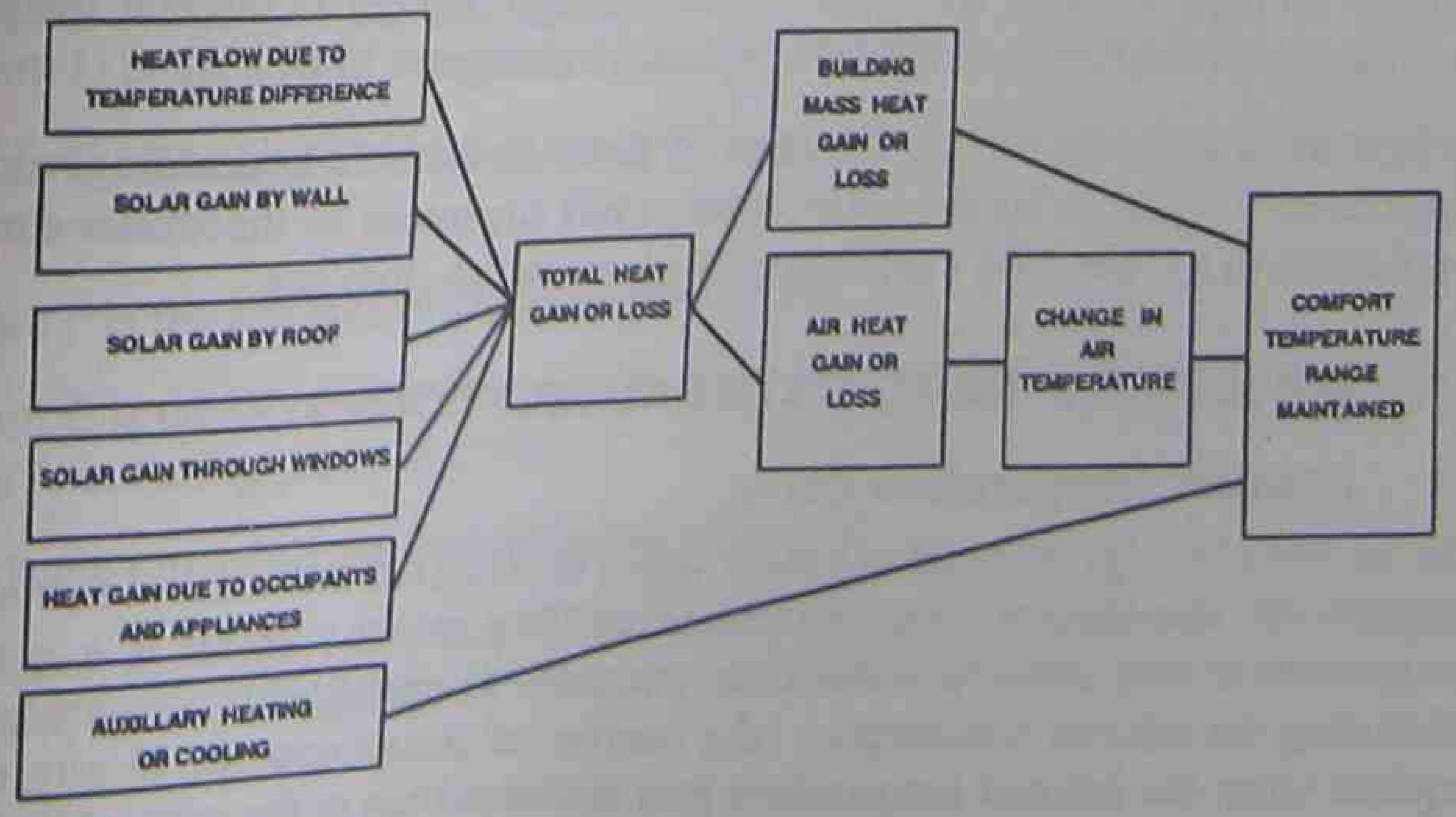


Figure 8 - Energy and temperature change processes in buildings.

The assumption of steady state conditions is only valid when a relatively large number of daily temperature cycles are considered, ie. over a period of a month or a complete heating or cooling season. The aim of steady state thermal analysis is to calculate the auxiliary heating or cooling required to keep the inside of the building within a specified comfort temperature range.

7 HEATING DEGREE DAY CALCULATIONS

The "Heating Degree Day" method is the simplest steady state modelling technique. In order to use this method it is necessary to know to what extent the temperature outside a building falls below a minimum base value, as well as the conduction and ventilation heat flows from the building.

One heating degree day describes the condition when the outside temperature is one degree below the base temperature for a period of one day. The number of heating degree days for a particular location is an indication of the severity of the heating season. The calculation of heating degree days from climatic data is covered in Unit 2 - Comfort and Climate.

The base temperature is the outside temperature which together with internal heat gains and the heating effect of sunlight is just able to maintain a comfortable temperature inside the building. This internal comfort temperature is often taken as 21°C. So using a base temperature of 18°C assumes that when the outside temperature is 18°C the temperature inside the building will be 21°C. Tables of heating degree days base temperatures 12°C, 15°C and 18°C are given in Table 1 of Unit 2.

The heating required over a full heating season will be:

$$Q_{hs} = S \times dd$$

where S - conduction and infiltration heat loss per degree day
$= \Sigma UA \times 0.0864 + AC \times V \times 0.0286$ MJ
dd - number of degree days

Table A1 of the appendix can be used to facilitate these calculations.

Degree hours have also been used for simple steady state modelling. This method may be more accurate for light structures which undergo changes in internal temperatures fairly rapidly in response to external temperature changes.

Perhaps the major problem using either of these methods is in deciding which base temperature to use. A building which takes full advantage of the winter sun will be comfortable at a lower base temperature than one which does not.

8 ADVANCED STEADY STATE CALCULATIONS

8.1 Comfort Temperature Zone

The amount of energy required to heat or cool a building depends on the internal comfort temperatures specified for the heating or cooling season. What is a comfortable temperature is very subjective but it is necessary to specify this comfort zone when calculating the relative performance of a number of design options. Ideally, cooling is required when the internal temperature gets above the top of the zone while heating is required when the internal temperature drops below this zone. To simplify calculations a temperature is selected which is in the centre of the comfort zone.

The comfort zone may be fixed (eg. 22 - 28°C) throughout the year (ASHRAE) or it may vary with climate, habits and outdoor mean temperature. For the purposes of these calculations the centre of the comfort zone will be taken as:

$$T = 17.6 + 0.31\ T_{av}$$

where T_{av} - average monthly temperature

8.2 Climate Data Input

Table B1 of Appendix B is used to input climatic data. Column B is used for average temperature for the month shown in column A. Often maximum and minimum temperatures are available. The average ambient temperature for the month is then:

$$T_{av} = \frac{T_{max} + T_{min}}{2}$$

Column C is found from the algorithm:

$$T_{comf} = 17.6 + (0.31 \times T_{av})$$

Column D is the temperature difference:

$$\Delta T = T_{comf} - T_{av}$$

Column E is the average daily horizontal irradiation, with units MJ/m^2/day.

8.3 Conductance Heat Transfer

Table B2 of Appendix B is used to calculate the conductance heat transfer.

Column A is the building element, i.e. door, floor, roof etc.

Column B is the height or length of the element.

Column C is the width of the element.

Column D is the area of the element including any doors, windows etc.

Column E is the area included in the gross area which is of a different construction e.g. area of windows.

Column F is the nett area of the building element.

Column G is the U-value if the element. This can be calculated from first principles or can be found using program UVAL.

Box I is the sum of all the UxA values of column H.

Calculation J is Box I converted from an instantaneous power per °C temperature difference to daily energy per °C temperature difference lost by conductance.

8.4 Infiltration Heat Transfer

The volume (in cubic metres) of the room spaces in the building and the number of air changes per hour are used to calculate the daily energy per ^{o}C temperature difference lost via infiltration, (Table B3).

8.5 Heat Gains Via Occupants and Appliances

The top table of Table B4 is used to calculate the heating effect of occupants. "Group" refers to people occupying the building at the same time. For example, for a family of 4, Group 1 may be made up of all four while they are at home at night for ten hours. Group 2 may be made up of one person at home for eight hours during the middle of the day.

Column D is used for the calculation of the daily heating contribution of each group. An average heating power of 105W per person is assumed.

Box E is the sum of the daily heat energy contributed by people.

The bottom table is used to calculate the heating contribution of appliances.

Column I is calculated as time (h) x power (kW) x 3.6 MJ.

Box J is the sum of the daily heat energy contributed by appliances.

Calculation K is the sum of the daily heat energy contributed by people and appliances.

8.6 Solar Heat Gained Through Glazing

Table B5 of Appendix B is used to calculate solar heat gains through windows. Columns B (orientation), C (window height), D (eaves width), E (eaves to window distance) and I (daily irradiation on a horizontal plane) are used to calculate column J, the daily irradiation on the window. Program RAD can be used to calculate column J (H_g).

Column G is the fraction of the window area that is glass, i.e. minus the window frame.

Column H, the shading coefficient has a value other than one if non standard glass is used and/or some internal shading device such as curtains or blinds are used during the daytime hours.

A solar heat gain factor of 0.76 is used to calculate the solar heat gain through each window. This assumes an average angle of incidence of 60^{o}.

Box L is the sum of the solar gains through windows.

8.7 Solar Heat Gain Through Walls

Table B6 of Appendix B2 is used to calculate solar heat gains through walls. Column I, the daily irradiation of the wall is calculated in a similar way to the daily irradiation on a window in Table B5. The only difference is that the eaves to window distance is taken as zero.

In order to calculate column J (daily solar gain through the wall) the absorptance (column F), the UxA factor (column E), and the outside air film resistance (column G) are required. The algorithm required is

$$Q_W = (U x A)\ \alpha\ R_o\ H_w\ 11.57\ MJ$$

Box K is the sum of the solar gains through all the wall elements.

8.8 Solar Heat Gain Through Roofs

Table B7 of Appendix B is used to calculate solar heat gain through roofs. Rather than calculating the daily irradiation on each section of sloping roof a useful short cut is to consider the roof as being horizontal with the same area as the floor. Then the horizontal irradiation data can be used when calculating heat gain.

The effective sky temperature T_{sky} (column E) for the average slope of the roof must be used.

The solar heat gain through each roof element is calculated for column G by using

$$Q_R = (U x A)\ [\alpha\ R_o \times 11.57 - T_{sky}].$$

Box H is the total solar heat gain through the roofs.

8.9 Monthly Heating or Cooling Load

The calculations to find the monthly heating or cooling load are given in Table B8. The source of the data for each column is given below the table. Positive loads are heating requirements, while negative loads require cooling.

Appendix A

Worksheet for Degree Day Calculation