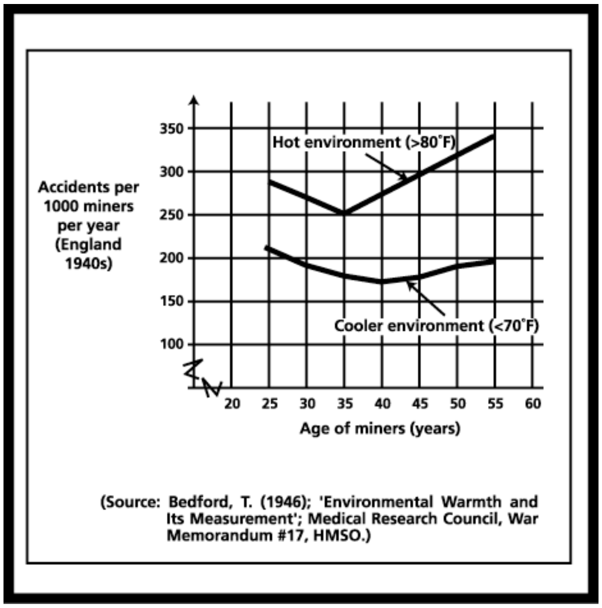
Chapter Three

Thermal Control by Building Design

Although acute physiological break-downs such as heat stroke and heat cramps will normally occur only at very high temperatures, it has been found that even moderately high temperatures can appreciably affect the capacity of persons to perform work. Studies conducted after World War II, involving both laboratory experiments and industrial surveys, have confirmed this beyond any reasonable doubt. Seasonal production statistics collected in heavy and light industries, such as steel and textile manufacturing plants, have consistently shown that excessive temperature and humidity will result in reduced output. Although increased temperature seems to have the greatest effect on the performance of physical work, both high and low temperatures will affect manual dexterity, concentration and the occurrence of accidents. For example, the statistics represented graphically in Figure 3.1 emphasize the effect of high temperatures on the rate of accidents in coalmines in England during the 1940s. It is interesting to note that in this work environment temperature also appears to influence the distribution of accidents in the various age groups. In the coolest mines the accident rate declined with increasing age, since under reasonably comfortable conditions the greater experience of older persons will tend to diminish their accident risk. On the other hand, in the hottest mines the rate of accidents increased sharply for the 35 to 55 age group. This age group is likely to be more easily fatigued, accompanied by greater loss of concentration and resulting in a higher accident rate.



(Source: Bedford, T. (1946); 'Environmental Warmth and Its Measurement'; Medical Research Council, War Memorandum #17, HMSO.)

Figure 3.1: Accident rates in British coal mines during the 1940s

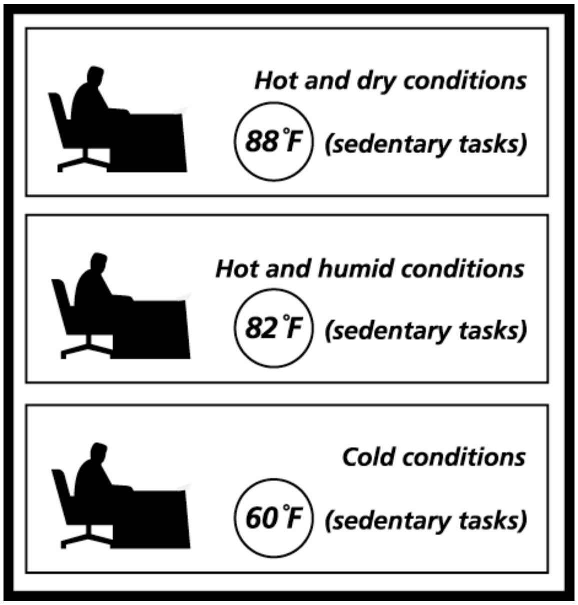


Figure 3.2: Limits of barely acceptable thermal conditions

3.1 How important is the Thermal Environment?

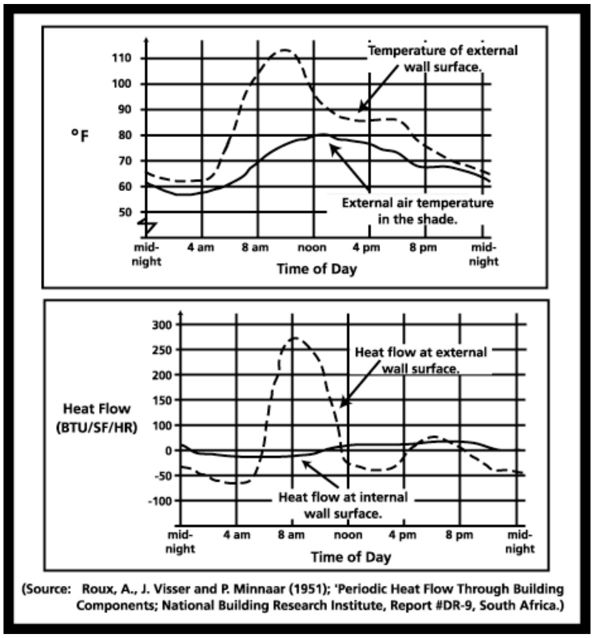
There is ample statistical evidence indicating that every improvement made in an uncomfortable thermal environment will result not only in an increase in production, but will also improve the quality of the product, reduce the accident risk and provide better labor relations. It is therefore essential that every effort be made at the design stage of a building to provide a comfortable thermal environment.

Before the advent of the energy crisis in the early 1970s, it was already recognized that even if a building is to be fully air conditioned by mechanical means careful consideration must be given to building orientation, solar heat protection, adequate thermal insulation, and the appropriate choice of construction materials. While the improvement of living and working conditions has become a well-established social criterion, the necessity of energy conservation has rather abruptly forced the owners and designers of buildings to abandon whenever possible mechanical environmental conditioning aids in favor of natural means. Although the degree of thermal control that can be achieved by building design alone is constrained by climatic conditions, very significant savings in energy (often exceeding 50%) are nearly always possible. In hot climates such design measures can ensure that the internal building environment will be at least no worse than conditions in the shade out of doors. In many cases, by the use of certain methods of construction conditions that are considerably better may be achieved at little extra cost. Nevertheless, as a rule, it is unlikely that completely unconditioned buildings will provide a comfortable thermal environment if the external climatic conditions are well outside the comfort zone. It is therefore necessary not only to establish optimum conditions, but also the upper and lower limits beyond which conditions are likely to produce an unacceptable degree of thermal discomfort.

According to studies undertaken by Drysdale, in Australia, the upper limit of acceptable thermal conditions under hot-dry conditions for persons engaged in sedentary tasks is approximately 88˚F (Figure 3.2). In hot-humid conditions this upper limit is likely to lie closer to 82˚F, due to the negative influence of humidity. The lower threshold is less clearly defined due to the latitude provided by clothing, but it is probable that air temperatures below 60˚F will produce definite discomfort. It has been argued that repeated exposure to conditions outside these limits is likely to have detrimental effects on the physical health of persons, but this does not seem to have been proven medically, to date.

3.2 Thermal Building Design Strategies

Both the heat capacity and thermal resistance of external walls will have a significant effect on the ability to regulate the internal environment by building design alone. Depending on the construction of the wall some of the heat gained during the day will be absorbed by the wall material before the wall can pass on heat to the inside of the building. At night, the heat stored in the wall will naturally dissipate to the outside before the cooling of the building interior can commence. Accordingly, an external wall capable of absorbing a considerable amount of heat during a hot day will allow the building environment to remain relatively cool. Conversely, during the night the same wall will need to lose much of the stored heat before it can have an appreciable cooling effect on the interior. Heavyweight wall construction tends to produce these effects, since the heat storing capacity for most types of walls is proportional to the weight per unit surface area of the wall. This is clearly demonstrated in experiments performed by Roux and others (1951) in South Africa, where variations in outdoor and indoor air temperatures and heat flows at the outside and inside surfaces of the east wall of a test building are plotted for a mild summer day in Pretoria (Figure 3.3). In this example, approximately five times more heat appears to have entered the outside surface of a 9 in. thick, unshaded brick wall than was passed into the interior of the building from the inside surface. It should be noted that since Pretoria is located in the Southern Hemisphere the sun is inclined to the north, and not the south as is the case in the Northern Hemisphere.



(Source: Roux, A., J. Visser and P. Minnaar (1951); 'Periodic Heat Flow Through Building Components; National Building Research Institute, Report #DR-9, South Africa.)

Figure 3.3: Heat flow through a heavyweight building envelope in a ***hot-dry*** climate

Climatic Characteristics

Temperature:
- **Very hot during daytime (100(+) ˚F)**
- **Cooler nights (80(+) ˚F)**

Humidity:
- **Very dry (RH < 30%)**

Design Strategies

Utilize the building envelope as a buffer and heat sink. Seal the building during the day and open it up at night to cool the envelope from the inside and the outside. Then repeat the cycle at sunrise.

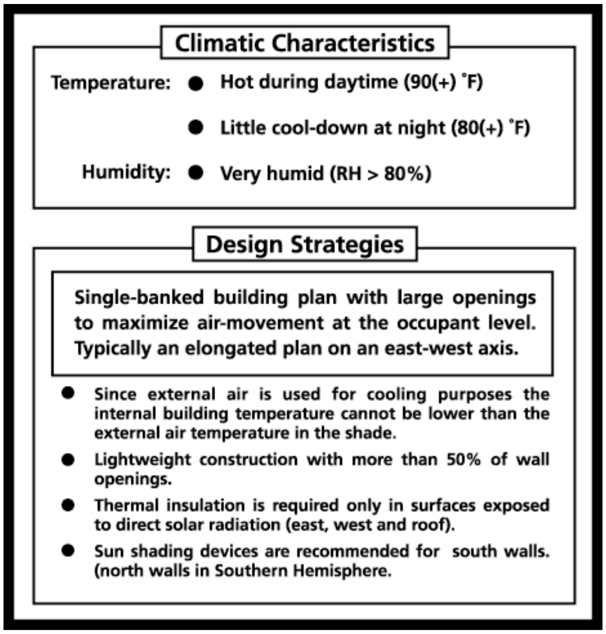
- **Heavy construction with high heat capacity for walls and roof.**
- **Small windows deeply recessed into the walls.**
- **Reflective external envelope (surfaces).**
- **Thermal insulation in walls (inside surface) and roof (also reflective foil).**

Figure 3.4: Design strategies for an (idealized) ***hot-dry*** climate

It can be seen in Figure 3.3 that there is a time delay between the maximum heat entry into the wall and the maximum dissipation of this heat into the building environment. This time lapse is of course related to the resistance to heat flow posed by the construction (i.e., the U-value of the wall). Generally speaking, heavyweight construction will reduce the ability of a building environment to follow any but the most considerable changes in outdoor conditions, and then only after an appreciable time lapse. This property of heavy wall construction is an advantage in those regions where there exist sharp differences between day and night temperatures (commonly referred to as the diurnal temperature range). Having been cooled at night, the wall will be able to absorb considerable heat before the temperature of the interior is raised. If the cool night air can be used to accelerate the cooling of the structure and interior by the provision of floor and ceiling openings to achieve ventilation at night, perhaps with the addition of a fan, then a very economical system of natural thermal control can be achieved.

As shown in Figure 3.4, heavyweight construction is particularly useful in hot-dry climates, which are characterized by high temperatures during the day, significantly lower temperatures at night, and a relative humidity that rarely exceeds 30%. In such desert-like environments the building envelope performs the functions of a thermal buffer between the external and internal environments. Small windows and a thermal insulation layer placed on the inside surface of the walls, allow the building to be virtually sealed off from the heat of the daytime hours. In addition, the windows are recessed deep into the walls so that the window reveal can act as a sunshading device. A light, reflective external wall finish ensures that at least some of the solar radiation is reflected back from the envelope.

For hot-humid climates an elongated east-west building shape with large openings in the elongated north and south elevations is in order (Figure 3.5). The large openings are required to facilitate air movement across the bodies of the building occupants. As discussed in the previous chapter, if the ambient temperature rises beyond the ability of the human vaso-motor control mechanism to maintain a normal deep body temperature (by losing heat at approximately the same rate as the body is gaining heat) then perspiration will set in. However, the ability of the body to lose more heat through the conversion of the liquid perspiration to gaseous water vapor (i.e., the energy used up in the latent heat of evaporation process) is severely limited because the humid air is already nearly saturated with water vapor. Therefore, the small amount of moisture that each particle of air can soak up from the skin will be multiplied by the movement of many particles across the skin. The result is a slightly accelerated loss of heat from the body.



Climatic Characteristics

Temperature:
- Hot during daytime (90(+) ˚F)
- Little cool-down at night (80(+) ˚F)

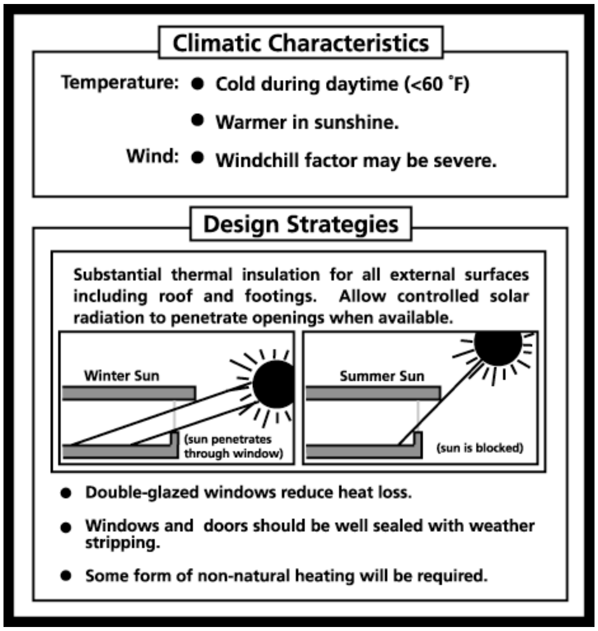
Humidity:
- Very humid (RH > 80%)

Design Strategies

Single-banked building plan with large openings to maximize air-movement at the occupant level. Typically an elongated plan on an east-west axis.

- Since external air is used for cooling purposes the internal building temperature cannot be lower than the external air temperature in the shade.
- Lightweight construction with more than 50% of wall openings.
- Thermal insulation is required only in surfaces exposed to direct solar radiation (east, west and roof).
- Sun shading devices are recommended for south walls. (north walls in Southern Hemisphere.

Figure 3.5: Design strategies for an (idealized) ***hot-humid*** climate



Climatic Characteristics

Temperature:
- Cold during daytime (<60 ˚F)
- Warmer in sunshine.

Wind:
- Windchill factor may be severe.

Design Strategies

Substantial thermal insulation for all external surfaces including roof and footings. Allow controlled solar radiation to penetrate openings when available.

- Double-glazed windows reduce heat loss.
- Windows and doors should be well sealed with weather stripping.
- Some form of non-natural heating will be required.

Figure 3.6: Design strategies for an (idealized) ***cold*** climate

There are several building design implications of this strategy. First, to facilitate the movement of air between the north and south walls care must be taken to avoid any physical obstructions such as intermediate partitions. This virtually mandates a building layout with single-banked rooms. The typical natural wind speeds that are found in hot-humid climates rarely exceed 6 to 8 mph and even a fly wire screen can reduce this by as much as 40%. Second, since external air is being used to cool the building interior, clearly the temperature inside the building will not be lower then the temperature in the shade of the external air. Accordingly, thermal insulation in hot-humid climates is only necessary for those sections of the building envelope that are exposed to direct solar radiation, namely the roof and the east and west walls. The south wall (in the Northern Hemisphere) is easily and effectively shaded from the sun, and the north wall will not be subjected to solar radiation. Third, as long as air movement serves as a primary cooling mechanism little purpose would be served in providing a heavyweight construction system. In fact, massive walls with their attendant heat capacity would tend to add an undesirable heat source during prolonged hot spells. Therefore, the predominant construction solution in hot-humid climates is lightweight, with homes often raised at some height above ground level to maximize air movement (i.e., wind speed is normally slightly reduced at ground level due to vegetation). Finally, since up to 90% of the heat transfer through roofs subjected to intense sunshine is by radiation, it is important to utilize a highly reflective layer (e.g., aluminum foil) facing an air space as the first barrier to heat transmission, in the roof. As this reflective layer heats up it becomes a heat radiator on its own account. Therefore, several inches of thermal insulation are normally provided directly on the underside of the reflective foil to prevent the transmission of this heat into the building.

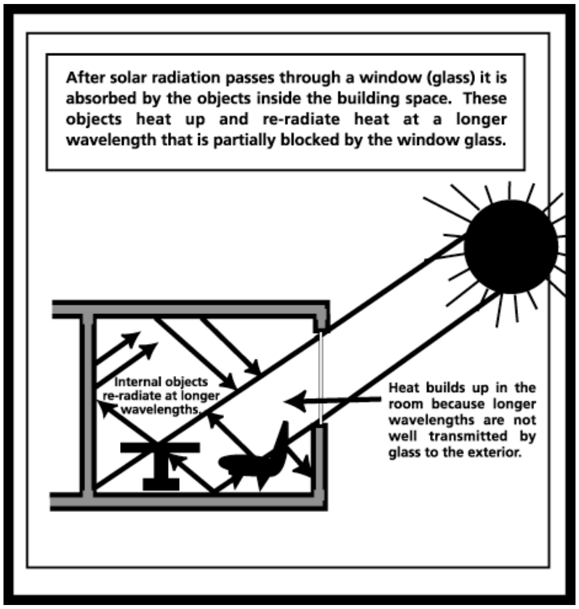
Cold climates are characterized by low day and night temperatures, snowfall during winter in some regions, and a wind-chill factor due to air movement that can easily lower the perceived temperature by another 5ºF to 10ºF (Figure 3.6). Under these adverse thermal conditions, the available design strategies are all aimed at minimizing the loss of heat from the building interior to the external environment. First, the building envelope must be well insulated. In the case of the roof the insulation layer is often provided with reflective foil facing both upward and downward, so that in winter heat radiated from interior sources is reflected back into the building and in summer excessive solar radiation is reflected back out of the building. Several such double-sided thermal insulation panel systems are commercially available. They typically consist of two to seven inches thick insulation bats lined on both sides with very thin aluminum foil. It is of course necessary for these double-sided panels to be installed so that they face an air space on each side. Second, care must be taken to minimize the infiltration of cold air into the building by sealing doors and windows with weather stripping. Third, attention now focuses on the windows as the least insulated component of the building shell. As will be seen in the next chapter, double-glazed windows will reduce the outward heat loss to more than half the heat loss through single-glazed windows. Fourth, a compact building plan will minimize the ratio of external wall and roof area to internal floor area. This leaves relatively less external surface area from which the building can lose heat.

Finally, in cold climates the sun must be looked upon as an important natural asset. Advantage can be taken of the difference in altitude of the sun during winter and summer. In winter the altitude of the sun, during the mid-day hours may be as much as 40 degrees lower than in the summer months. This allows horizontal shading devices on south elevations (north elevations in the Southern Hemisphere) to be designed to prevent solar radiation from penetrating windows in the summer and serve as a welcome natural source of heating in the winter (Figure 3.6). However, despite all of these design measures some form of supplementary, non-natural heating will be required in virtually all cold climates.

3.3 Importance of Sunshading Devices

Heat transmission through glass is virtually instantaneous and very much aided by the penetration of direct solar radiation. At first sight it would appear that the most effective way of reducing this type of direct heat gain is to keep the sun off windows entirely by using various types of sunshading devices. This solution may be appropriate to reduce summer heat gains and, at the same time, quite inappropriate for winter conditions. In winter, and perhaps throughout the year in colder climates, the sun is most useful as a heating device. As mentioned in the previous section, since the elevation or altitude of the sun is considerably lower in winter than in summer it is possible to design horizontal sunshading devices on south facing windows to allow some direct solar radiation to penetrate through windows during the winter and totally exclude the sun during the summer (Figure 3.6).

The heat gain that can be achieved by capturing solar radiation through closed windows in winter is magnified by the greenhouse effect (Figure 3.7). The cause of this increased build-up of heat in spaces with large glazed areas is often misunderstood. It is a common misnomer that the wavelength of the solar radiation changes as it passes through the glazing, and that the resultant radiation becomes trapped in the enclosed space because it cannot easily pass back through the glass. The correct explanation is quite different. In fact, when the solar radiation passes into the space it is readily absorbed by the objects in the space. Naturally, as these objects heat up they become heat radiators themselves. However, this radiation is of a longer wavelength and therefore cannot pass easily back through the window glass to the exterior. Most of it becomes trapped in the space, causing the space to progressively heat up beyond the contribution of the direct solar radiation.



After solar radiation passes through a window (glass) it is absorbed by the objects inside the building space. These objects heat up and re-radiate heat at a longer wavelength that is partially blocked by the window glass.

Figure 3.7: The 'greenhouse' effect

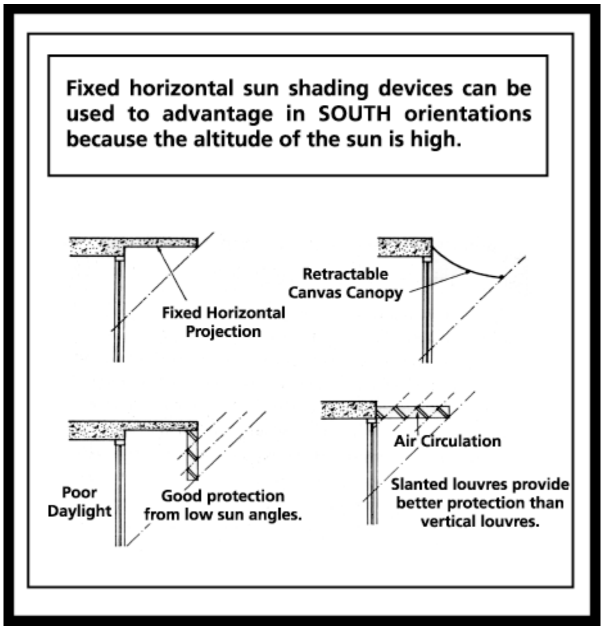
- **The altitude of the sun is much lower during the winter (about 30° at noon) than in summer (about 70° at noon).**
- **Heat transmission through glass (single-glazing) is virtually instantaneous.**
- **External sun shading devices are the most efficient form of solar heat protection.**
- **However, external sun shading devices interfere with interior daylighting (and possibly air movement).**
- **External sun shading devices should have a reflective finish and allow free air flow over their surface, because they can become a heat source.**

Figure 3.8: Sunshading design considerations

There is no doubt that external shading is the most efficient form of solar protection from the point of view of heat control, since the heat radiation can be completely blocked if necessary. Unfortunately, it carries with it the disadvantages of interference with interior daylighting and natural ventilation. Furthermore, precautions must be taken to ensure that the shading device itself does not become unnecessarily hot, thereby assisting the transmission of heat by direct conduction to the wall or convection to the air surrounding the window opening (Figure 3.8). Accordingly, the device should have a reflective finish and allow free air flow over its surface for cooling purposes.

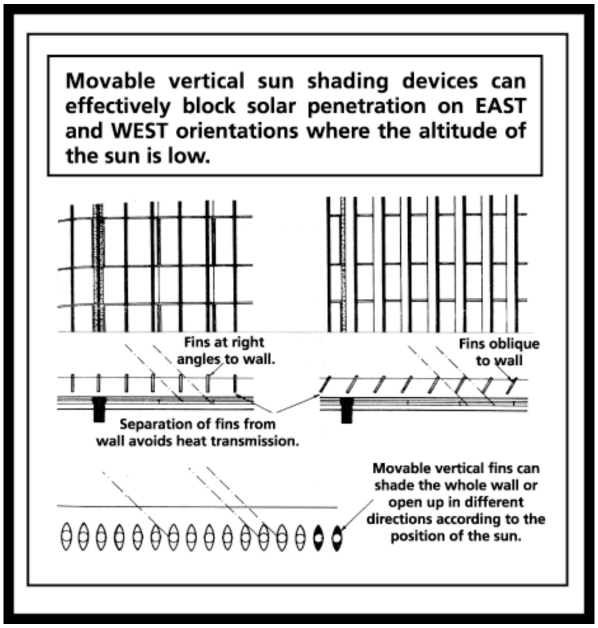
While horizontal sunshades may be used to advantage (i.e., summer shading and winter heating) for south facing windows (Figure 3.9), they are definitely not appropriate for east and west orientations where the altitude of the rising and setting sun is low. For these orientations vertical sunshading devices (Figure 3.10), particularly if they are movable, are able to exclude the sun and yet allow the penetration of daylight.

Internal shading devices are only as effective as the relative amount of direct solar radiation that they are capable of reflecting back through the opening. The approximate percentage reductions in total heat transfer resulting from typical internal shading devices in comparison with similar externally applied devices are shown in Figure 3.11 (ASHRAE 1989).



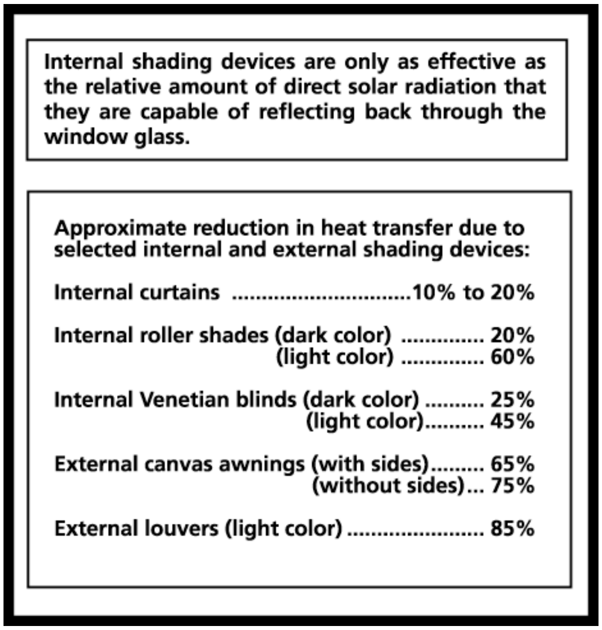
Fixed horizontal sun shading devices can be used to advantage in SOUTH orientations because the altitude of the sun is high.

Figure 3.9: Horizontal sunshading devices



Movable vertical sun shading devices can effectively block solar penetration on EAST and WEST orientations where the altitude of the sun is low.

Figure 3.10: Vertical sunshading devices

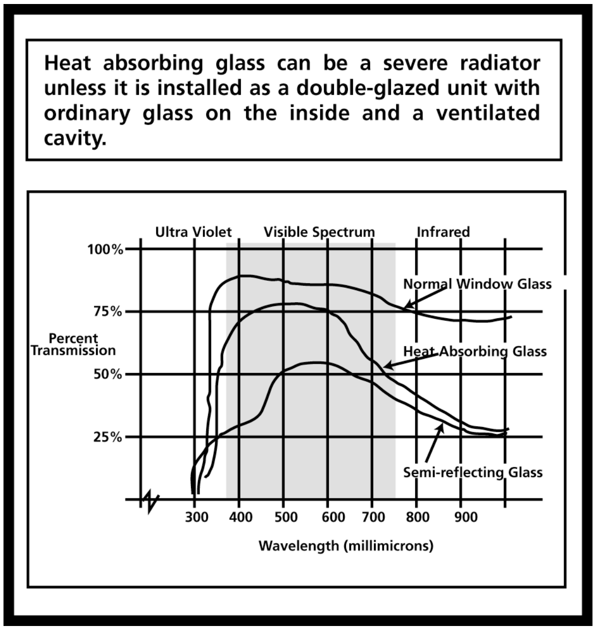


Internal shading devices are only as effective as the relative amount of direct solar radiation that they are capable of reflecting back through the window glass.

Approximate reduction in heat transfer due to selected internal and external shading devices:

Internal curtains		10% to 20%
Internal roller shades	(dark color)	20%
	(light color)	60%
Internal Venetian blinds	(dark color)	25%
	(light color)	45%
External canvas awnings	(with sides)	65%
	(without sides)	75%
External louvers	(light color)	85%

Figure 3.11: Internal shading devices



Heat absorbing glass can be a severe radiator unless it is installed as a double-glazed unit with ordinary glass on the inside and a ventilated cavity.

Figure 3.12: Transmission spectrum of various types of window glass

In recent years much research has been undertaken by glass manufacturers and allied industries, aimed at the development of glass and window units capable of substantially reducing heat transmission without proportional reductions in light transmission and transparency (Figure 3.12). One of the first of these glass products was the green tinted, heat absorbing or non-actinic glass. Heat absorbing glass in conformity with its name, absorbs a large proportion of the solar energy falling upon it, with the result that its temperature is substantially raised and it can act as a radiator. Despite this drawback, it has many applications in industrial and commercial buildings where occupants are unlikely to be in close proximity to the glazing (e.g., used as external sunshades in the UNESCO building in Paris). Although there are problems in its use for offices where staff are required to sit close to a window wall, many of these can be overcome if a sheet of ordinary glass is fitted parallel to but on the inside of the heat-absorbing glass and provision is made for ventilation of the air cavity between the two sheets so that the hot air can be removed.

The next development in the reduction of solar heat transmission was to seal a series of small, metal louvers between two sheets of glass. Such glasses incorporating built-in shading devices were initially used to advantage in a number of buildings in the US, but never gained wide-spread acceptance due to their relatively high cost. Probably the most notable achievement in this field has been the development of thin coatings that will transmit light but reflect heat. It has long been known that very thin films of some metals such as gold and copper have these properties and by combining this effect with techniques developed for attaching electrically conducting coatings to glass (e.g., for use as de-icing devices in aircraft wind screens), a completely new product known as semi-reflecting glass became commercially available in the 1970s. Figure 3.12 shows the properties of this type of glass when used in the form of a double glazed unit.

More recently, during the early 2000s, several window systems with low-emissivity (Low-E) glass have become commercially available. They typically utilize a special glass with low solar heat gain and high transparency properties. For example, the Solarban 60 glass manufactured by PPG Industries (Pittsburgh, Pennsylvania) relies on a 17-layer coating to reduce heat gain by 60% and heat loss by 75%, in a double-glazed window assembly. There are two types of Low-E glass. In hard coat Low-E glass tin is applied directly to the molten glass. This provides a hard coating that is difficult to scratch off. Soft coat Low-E glass is manufactured by applying a thin layer of silver while the glass is in a vacuum. Since this coating is delicate, the soft Low-E glass is sandwiched with another layer of glass.

3.4 Radiation through Roofs

Transmission of heat through roofs is a legitimate concern even in moderately warm climates. It is now well known that most of this heat transfer occurs by radiation and that therefore the ventilation of roof spaces will contribute little to ameliorate conditions. It is advisable to provide reflection by using a light-colored finish on the outside of the roof and to provide some form of reflecting foil suspended on the underside of the roofing surface in conjunction with six or more inches of insulating material. It is essential that this reflecting foil faces an air space between itself and the underside of the roof.

Perhaps another effective method is provided by spraying water onto the outside roof surface. Although, this method makes use of the evaporative cooling effect of a fluid, it has as yet found little practical application due to reasons of maintenance and capital cost. On the other hand, a similar system has been applied with success to multi-story buildings, where the entire roof surface is flooded with a permanent pool of water up to 12 inches deep. In this way a reinforced concrete roof slab covered with layers of bituminous felt, which would under severe solar exposure act as a radiator, can be economically insulated. In addition, the water layer protects the otherwise inevitable deterioration of the asphalt binder in bituminous roofing material under cyclic exposure to solar radiation. Normally, flat roofs are typically covered with mineral chippings to mitigate the deterioration of the roofing material. Unfortunately, over time the mineral chippings are either blown off the roof during windy conditions or sink into the asphalt when it softens during hot summer days.

Studies conducted by Richards (1957) in the 1950s in South Africa have shown that high ceilings have no significant effect on ventilation, indoor temperature, or the subjective sensation of radiation from the internal ceiling surface. It was concluded that from a thermal viewpoint a minimum ceiling height of around eight feet should be acceptable in any part of the world.

3.5 Sun Position and Orientation

Although we may reduce the heat exchange between the external environment and the building interior through the judicial use of thermal insulation, it is nevertheless very important that careful consideration be given to building orientation during the earliest design stages. By using readily available computer programs or solar charts, it becomes a relatively simple matter to calculate the degree of exposure of walls, windows, and the roof, to solar radiation. The results of these calculations provide the basis for optimizing the shape and orientation of the building, and the design of external sunshading devices.

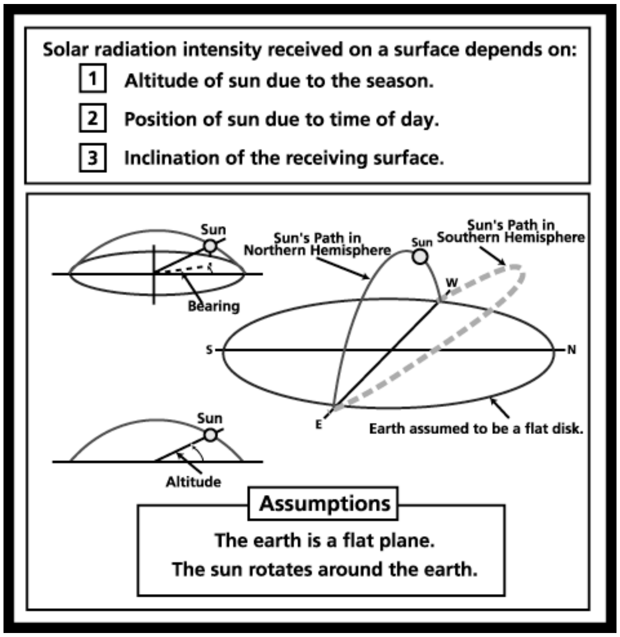


Figure 3.13: Sun variables and assumptions

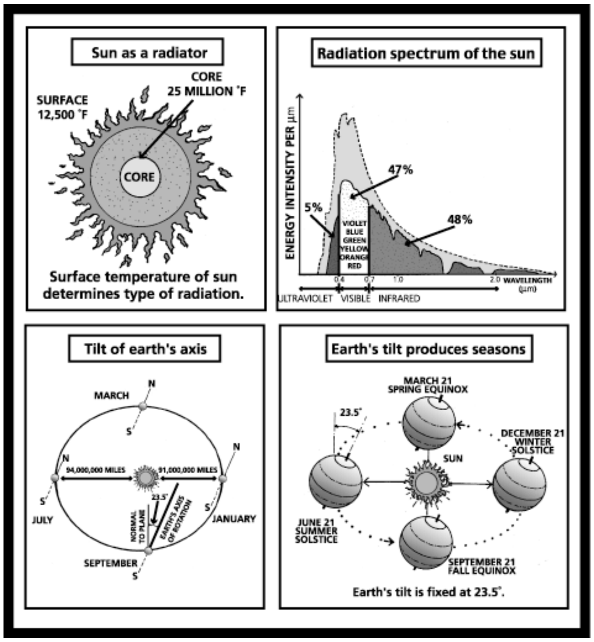


Figure 3.14: Radiation spectrum and seasons

Based on the supposition that solar radiation is of importance both positively in cold periods and negatively in hot periods, Olgyay (1952) has divided the year into *underheated* and *overheated* periods. This allows the optimum orientation of a building to be determined by the point where the average radiations for the underheated and overheated periods are a maximum and minimum, respectively.

From a general point of view, as shown in Figure 3.13, the amount of solar radiation received on a surface is dependent on three factors: (1) the altitude of the sun due to the season; (2) the position of the sun due to the time of day; and, (3) the inclination of the receiving surface. It has been found expedient to make two fundamental assumptions for purposes of simplifying the calculation of the sun's position in relationship to a building, namely: that the sun rotates around the earth; and, that the earth is flat.

The earth’s axis is tilted at 23.5º, which accounts for the seasons (Figure 3.14) and forms the basis for the equinox and solstice designations. As illustrated in Figure 3.15, the spring equinox and fall equinox occur on March 21 and September 21, respectively. On those dates the sun is directly overhead (90º) at the equator, the sun’s altitude at noon anywhere on the earth is exactly 90º minus the latitude of that location, and daytime hours are equal to nighttime hours. Similarly, the summer solstice and winter solstice occur on June 21 and December 21, respectively. During the summer solstice the sun is directly overhead (90º) at the Tropic of Cancer and during the winter solstice the sun is directly overhead (90º) at the Tropic of Capricorn. The equinox and solstice designations are more historical and mystical then technical in nature. Their significance stems mainly from pagan rites that were performed on these days to persuade gods to provide a plentiful harvest or a mild winter. The ancient goddess, Eostre, a Saxon deity who marked not only the passage of time but also symbolized new life and fertility, was a key symbol of the equinox celebration.

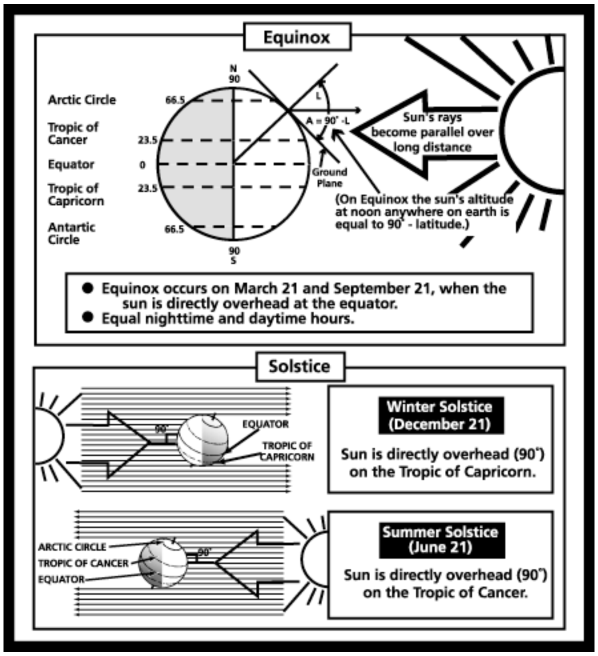
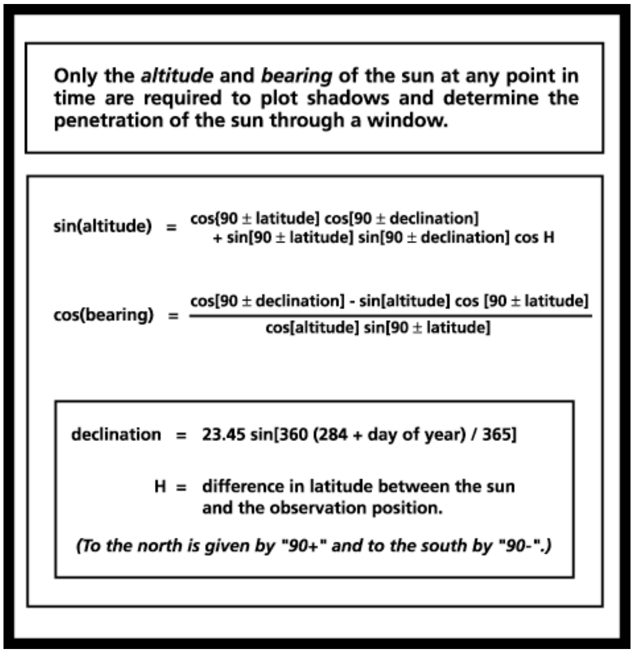


Figure 3.15: Equinox and solstice



Only the *altitude* and *bearing* of the sun at any point in time are required to plot shadows and determine the penetration of the sun through a window.

$$\sin(\text{altitude}) = \cos\{90 \pm \text{latitude}] \cos[90 \pm \text{declination}] + \sin[90 \pm \text{latitude}] \sin[90 \pm \text{declination}] \cos H$$

$$\cos(\text{bearing}) = \frac{\cos[90 \pm \text{declination}] - \sin[\text{altitude}] \cos[90 \pm \text{latitude}]}{\cos[\text{altitude}] \sin[90 \pm \text{latitude}]}$$

$$\text{declination} = 23.45 \sin[360\,(284 + \text{day of year}) / 365]$$

H = difference in latitude between the sun and the observation position.

(To the north is given by "90+" and to the south by "90-".)

Figure 3.16: Algebraic sun path solution

Based on the expedient assumptions that the earth is flat and that the sun rotates around the earth, it is necessary to ascertain only the altitude (A) and the bearing or azimuth (B) of the sun to plot shadows or predict the degree of penetration of the sun into a building space. These two parameters of the sun position at any time of day on any date can be either mathematically calculated (ASHRAE 1976, Duffie and Beckman 1974) or determined graphically (Libby-Owens-

Ford 1951, Hand 1948) on the basis of readily available solar charts. As shown in Figure 3.16 the algebraic solution of the sun path is given by two principal equations, based on the latitude (LAT) of the observation point, the declination of the sun (D) and the difference in latitude between the observation point and the sun (H):

$$\sin(A) = \cos(90^\circ \pm LAT)\cos(90^\circ \pm D) - (\sin(90^\circ \pm LAT)\sin(90^\circ \pm D)\cos(H) \quad \ldots\ldots\ldots\ (3.1)$$

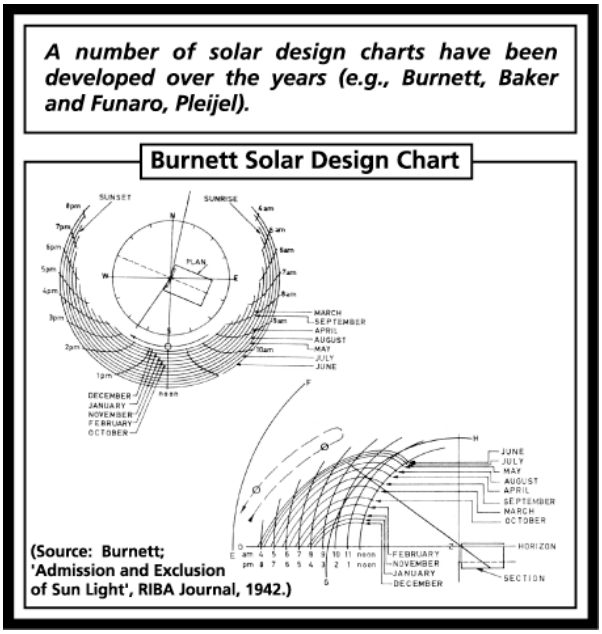
$$\cos(B) = \cos(90^\circ \pm D) - \sin(A)\cos(90^\circ \pm LAT) / (\cos(A)\sin(90^\circ \pm LAT)) \quad \ldots\ldots\ldots\ldots\ (3.2)$$

$$D = 23.45\,(\sin(360^\circ\,(284 + \text{day of the year}) / 365) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.3)$$

$$H = (\text{difference in latitude between sun and observation point}) \quad \ldots\ldots\ldots\ldots\ (3.4)$$

In equations 3.1 and 3.2, to the north is given by '90º +' and to the south is given by '90º -'. While the bearing (or azimuth) is usually measured from the south, the altitude is always measured as the angle from the point of observation between the horizon and the sun.

Clearly, the algebraic solution is rather laborious and is unlikely to be performed by architects. However, it is readily translated into computer software code and therefore forms the basis of several computer-aided design (CAD) programs that perform sun path calculations as part of their shadow or daylight rendering capabilities. If the required computer program is not available then graphical sun charts provide a practical alternative. A number of solar design charts have been prepared by various authors in past years, such as the Burnett chart and the Baker-Funaro chart.

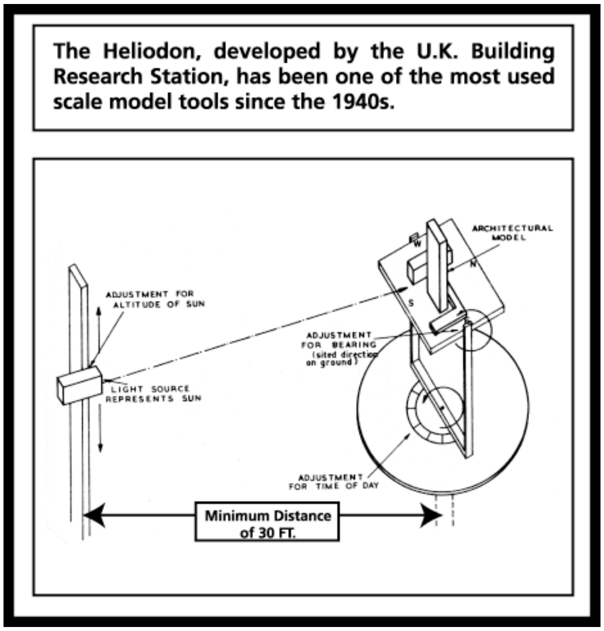


A number of solar design charts have been developed over the years (e.g., Burnett, Baker and Funaro, Pleijel).

Burnett Solar Design Chart

(Source: Burnett; 'Admission and Exclusion of Sun Light', RIBA Journal, 1942.)

Figure 3.17: The Burnett sun path chart



The Heliodon, developed by the U.K. Building Research Station, has been one of the most used scale model tools since the 1940s.

Figure 3.18: The UK Heliodon

The Burnett system consists of two diagrams that are available in printed form and may be used to solve most sun penetration problems as soon as small-scale plans and sections are available. The first diagram (upper left in Figure 3.17) shows the position of the sun in plan, at different times of the day and season. The second diagram (lower right in Figure 3.17) shows the altitude of the sun and is intended to be used in conjunction with the section of a building or room. The plan diagram consists of parts of concentric circles each representing the center day (i.e., the 15th) of a month, the hours of the day, sunrise and sunset, and the points of the compass. The plan of the building or room under consideration (drawn to a suitable scale) is positioned on the chart as shown in Figure 3.17, so that the hours of the day during which the sun can penetrate that particular building space can be read off for any month of the year between the boundaries AB and CD. Since the plan diagram cannot provide any information about the depth of the room, the second (section) diagram shows the altitude of the sun for the center day of each month in relationship to a reference point (Z). The times indicated by the boundaries AB and CD in the first (plan) diagram are drawn on section diagram (i.e., GH and EF), so that the sunlight available for admission to the room is represented by the month and time curves enclosed between the boundaries EF and GH.

A third alternative available to the building designer for determining sun angles is to build a small-scale model of a room or entire building. Such a model can be simply constructed out of cardboard, with the only requirement that it be geometrically fairly accurate. Model analyses of the sun path are particularly valuable for visualizing the impact of the sun path on a particular building design; however, they do depend on access to a testing facility. One of the most popular sun path model testing facilities is the Heliodon developed by the UK Building Research Station during the 1930s (Figure 3.18). The model is placed on a movable platform, which is easily tilted or rotated to simulate the particular latitude and time of day under consideration. A pin-hole light source, placed at a specified distance from the model (normally 30 feet) may be moved vertically to allow for the seasons of the year.

An Australian modification of this basic test arrangement is the Solarscope (Figure 3.19), which allows all variables to be controlled at the light source. The Solarscope is a very convenient, simplified and less expensive version of the Heliodon. However, it is also less accurate due to the relatively small distance between the light source and the model (i.e., the light rays are not parallel).

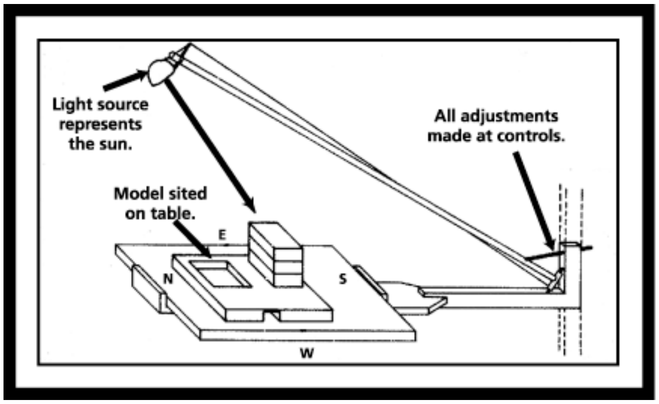


Figure 3.19: The Australian Solarscope

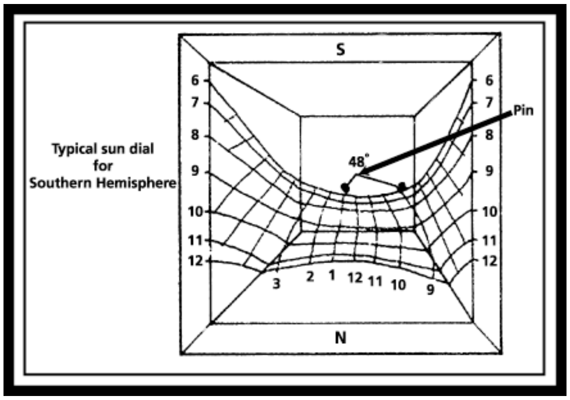


Figure 3.20: Pleijel's Sun Dial

3.6 Solar Design Steps

Whether or not mechanical or natural means of air conditioning are employed in a building, the need for energy conservation requires careful consideration of sun control for all window areas. While the glass element in walls is by far the most vulnerable source of heat transmission and glare, it is also the largest single factor that lends itself to simple preventive measures. In warm and hot climates, it is usually cheaper to keep heat out of the building environment initially, than to remove it from the interior by mechanical cooling equipment. Accordingly, in summer, the protection of windows from solar radiation is of primary importance, even when the actual window area is small.

In winter and particularly in colder climates the sun can become a useful source of heat, and its inclusion or exclusion must therefore be given careful consideration. The design steps that should be followed to optimize this aspect of environmental control are summarized below:

Step 1: A fundamental decision must be made regarding the type and degree of solar control required (i.e., reflection, diffusion, part or complete exclusion).

Step 2: The building layout and the orientation of all elevations must be considered next, before an attempt is made to settle the secondary question of shading. Should all solar radiation be excluded in summer? How much solar penetration is desirable in winter?

Step 3: The size and location of window areas will largely determine the amount of heat transmission through the external walls, and the amount of cooling and ventilation that can be provided by non-mechanical air movement. Consideration, at this stage, should also be given to glare and levels of illumination. Every attempt must be made to provide at least sufficient daylight for background lighting in the majority of building spaces.

Step 4: Finally, the selection of suitable shading devices will be largely a matter of economics. Available means of solar control in the form of fixed or movable devices, with or without remote control, must be analyzed in respect to capital cost, saving in energy, reliability, and durability.

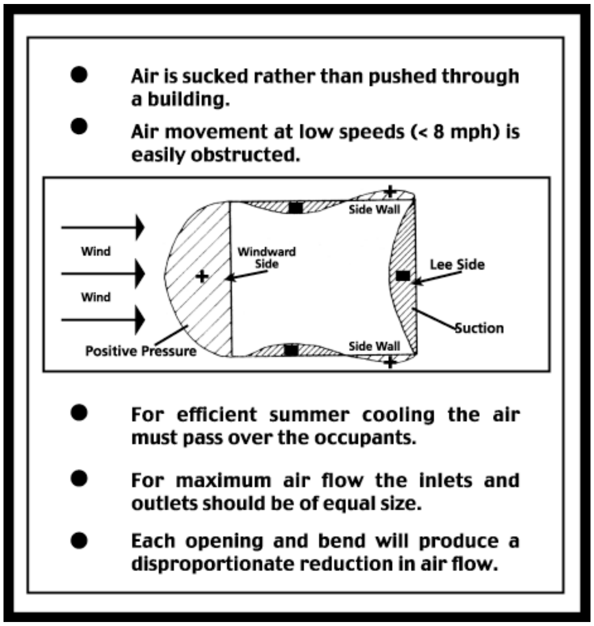
Datta and Chaudri (1964) published a very elaborate system of charts and graphs that furnish the required data for the design of numerous types of shading devices for tropical regions. Although these charts are rather complicated, they may be used to establish the following rules of thumb for practical guidance:

- For east and west orientations, where the altitude of the sun is likely to be low, inclined vertical louvers are most effective. If the inclination is perpendicular to the critical altitude of the sun, then the shadow coverage provided by the louvers will be a maximum.
- Horizontal shades are effective for the south orientations (or north orientations in the Southern Hemisphere), where the altitude of the sun is normally high. However, if these shades are inclined at less than 45° to the face of the wall, they are likely to interfere excessively with desirable solar penetration during the winter months.
- Orientations to the east and west of south (or northeast and northwest in the Southern Hemisphere), where the altitude of the sun is considered to be intermediate, will require a combination of horizontal shades and vertical shades. The latter may be inclined to be perpendicular to the critical altitude, while the horizontal shades take care of the higher altitudes of the sun, for which the vertical shades are ineffective.

3.7 Achieving Air Movement Naturally

In the absence of temperature and humidity control, the only remaining natural means of cooling a building environment is by means of air movement. It is understood, however, that the exposure of building occupants to air movement is most desirable in a hot humid climate where the perspiration mechanism of the human body is assisted by the accelerated passage of air over the skin. In hot dry climates, air movement would normally be restricted to the late afternoon and evening for the purpose of cooling the building shell from the inside.

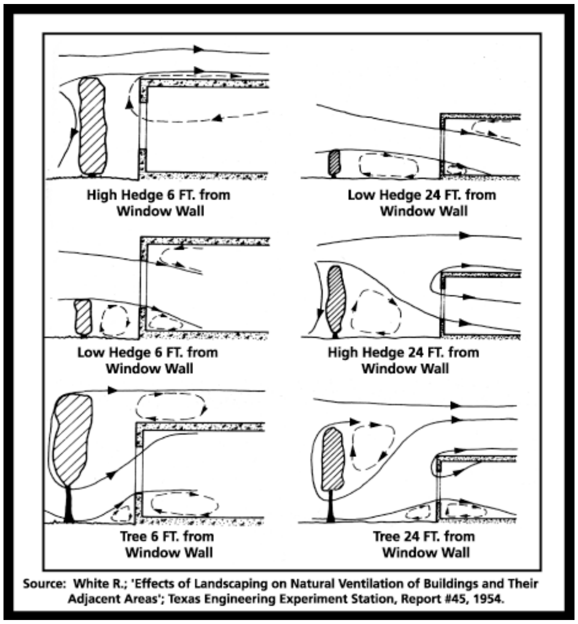
Research into aspects of natural ventilation has been mainly confined to a study of the size, shape and position of air inlets and outlets in building walls, and the geometry of the building plan in relationship to the air flow produced by naturally occurring winds. The artificial production of air movement by means of thermal currents has been largely abandoned as an effective measure for producing cooling in low structures.



- **Air is sucked rather than pushed through a building.**
- **Air movement at low speeds (< 8 mph) is easily obstructed.**

- **For efficient summer cooling the air must pass over the occupants.**
- **For maximum air flow the inlets and outlets should be of equal size.**
- **Each opening and bend will produce a disproportionate reduction in air flow.**

Figure 3.21: Impact of wind on buildings



Source: White R.; 'Effects of Landscaping on Natural Ventilation of Buildings and Their Adjacent Areas'; Texas Engineering Experiment Station, Report #45, 1954.

Figure 3.22: Effect of external vegetation

When wind impinges on a building shell a region of high pressure (positive) is normally produced on the windward surface of the building. As the air is deflected around the building it accelerates thereby causing regions of low pressure (suction) to be set up just behind the windward surface on the side walls and along the entire leeward side (Figure 3.21). Fundamentally, it would therefore appear to be necessary only to provide air inlets in the walls experiencing high pressure and air outlets in the walls subjected to low pressure or suction. Unfortunately, complications due to the inertia of the air, turbulence and the extremely variable nature of architectural planning arise, and have necessitated much experimental work on scale models. Sufficient test data has now been collected to make some general predictions about the nature of the parameters that control the desired air-flow patterns for effective summer cooling.

Effects of landscaping: In regions of varying topography, microclimatic considerations may dictate the appropriate orientation and internal planning of a building. For example, depending on the slope of a site it is likely that at night cool air will move downhill independently of the orientation, thereby producing air currents that may be utilized for ventilation purposes. Such air currents normally do not exceed speeds of three mph, but even at these low speeds they are capable of removing substantial quantities of heat from an exposed building shell.

Similar microclimatic influences occur in coastal regions where periodic land and sea breezes are produced by the unequal rates of heating and cooling of the adjacent land and sea masses. During the day under solar radiation the land becomes warmer than the sea thereby generating on-shore winds, while during the cooler night the reverse procedure occurs.

Most of the research dealing with the effects of wind breaks and their influence on the microclimate has been related to agriculture. However, in the mid 1950s the Texas Engineering Experiment Station published the results of an empirical study focused on the screening effects of hedges of various sizes and trees in proximity of buildings, shown in Figure 3.22.

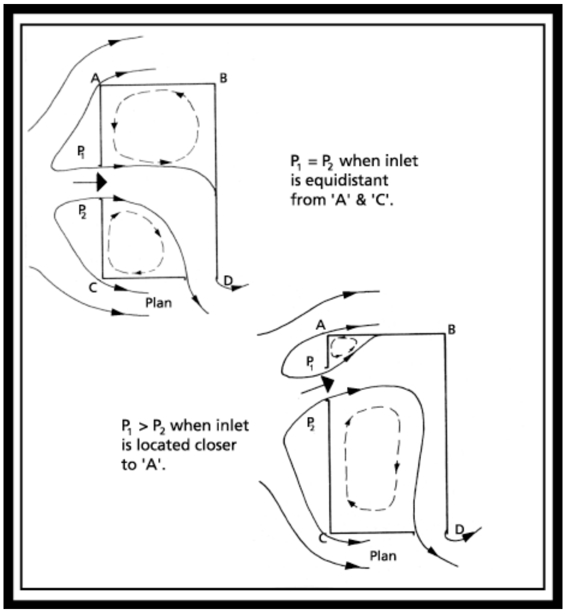


Figure 3.23: Impact of door location on air flow patterns

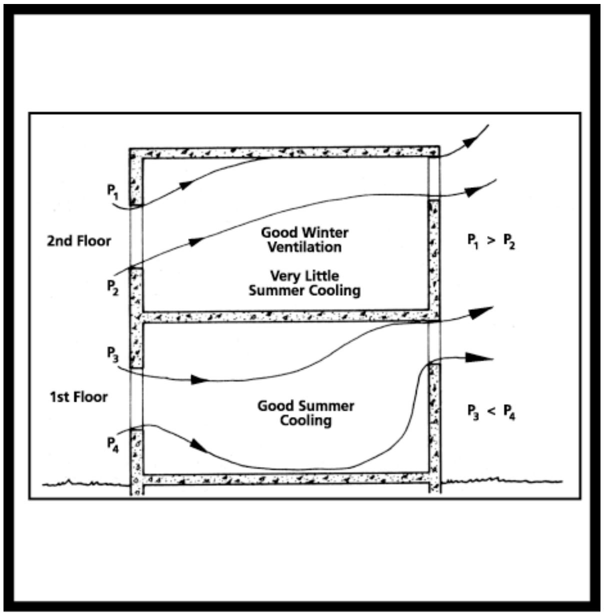


Figure 3.24: Impact of vertical room location on air flow patterns

Effects of building design: There are five factors that determine the air-flow pattern within building spaces; namely, the location, dimensions and type of inlets, and the location and size of the outlets. Of these, the location and type of inlet are by far the most important aspects. For example, Caudill and Reed (1952) have demonstrated (Figure 3.23) with wind-tunnel tests that the position of the inlet has a significant impact on the air pattern. When the opening is located symmetrically, similar pressures will exist on either side of the opening resulting in a fairly straight air flow. However, if the inlet is located asymmetrically the pressures on either side of the opening will be unequal forcing the air stream to enter diagonally. Similarly, in the case of a two-story building such pressure differences can decisively affect the air-flow pattern. As shown schematically in Figure 3.24, within the same building, rooms featuring identical location, size and type of inlets will be subjected to quite different air-flow patterns depending on whether they are situated on the first or second floor of the building. These and similar studies have produced some useful building design and floor plan layout guidelines.

1. To achieve maximum air-flow, inlets and outlets should be of approximately equal size. However, the concept of air change or ventilation rate has little bearing on summer cooling. The latter is influenced by the air-flow pattern. To achieve a satisfactory degree of summer cooling the air flow must pass over the occupants of the building and should therefore be directed downward to a level that is about two to five feet above the floor. For good winter ventilation, on the other hand, the air flow should be directed upward to the ceiling so that the building occupants are not exposed to an undesirable cold draft. However, if air-flow of a certain speed produces the required cooling effect then the air change requirements are likely to be more than satisfied. The design dilemma posed by a building space that must cater for both summer cooling and winter ventilation, can be resolved by the judicious use of window panes that can be pivoted and movable louvers.
2. The popular practice of locating extremely large openings on the windward wall of a building, as a means of increasing air flow within the building, is completely erroneous. In fact, slightly higher air speeds may be obtained whenever the outlet is larger than the inlet. This is because air is sucked, rather than pushed, through a building.
3. Openings that are partly obstructed will reduce air-flow by a disproportionate amount, especially at low wind speeds. For example, a 16-mesh mosquito screen will reduce the air-flow by about 60% when the wind speed is 1.5 mph and by only about 30% when the wind speed is 4 mph.
4. Each opening and bend to be negotiated by an air stream will produce a reduction in flow. Accordingly, the optimum flow is obtained by uninhibited cross-ventilation. Further to this, air-flow within building spaces is very much reduced if the direction of the wind is inclined more than about 30° to the normal axis of the inlet.
5. City and regional planning, landscaping, and architectural variables, such as building clusters, vegetation and overhangs will normally have a significant effect on the air-flow pattern around buildings.

3.8 Removal of Heat by Ventilation

Apart from the permanent ventilation requirements stipulated by building codes (i.e., number of air changes per hour), which are aimed at preserving the health and efficiency of the occupants, ventilation provides a means of removing heat from a building environment. In quantitative terms, the ventilation rate (V_R cubic feet per hour) required to remove heat (Q British Thermal Units per hour) is given by the following equation (Figure 3.25):

$$V_R = Q / (P\ S)(T_1 - T_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

where: V_R = Required ventilation rate (CF/HR)

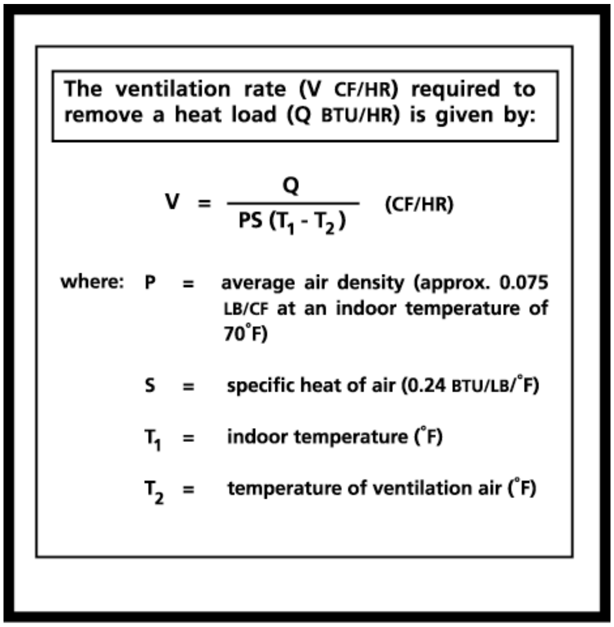
Q = Total heat load to be removed by ventilation (BTU/HR)

P = Average air density (0.075 LB/CF at 70º F indoor temperature)

S = Specific heat of air (0.24 BTU/LB/ºF)

$(T_1 – T_2)$ = The total rise in temperature of the incoming air (˚F). Since the ventilation rate is inversely proportional to $(T_1 - T_2)$ it will not be possible to remove all of the heat liberated within the building environment.)

An example application of equation (3.5) is shown in Figure 3.26, where the number of air changes per hour required to maintain an indoor temperature of 70˚F by removing a heat load of 12,000 BTU/HR in a room 12 FT by 14 FT and 8 FT height while the outside air temperature is 65˚F, is calculated to be just under 100 (air changes per hour).



The ventilation rate (V CF/HR) required to remove a heat load (Q BTU/HR) is given by:

$$V = \frac{Q}{PS\,(T_1 - T_2)} \quad \text{(CF/HR)}$$

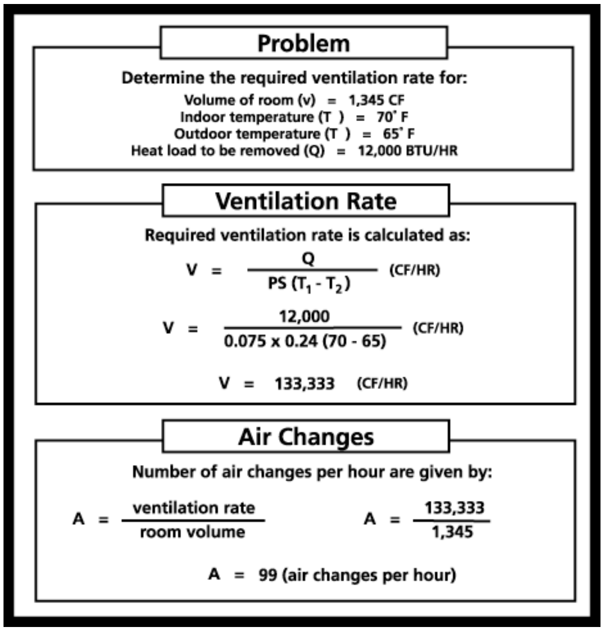
where: P = average air density (approx. 0.075 LB/CF at an indoor temperature of 70˚F)

S = specific heat of air (0.24 BTU/LB/˚F)

T_1 = indoor temperature (˚F)

T_2 = temperature of ventilation air (˚F)

Figure 3.25: Ventilation rate formula



Problem

Determine the required ventilation rate for:

Volume of room (v) = 1,345 CF

Indoor temperature (T) = 70˚ F

Outdoor temperature (T) = 65˚ F

Heat load to be removed (Q) = 12,000 BTU/HR

Ventilation Rate

Required ventilation rate is calculated as:

$$V = \frac{Q}{PS\,(T_1 - T_2)} \quad \text{(CF/HR)}$$

$$V = \frac{12{,}000}{0.075 \times 0.24\,(70 - 65)} \quad \text{(CF/HR)}$$

$$V = 133{,}333 \quad \text{(CF/HR)}$$

Air Changes

Number of air changes per hour are given by:

$$A = \frac{\text{ventilation rate}}{\text{room volume}} \qquad A = \frac{133{,}333}{1{,}345}$$

A = 99 (air changes per hour)

Figure 3.26: Ventilation rate calculation

3.9 Questions Relating to Chapter 3

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at back of the book.

1. **Experimental studies have shown that there exists a time delay between the maximum heat entry into the external wall of a building and the maximum dissipation of this heat into the building environment. This time lapse is related to the ___________________. Normally, _______________ construction will reduce the ability of a building environment to follow any but the most considerable changes in outdoor conditions, and then only after an appreciable time lapse. Choose the missing words.**

   A. Orientation of the wall; lightweight.

B. Exposure of the wall; curtain wall.
C. Porosity of the wall; heavyweight.
D. Thermal transmission value of the wall; lightweight.
E. All of the above (i.e., A, B, C and D) are incorrect.

2. **Air movement in buildings is most desirable in _______________ climates. Choose the missing words.**

A. hot
B. hot-arid
C. hot-humid
D. temperate
E. dry

3. **The ability of a material to store heat is a function of its ____________, which is a product of the ___________ and the _____________. Choose the missing words.**

A. temperature, solar radiation, specific heat
B. heat capacity, density, surface area
C. surface configuration, temperature, density
D. heat capacity, specific heat, temperature
E. All of the above statements (i.e., A, B, C and D) are incorrect.

4. **Which (if any) of the following statements is a correct description of the *Greenhouse Effect*?**

A. The inter-reflections of heat radiation within a building space cause a build-up of heat within the space.
B. The wavelength of solar radiation is changed as it passes through glass and the new shorter wavelength cannot pass easily through the glass for the heat to escape from a building space.
C. After solar radiation has passed through glass it is absorbed by the objects within a building space. As these objects heat up, they become radiators themselves and produce much shorter wavelength radiation. This shorter wavelength radiation cannot pass through the glass for the heat to escape from the space to the outside.
D. All of the above statements (i.e., A, B and C) are incorrect.

5. **On which external wall of a building would you recommend the use of <u>horizontal projections</u> or <u>horizontal louvers.</u>**

A. South orientation.
B. East orientation.
C. East and west orientations.
D. West orientation.
E. South-west and south-east orientations.

6. **On which external wall of a building would you recommend the use of egg-crate shading?**

   A. South orientation.
   B. East orientation.
   C. East and west orientations.
   D. West orientation.
   E. South-west and south-east orientations.

7. **On which external wall of a building would you recommend the use of vertical projections and movable vertical fins?**

   A. South orientation.
   B. East orientation.
   C. East and west orientations.
   D. West orientation.
   E. South-west and south-east orientations.

8. **Which (if any) of the following statements relating to heat absorbing glass is not correct?**

   A. Although there are problems in its use for office buildings where persons are required to sit close to a window wall, these can be largely overcome if a sheet of ordinary glass is fitted parallel to but on the outside of the heat absorbing glass.
   B. When heat absorbing glass is used in a double-glazed window unit provision should be made for ventilation of the air cavity between the two sheets of glass.
   C. Heat-absorbing glass absorbs a large proportion of the solar energy falling upon it and can therefore act as a radiator.
   D. Heat-absorbing glass can be used successfully as external shading in multi-story buildings.
   E. All of the above statements (i.e., A, B, C and D) are correct.

9. **In hot-humid climates, thermal insulation in roofs is best provided by:**

   A. Two-inch thick polystyrene foam.
   B. Reflecting foil facing a cavity on the underside.
   C. Reflecting foil facing a cavity above and four-inch polyurethane attached to the underside.
   D. One-inch-thick polystyrene foam with an aluminum foil attached to its underside.
   E. Ventilation of the roof space.

10. **From the point of view of thermal considerations, the ceiling heights of naturally ventilated buildings _____________________. Choose the missing words.**

A. Should be around 8 feet.
B. Should be as high as possible.
C. Need not be considered.
D. Should be as low as possible.
E. All of the above are incorrect.

11. **Which (if any) of the following statements are not correct?**

A. At the Equinox, which occurs on March 21 and September 21, the sun is directly overhead at noon at the equator.
B. At the Equinox the altitude of the sun at noon anywhere on earth is equal to '90° minus the latitude' of that location.
C. At the Equinox daytime and nighttime hours are equal.
D. At the Winter Solstice (on December 21) the sun is directly overhead on the Tropic of Capricorn.
E. All of the above statements (i.e., A, B, C and D) are correct

12. **From a general point of view, the amount of radiation received on the earth's surface is dependent on two of the following factors:**

1. Position of the sun due to the seasons.
2. Texture of the surface.
3. Position of the sun due to the time of day.
4. Appearance from time to time of sunspots.
5. Position of the sun in relation to the equator.
6. Relative distance between sun and earth.

Which of the above factors apply:

A. 1 and 2
B. 4 and 5
C. 2 and 6
D. 1 and 3
E. 2 and 5

13. **Air movement in buildings is most desirable in _______________ climates. Choose the missing words.**

A. hot
B. hot-arid
C. hot-humid
D. temperate
E. dry

14. **When wind impinges on a building shell, a region of ______ is normally produced on the windward surface of the building. As the air is deflected around the**

building it accelerates, thereby causing regions of _______ to be set up just behind the windward surface on the side walls and along the entire ________________. Choose the missing words.

A. low pressure; suction; roof.
B. high pressure; suction; lee wall.
C. suction; high pressure; lee side.
D. suction; low pressure; roof.
E. All of the above (i.e., A, B, C and D) are incorrect.

15. **Which of the following (if any) factors has no bearing on the air-flow pattern within building spaces?**

A. Location and type of windows acting as inlets.
B. Dimensions of the inlets.
C. Location of the outlets.
D. Size of the outlets.
E. All of the above (i.e., A, B, C and D) have bearing on the air-flow pattern within buildings.

16. **Which (if any) of the following statements is not correct?**

A. To achieve maximum air-flow in buildings, inlets and outlets should be of approximately equal size.
B. Summer cooling in buildings is mainly governed by the number of air changes per hour rather than the air-flow pattern.
C. It is good practice to locate extremely large openings on the windward wall of a building in order to improve the air-flow within the building.
D. All of the above statements (i.e., A, B and C) are correct.
E. More than one of the above statements (i.e., A, B, C and D) are incorrect.

17. **In the Northern Hemisphere, the sun rises in the ______, while in the Southern Hemisphere the sun rises in the ___________. Choose the missing words.**

A. east; east
B. east; west
C. west; east
D. west; west

18. **One of the major shortcomings of the Solarscope is that:**

A. It is only useful for analyzing small models of buildings.
B. It cannot simulate the time of day.
C. It is not suitable for measuring illumination levels inside buildings.
D. The distance between the light source and the model is short.
E. The light source cannot adequately reproduce the quality of sunlight.