PASSIVE AND HYBRID SOLAR LOW ENERGY BUILDINGS

ENERGY DESIGN PRINCIPLES IN BUILDINGS

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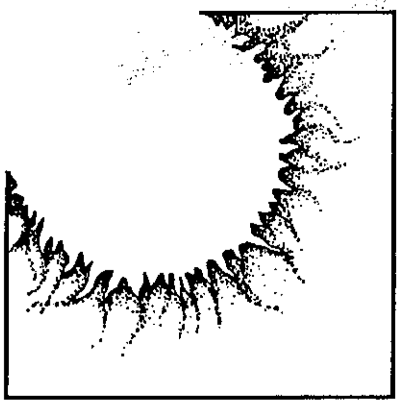
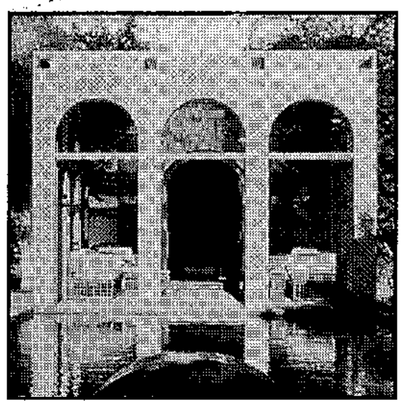
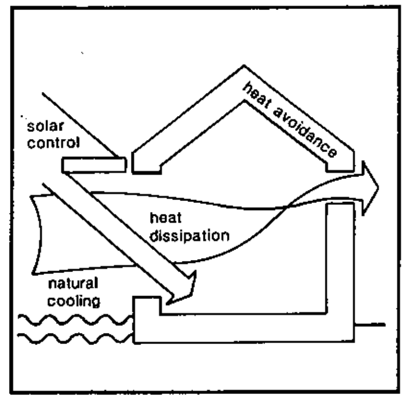
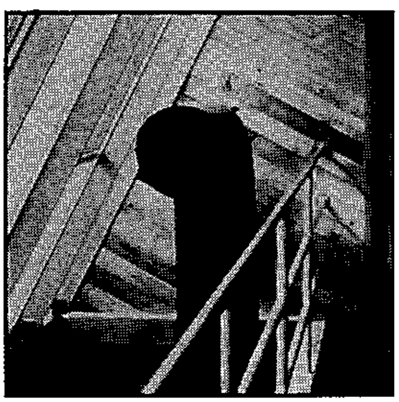
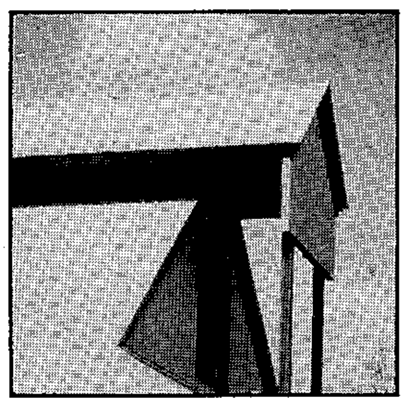
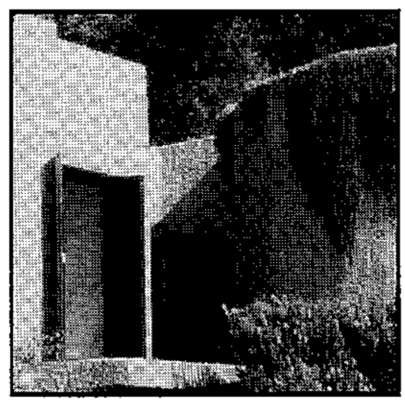
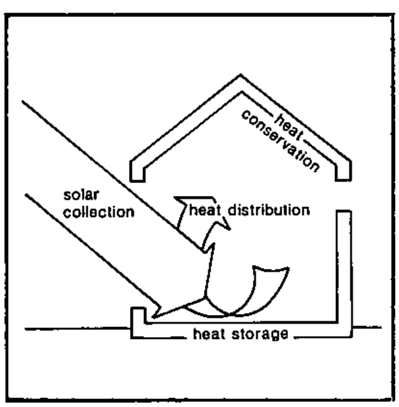
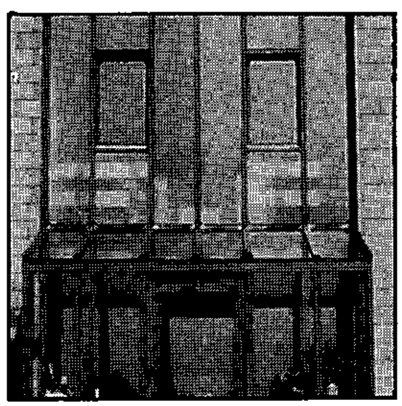
DESIGN INFORMATION BOOKLET NUMBER ONE

JULY 1988




INTERNATIONAL ENERGY AGENCY: SOLAR HEATING AND COOLING PROGRAM

PASSIVE AND HYBRID SOLAR LOW ENERGY BUILDINGS

ENERGY DESIGN PRINCIPLES IN BUILDINGS

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JULY 1988

Anne Minne

Prepared on the basis of the book "Architecture et Climat: Guide d'aide à la Conception Bioclimatique", M. le Paige, E. Gratia and André De Herde.

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INTERNATIONAL ENERGY AGENCY: SOLAR HEATING AND COOLING PROGRAM, TASK VIII

FOREWORD

The International Energy Agency (IEA), headquartered in Paris, France, was formed in November 1974 to establish cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development. Twenty-one countries are presently members, with the Commission of the European Communities participating under a special arrangement.

One element of the IEA's program involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies that have the potential of making significant contributions to global energy needs were identified for collaborative efforts. Solar heating and cooling was one of the technologies selected for joint activities. Cooperative research is conducted under terms of a formal Implementing Agreement signed by the participating countries. One of the collaborative projects, Task VIII, concerns passive and hybrid solar, low energy buildings.

The goal of Task VIII is to accelerate the technical understanding and marketplace availability of energy efficient, passive solar homes. Fourteen countries have participated in the research - Austria, Belgium, Canada, Denmark, Federal Republic of Germany, Italy, Netherlands, New Zealand, Norway, Spain, Switzerland, Sweden, United Kingdom and United States.

The knowledge gained during this collaboration has been assembled in a series of eight booklets. The Design Information Booklets in the series are listed and described on the opposite page.These booklets can be purchased by contacting the following organizations:

Austria
Osterreichisches
Forschungzentrum Seibersdorf
A - 2444 Seibersdorf

Belgium
Science Policy Office
Rue de la Science 8
B - 1040 Brussels

Canada
Solar Energy Development Program
Energy, Mines and Resources
460 O'Connor Street
Ottowa, Ontario K1A OE4

Denmark
Thermal Insulation Laboratory
Technical University of Denmark
Building 118
DK - 2800 Lyngby

Germany
Projektleitung Biologie, Okologie und Energie
KFA Jülich
Postfach 1913
D - 5170 Julich

Italy
Consiglio Nazionale Ricerche
Progetto Finalizzato Energetica
Via Nizza 128
I - 00198 Roma

Netherlands
Management Office for Energy Research (PEO)
P.O. Box 8242
NL - 3503 - RE Utrecht

New Zealand
School of Architecture
Victoria University of Wellington
Private Bag
Wellington 1

Norway
A/S Miljoplan
Kjorboveien 23
N - 1300 Sandvika

Spain
IER - CIEMAT
Avda Complutense 22
28040 Madrid

Sweden
Svensk Byggtjänst,
Litteratutjänst
Box 7853,
103 99 Stockholm

Switzerland
Federal Office of Energy
CH - 3003 Berne

United Kingdom
Renewable Energy Enquiries Bureau
Energy Technology Support Unit
Harwell Laboratory, Building 156
Oxfordshire OX 11 ORA

United States
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

The U.S. Department of Energy (DOE) is the Operating Agent of IEA Task VIII: Passive and Hybrid Solar Low Energy Buildings. Michael J. Holtz of Architectural Energy Corporation, Boulder, Colorado, serves as Task Chairman on DOE's behalf.

DESIGN INFORMATION BOOKLET SERIES

Booklet No. 1 Energy Design Principles In Buildings
This Booklet is essentially a primer of heat transfer in buildings. Fundamental heat transfer concepts and terminology are defined, followed by a discussion of heating and cooling strategies and principles for passive and hybrid solar buildings. It is written in non-technical language for the designer or builder not familiar with general heat transfer principles in buildings.

Booklet No. 2 Design Context
Booklet number 2 defines, in a checklist format, the issues that are unique to energy conserving, passive solar design that must be considered early in the design process. Issues discussed include site and climate analysis, building organization and design, building system options, space conditioning options, user influence and building codes and zoning ordinances.

Booklet No. 3 Design Guidelines: An International Summary
Passive solar and energy conservation design guidelines have been developed by each participating country. These guidelines are presented in national design guidelines booklets. Booklet number 3, Design Guidelines: An International Summary, summarizes the major findings and patterns of performance observed from the national passive solar and energy conservation guidelines.

Booklet No. 4 Design Tool Selection And Use
This Booklet addresses the characteristics desirable in a design tool and a means to select one or more for use. The selection process is organized around the design process; what design questions are being addressed, what information is available, what output or result from a design tool for which one is looking. A checklist is provided to assist in design tool selection. The use of benchmark test cases developed from detailed building energy analysis simulations is presented as a means to evaluate simplified design tools.

Booklet No. 5 Construction Issues
Construction problems unique to the use of passive and hybrid solar features are defined in this booklet as well as several proven solutions. Due to the unique construction technology in each country, representative construction details are provided. The intent is to define where construction detailing is crucial to the performance of low energy, passive solar homes and provide some ideas on how these detailing problems can be solved for a range of construction technology.

Booklet No. 6 Passive Solar Homes: Case Studies
This Booklet describes the passive and hybrid solar houses designed, constructed and monitored under the IEA Task VIII project, as a means of showing the architectural impact of energy conservation and passive/ hybrid solar features. This booklet reinforces the idea that good energy design is also good architecture and is cost effective. Each of the passive solar houses is presented as a case study on the design, construction and performance results.

Booklet No.7 Design Language
Booklet number 7 is aimed at designers , architects and educators. It defines an approach to generating whole building solutions based on climate analysis and design context analysis. It also addresses architectural typologies based on climatic/ energy principles.This booklet forms a general, universal companion to Booklet No.3, Design Guidelines.

Booklet No. 8 Post Construction Activities
Post Construction Activities defines issues to be considered once the project is constructed and occupied. It addresses those elements of the passive solar building that are unique and may require special attention by the occupants. Performance evaluation of the home in terms of energy performance, comfort and occupant satisfaction is also addressed as a means of providing information back to the designer on how well the project is performing.

ACKNOWLEDGEMENTS

This report was made possible by the support of the Belgian Scientific Research Policy-Services of the Prime Minister(SPPS- DPWB). The author wishes to acknowledge the support, assistance and technical review provided by the project participants and the other authors in this booklet series including G. Lohnert, M. Holtz, D. Anderson, H. Kok, S. Los and R. Brewer. Also, the editorial and production assistance of the Operating agent, M. Holtz, and of Joel Swisher and Chris Mack all of Architectural Energy Corporation is gratefully acknowledged.

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CONTENTS

INTRODUCTION

The purpose of this Booklet is to define and explain the basic principles of energy processes in buildings. The level of technical detail is meant to be sufficient to help the designer understand the strategies which may be used to design energy efficient passive solar buildings. For a more rigorous technical treatment of these topics, the reader is referred to the standard texts in the fields of thermodynamics and heat transfer.

For most locations throughout the world, climatic conditions range beyond the limits of normal human comfort, requiring the use of thermal controls, through building design and/or mechanical equipment, to maintain acceptable levels of interior thermal comfort. Passive solar design strategies can realize the thermal control potential of the building envelope. This is accomplished by directing the natural energy flows, caused by sun, wind, and temperature differences, to provide heating in the winter and cooling in the summer.

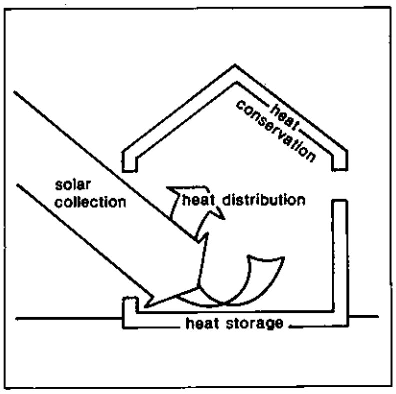
This Booklet covers the basic concepts necessary to design various types of passive solar systems. The choice of how to use these concepts, and how to integrate them with other design goals, is the responsibility of the designer. Neither this Booklet, nor any other document, can teach good design. Such information can only provide the designer with additional tools to evaluate and select a good design from the infinity of possibilities.

The various types of passive solar systems are each a specific combination and application of the principles described in this Booklet. Each system is a complete process for heating or cooling, where several different principles interact to provide a desirable balance between energy efficiency and comfort, between heating and cooling, between solar energy collection and thermal storage, and so on. Some of these principles have interdependent effects. For instance, it is not useful to increase the glazing area to collect solar energy if the thermal storage mass is not sufficient to store that energy.

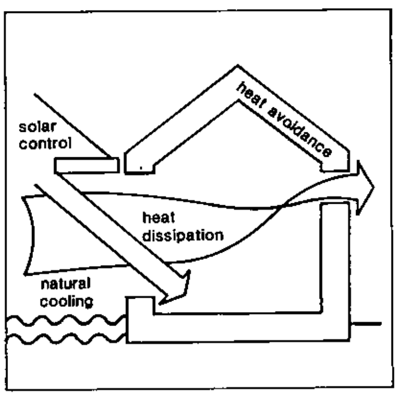
Climate deviates from the ideal conditions in two directions: too cool or too warm. The design strategies to solve these two problems are referred to in this Booklet as "Heating Strategy" and "Cooling Strategy", respectively. In most locations, climate variations require the use of both strategies at some time during the year.

In this Booklet, each strategy is divided into four principles. The purpose of this division is to provide an understanding of the different elements which one can use to achieve a successful passive solar design. The comparative importance of these different principles depends on the type of climate and a certain flexibility is always possible. In colder climates, heating strategies deserve a higher priority, while cooling strategies should be emphasized in warmer climates. However, both heating and cooling must be considered in designing for year-round thermal comfort.

The effectiveness of an individual design will depend on the careful balance between the principles. Although the designer may choose to emphasize the heating strategy in order to minimize purchased energy use, the cooling strategy must not be forgotten. Otherwise overheating and poor thermal comfort will result. Conversely, designs which favor the cooling strategy must also include the heating strategy for winter comfort. Every design must balance the two strategies, and some principles are helpful in achieving both. For example, insulating the building envelope can hold heat inside the building during the winter, and keep heat out during the summer. Other features, including orientation, thermal mass, and air circulation, can also be used beneficially in both the heating and the cooling strategies.



The heating strategy is defined in a positive way with regard to the sun: it is a matter of making use of solar radiation as much and as long as possible. The first goal is to collect the sun's rays and to convert them into heat (first principle: solar collection). Because of daily and seasonal climatic cycles, it is judicious to collect more solar energy during a sunny day than immediately necessary, and to store the excess for later use (second principle: heat storage). For the sake of comfort, this solar heat must be distributed in the whole building (third principle: heat distribution). Finally, the heat collected and that produced inside the building must be contained inside the building as long as possible while allowing adequate fresh air entry (fourth principle: heat conservation).

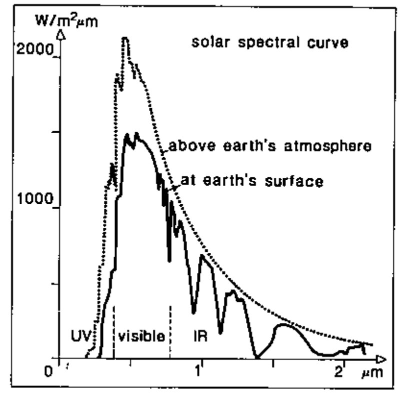


The cooling strategy is negatively defined: the main concern is to avoid or remove the sun's energy in order to keep the inside temperature comfortable. The first goal is to keep the sun's rays from reaching and entering the building (first principle: solar control). Protection against heat conduction through the building envelope and against hot air infiltration is also necessary (second principle: heat avoidance). Despite the observance of these two principles the building can overheat, partly because of the internal gains (appliances and people). The hot air must be removed and replaced by cooler outdoor air if the outdoor air temperature is comfortable (third principle: heat dissipation). Some natural ways of cooling can also be used to decrease the temperatures of the envelope and the inside air (fourth principle: natural cooling).

FUNDAMENTALS

SOLAR RADIATON

The closest fixed star to the earth is the sun. It releases a power flux of 63 million watts per square meter surface area. This energy is produced by nuclear chain reactions. Only a part of the emitted energy reaches the outer edge of the earth's atmosphere. This is the **solar constant,** and it has a value of 1367 W/m^2. The total power received at that level is 220 billion megawatts (2.2 × 10^{17}W). The solar spectrum extends from about 0.29 μm to 4.0 μm (1 μm =10^{-6}m). Less than 1% each are contributed to the solar constant from spectral ranges beyond these limiting wavelengths.



The power received at ground level is less because the atmosphere absorbs about 20% of the radiation and reflects about 25%. A fraction of the radiation reaches the ground directly while the remainder reaches it after being diffused by the atmosphere. The global radiation is defined as the sum of direct and diffused radiation.

The amount of energy received depends on the location, the hour of the day, the time of year, and the meteorological conditions.

When solar radiation strikes a body:

REFLECTION

- a part of the radiation is **reflected.**
The fraction reflected depends on the angle at which the rays strike the body and on its surface color and texture.
White and smooth surface: high reflection.
Black and rough surface: low reflection.
Reflectance is the ratio of the total reflected flux to the total incident flux.

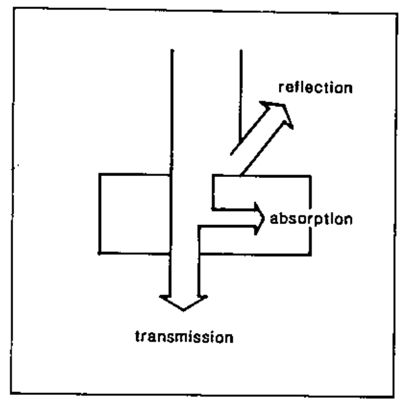
TRANSMISSION

- another part is **transmitted.**
This happens only if the material is transparent or translucent. Glass lets the sun's rays pass through it while metal doesn't.
Transmittance is the ratio of the total transmitted flux to the total incident flux.

ABSORPTION

- the remainder is **absorbed.**
This part is transformed into heat.
Absorptance is the ratio of absorbed flux to the total incident flux.

Materials can be selective with regard to radiation. This means that they do not reflect, absorb or transmit in the same proportions at every wavelength. Thus the materials can also be characterized by their spectral curve of reflectivity, transmissivity, or absorptivity, over a range of wavelengths.



HEAT

Heat is one of form of energy. It appears as a molecular movement in a body, liquid or gas, or as radiation in space. Heat is measured in Joules as any other form of energy.

TEMPERATURE

Temperature is a measure of the thermal state of a substance. Different scales exist. The Celsius scale (or centigrade) takes the freezing point of water as 0° and its boiling point as 100° (under standard atmospheric pressure). The Kelvin scale (or absolute temperatures) takes the absolute zero as 0°, and keeps the intervals of Celsius scale. Absolute zero is the lowest temperature one can achieve. Its value in the Celsius scale is minus 273.15°C. Thus x K = x - 273.15°C. A Kelvin degree is noted K. Kelvin degree is the unit of the International System.

SPECIFIC HEAT (c_p)

This is the amount of energy needed to raise a unit mass of a given substance through 1 K. It is measured in J/kgK. The specific heat of fluids varies with temperature and pressure.

THERMAL STORAGE CAPACITY

The specific heat may be related to volume by multiplying c_p by density (expressed in kg/m^3). The product is the thermal storage capacity, expressed in J/m^{3}K.

SENSIBLE HEAT

Sensible heat is the thermal energy which, when absorbed by a body, increases its temperature without changing its state.

LATENT HEAT

Latent heat is the heat necessary to cause a change of state of a substance (from solid to liquid, for instance). The change of state of the elements occurs at constant temperature. The same amount of heat is released at a change of state in either direction.

THERMODYNAMICS PRINCIPLES

First Principle: Energy Conservation
Energy exists in different forms. It cannot be created or destroyed but only converted from one form to another. Thus in any system the energy input equals the energy output plus the change in stored energy.

Second Principle: Energy Quality and Temperature
Energy transfer takes place spontaneously in one direction only: from a higher grade to a lower grade. In other words, for thermal energy, heat transfer takes place from a warmer body to a cooler one. It is impossible to reverse the direction of heat delivery without any external energy input. Another corollary is that the establishment of heat flow requires both a source and a sink.

HEAT FLOW

Heat flow is the transfer of thermal energy toward a lower temperature sink. This takes place in different ways: by conduction, by convection or by radiation. **The heat flow rate** through a body or a plane in space is the amount of energy passing through in unit time. This is expressed in Watts. **The heat flux density** is the heat flow rate per unit area, measured in W/m^2.

CONDUCTION

Heat can be transferred through an object by conduction. Molecular movement is transmitted gradually through a body or between bodies in direct contact. The magnitude of heat flow through a body depends on the area of the section perpendicular to the heat flow direction, on the thickness of the body, on the difference in temperature between the two points considered, and on the conductivity of the material.

Conductivity (k) is defined as the heat flow rate through a unit area and unit thickness of that material with unit temperature differences across the thickness of the body. The lower the k-value, the better its insulating effect. It is expressed in W/mK.

Resistivity (r) is the reciprocal of conductivity, $1/k = r$ (mK/W).

Resistance (R) is the product of resistivity and thickness of a body (m^2K/W).

Conductance (U) is the reciprocal of resistance, $1/R = U$ (W/m^2K). It represents the thermal transmission per square meter of a particular material or assembly per degree K of temperature difference between its inside and outside surfaces.

THERMAL INERTIA

Thermal inertia is an expression of the resistance of a body to decrease its temperature. This depends on its thermal storage capacity and its thermal resistance.

THERMAL DIFFUSIVITY

Thermal diffusivity expresses the rate of heat diffusion throughout a material. The greater the value the greater the heat diffusion. Thermal diffusivity of a substance depends on its thermal conductivity, its density and its specific heat. It can be considered as the surface area of a sphere over which heat spreads from a point input in unit time. It is measured in m^2/s.

DIURNAL HEAT CAPACITY

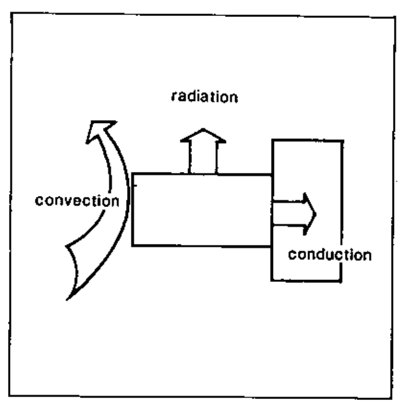
The diurnal heat capacity of a material is the daily amount of heat, per unit of surface area, that is stored and then given back per unit of temperature swing.

CONVECTION

Convection is heat transfer from the surface of a solid body to a fluid, gas or liquid, or inversely from a fluid to a solid body. The rate of heat flow depends on the area of contact, the temperature difference between solid and fluid, and the convective heat transfer coefficient (or film coefficient), which depends on the flow geometry, the viscosity and velocity of the fluid, and whether the fluid flow is laminar or turbulent.

RADIATION

Heat can also be transmitted through space (in a vacuum or a transparent or semi-transparent gas) in the form of radiation from one body to another. The emission wavelength spectrum depends on the nature and on the temperature of the surface of the body. The magnitude of radiant heat flow depends on the temperatures of the radiating and receiving surfaces and on the emissivity and absorptivity of those surfaces, respectively. Solar energy reaches the earth in the visible band of the radiation spectrum, as well as the longer wavelength infrared and shorter wavelength ultraviolet bands.



Emittance is the ratio of the thermal radiation from a unit area of a surface to the radiation from unit area of a full emitter ("black body") at the same temperature.

PSYCHROMETRIC TERMS

Atmosphere is composed by air (mostly oxygen and nitrogen) and water vapor. The vapor content of air, expressed in grammes of moisture per kg of dry air, is called **absolute humidity** (g/kg). The maximum quantity of water vapor air can contain depends on the air temperature and is called **saturation humidity.** It increases with temperature. **Relative humidity** is a measure of the quantity of moisture contained in the air. It is defined as the ratio of the vapor pressure to the saturation pressure at a given temperature.

PSYCHROMETRIC PROCESSES

Dehumidification and Condensation by Cooling
For any value of absolute humidity, there is a temperature at which this becomes the saturation humidity. Thus, when cooling air which has a certain moisture, a temperature is reached called **dew point temperature** where the amount of vapor is the maximum air can support, and the moisture begins to condense. Consequently, the quantity of water vapor decreases. This phenomenon can cause condensation problems in non watertight building elements when the outdoor temperature is lower than the dew point temperature corresponding to the indoor moisture, causing the moist air leaking out to condense as it cools to the outdoor temperature.

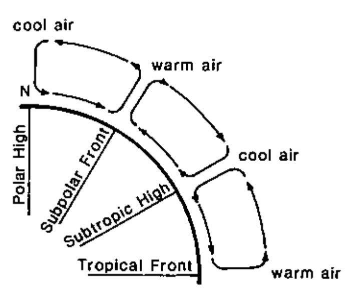
Evaporative Cooling
The evaporation of liquid water to vapor requires a certain amount of heat. An increase in moisture by evaporation, without any heat input or removal, takes the latent heat necessary from the atmosphere, decreasing its temperature. This process is limited by saturation, so it is most effective in drier climates where more vapor can be added to the air before reaching saturation.

AIR PRESSURE

All fluids exert a pressure due to gravitational force. Contrary to the solid bodies which have only a vertical downward pressure component, the free molecules of fluids transmit the same pressure horizontally. The vertical and horizontal pressure components at one point are equal, and depend on the vertical height of the fluid above and on the fluid density, which in turn depends on temperature.

AIR MOVEMENT

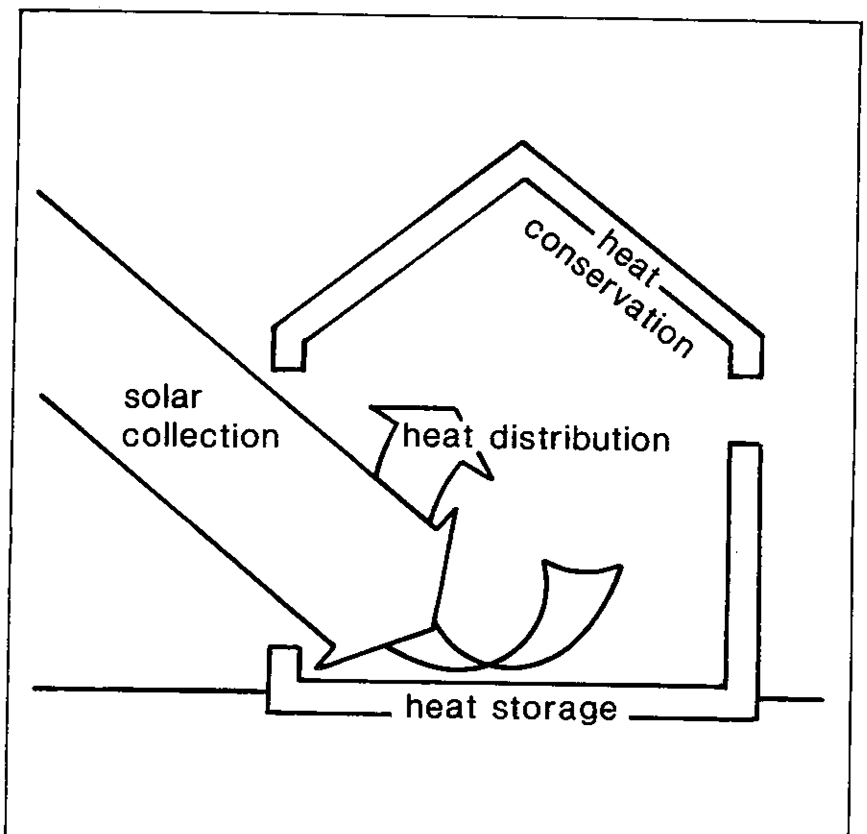
Air masses can be at a different temperature, and their pressures can vary from one location to another. By the principle of equilibrium of forces, air from high-pressure areas flows to low-pressure areas tending to equalize the differential pressure and heating of the two air masses. This movement in the atmosphere creates wind.



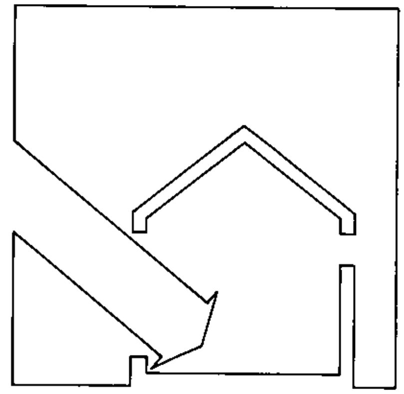
Solar radiation received at the earth's surface depends mostly on the latitude and the resulting duration of sunshine. Small local variations are induced by cloudiness and atmospheric pollution. At the zone of maximum radiation, air is heated and consequently its density decreases. Warm air masses rise causing flow toward cooler zones at high level. At high altitude the air becomes cooler and part of this air mass flows down to the surface. The air currents are deflected by the Coriolis forces induced by the earth's rotation. In the northern hemisphere surface air circulation around a high pressure zone (anticyclone) is always clockwise and anticlockwise around a low pressure zone (cyclone). It is the opposite in the southern hemisphere. These broad patterns are widely modified by local conditions deflecting the wind stream or inducing differences in pressure and temperature.

HEATING STRATEGY

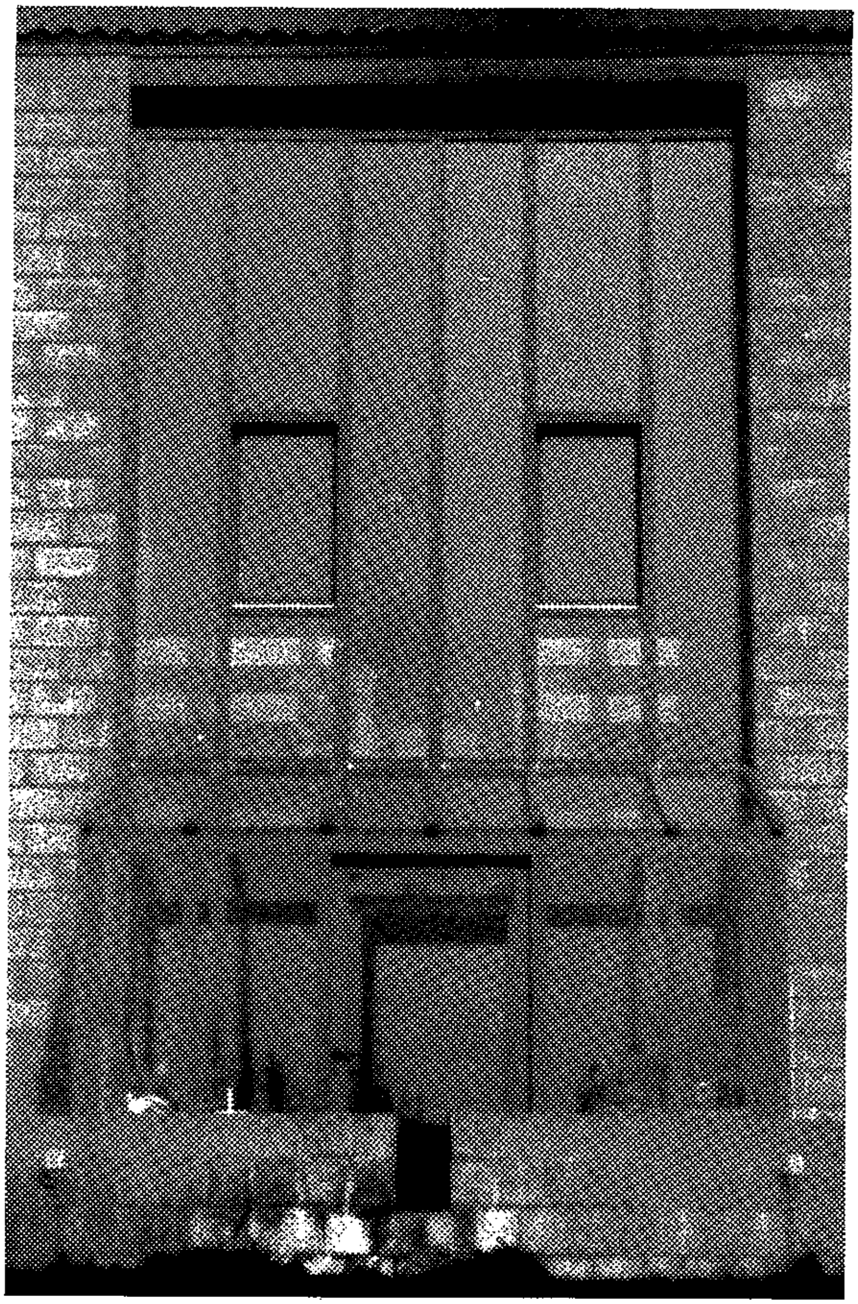
The primary heating strategy is to use as much solar radiation as much of the time as possible. The first goal is to collect the sun's rays and to convert them into heat (first principle: solar collection). Because of daily and seasonal climatic cycles, it is judicious to collect more solar energy during a sunny day than immediately necessary, and to store the excess for later use (second principle: heat storage). For the sake of comfort, this solar heat must be distributed in the whole building (third principle: heat distribution). Finally, the heat collected and that produced inside the building must be contained inside the building as long as possible while allowing adequate fresh air entry (fourth principle: heat conservation).



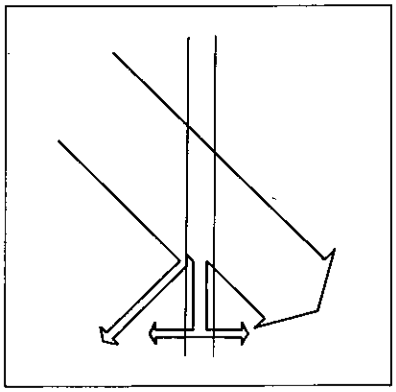
SOLAR COLLECTION 1.0



The collection of solar radiation is its conversion into thermal energy, i.e. its direct transformation into heat.



1.1. GLAZING ELEMENT

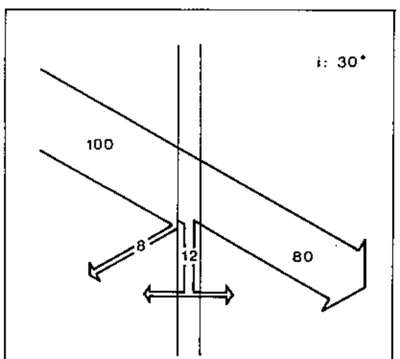


When the sun's rays strike a glazing surface, a certain fraction is reflected, another fraction is absorbed, and the remainder is directly transmitted. The absorbed fraction is re-emitted inwards and outwards by convection and longwave radiation in proportions depending on the temperature and the air speed on each side of the glazing. The sum of the fractions directly transmitted and of those re-emitted inward constitutes the total transmission.

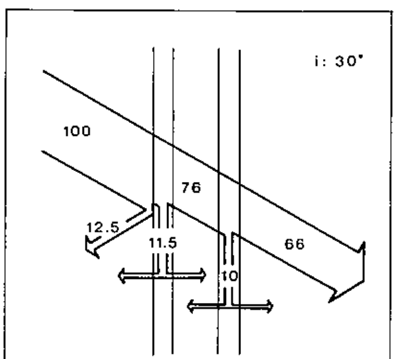
Once the solar radiation has been transmitted, it can be absorbed by an opaque element and transformed into heat.

The total energy transmission, and therefore the solar gains through a glazing element depends on the amount of source radiation, on the angle of incidence of the sun's rays, (the angle between the perpendicular to the glazing plane and the sun's rays) and on the optical properties, thickness, and number of layers of the glazing material utilized.

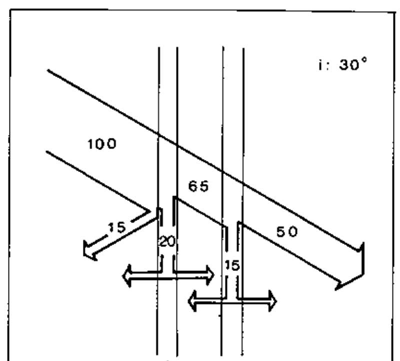
The diagrams below illustrate the energy transmitted by several common types of glass and synthetic materials according to the angle of incidence "i" of solar radiation. The radiation absorbed by the glazing is re-emitted outwards and inwards in proportions depending on the surrounding temperatures and the air speed on both sides of the glazing.



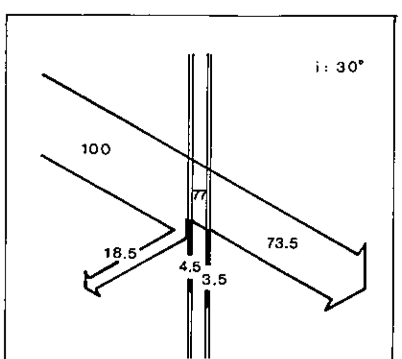
clear simple glazing 6mm



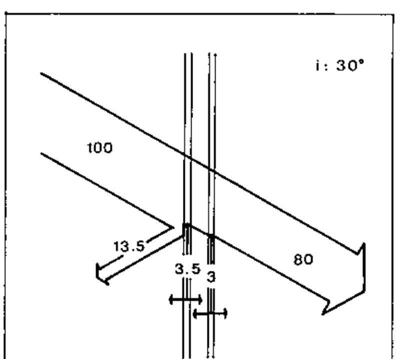
clear double glazing 6mm-12mm-6mm



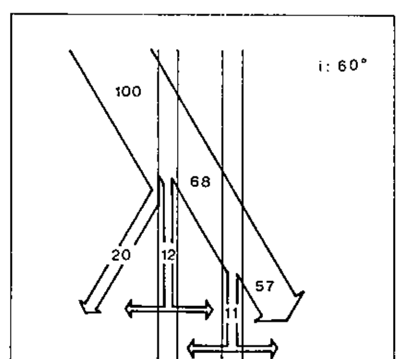
special double glazing 6mm-12mm-6mm



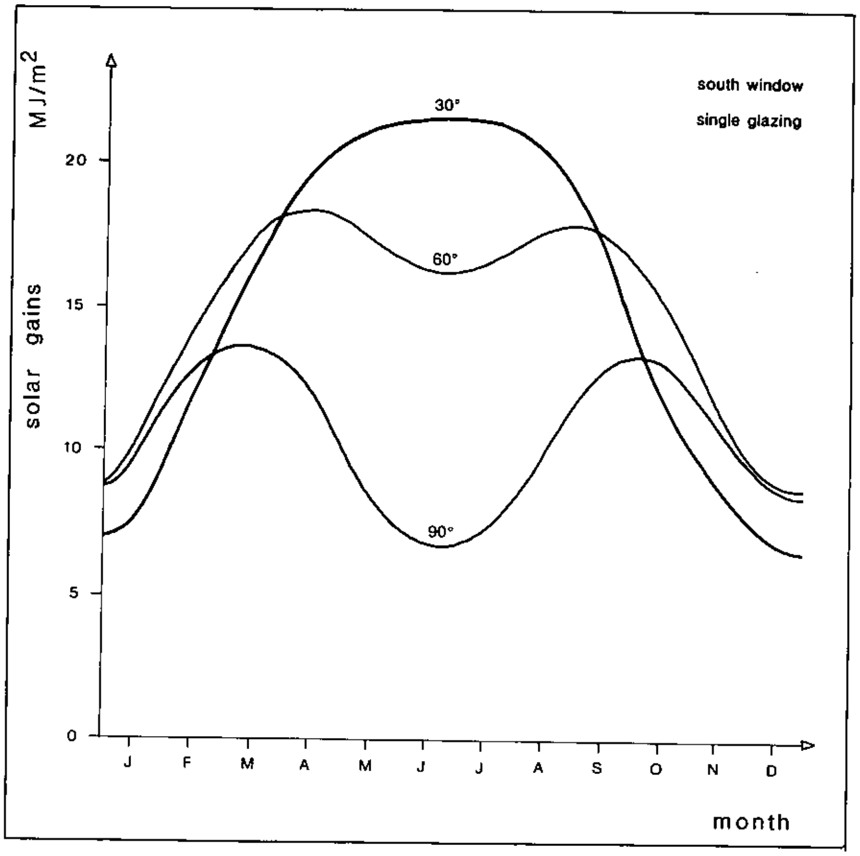
polycarbonate 6mm



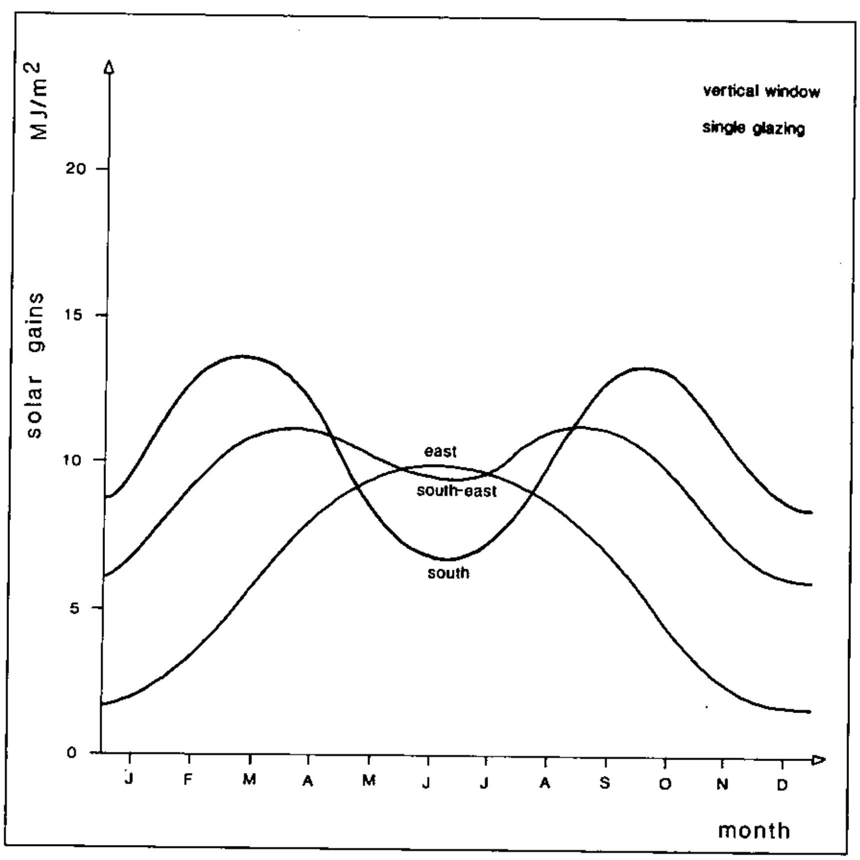
polymethylmetacrylate 8mm



clear double glazing 6mm-12mm-6mm

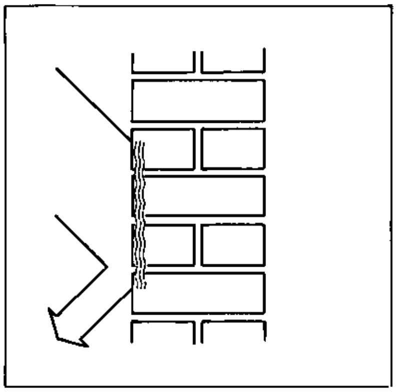


Influence of the glazing tilt angle on clear day solar gains through south-facing single glazing (latitude 51°N). Summertime gains through vertical windows (90°) are small since the sun is high in the sky and the angle of incidence is large. With steeply tilted windows, overheating can occur in summer while gains are smaller in winter.



Influence of glazing orientation on clear day solar gains through vertical single glazing (latitude 51°N). South-facing windows gain the most in winter and the least in summer. Thus they follow most closely the building heating needs. West and south-west orientations are not given because they correspond closely to east and south-east orientations.

1.2. OPAQUE ELEMENT

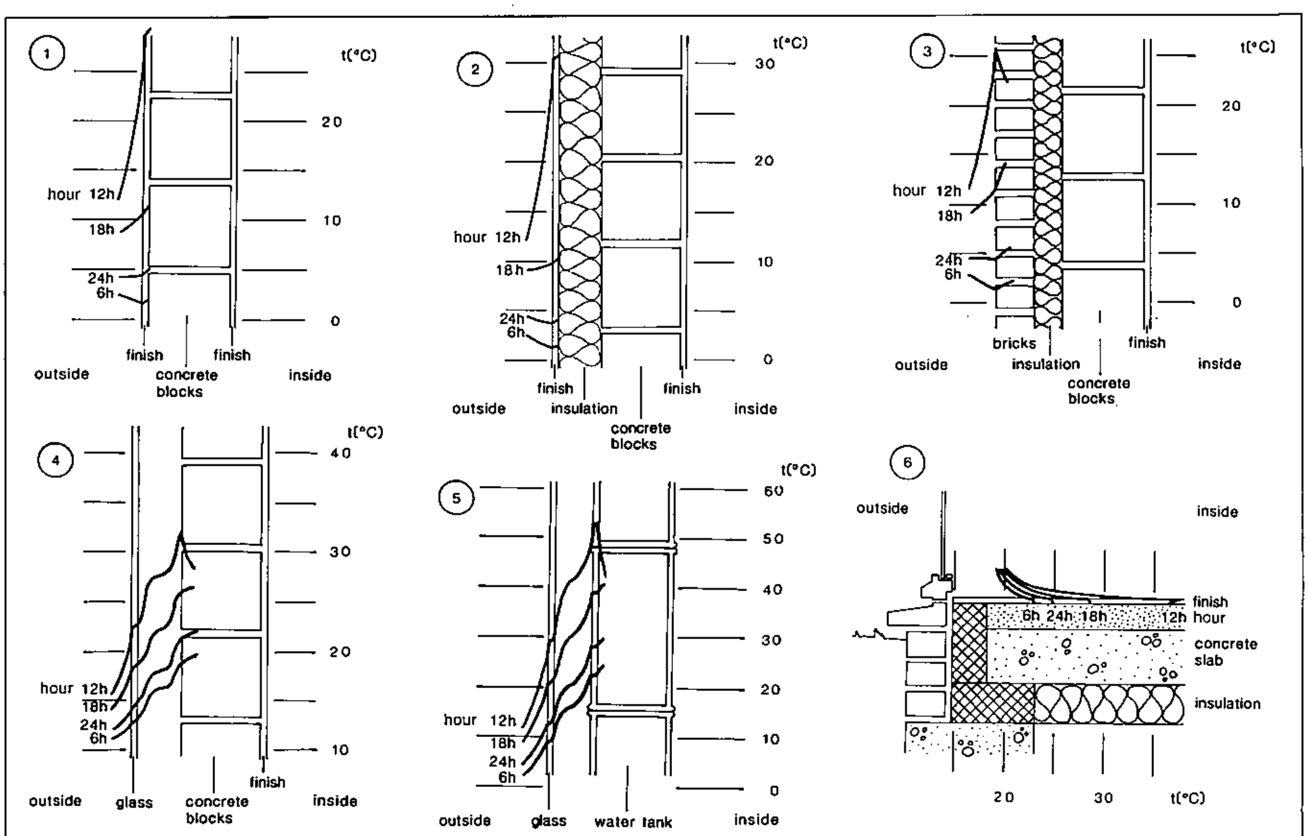


When the sun's rays strike an opaque body, part of the radiant energy is absorbed and converted into heat while the remainder is reflected. There is no direct transmission. The heated element emits longwave infrared radiation and loses heat by convection. The remainder of the absorbed energy is conducted through to the other side with a certain time lag.

In regions where it is only necessary to heat during the night, this thermal time lag delays the contribution of solar heating. In any case, the wall exposed to the sunshine becomes warm and consequently heat losses from the building interior are reduced (See 4: Heat Conservation).

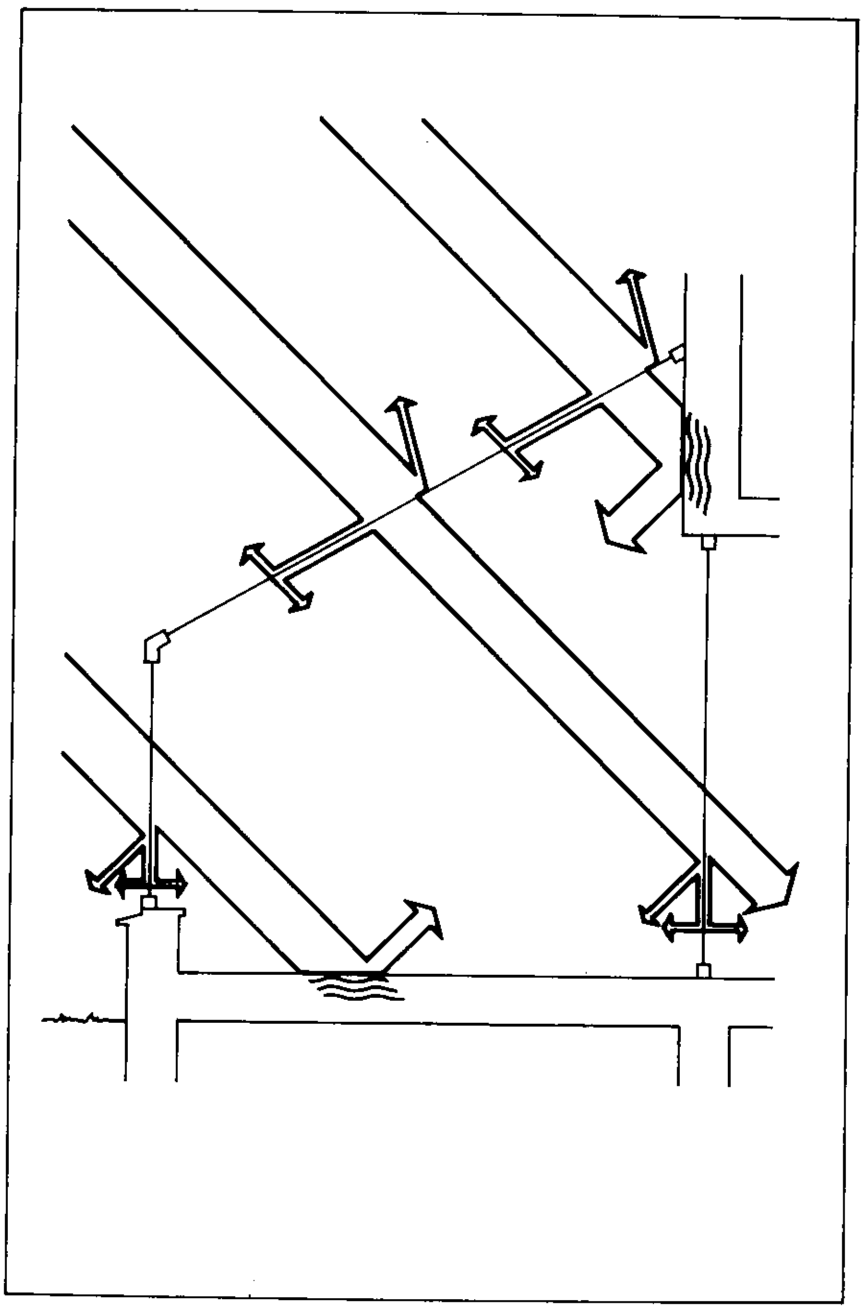
The solar energy absorbed by a vertical opaque surface depends on the angle of incidence of the sun's rays, i.e. on the orientation, the tilt of the element and the sun's position, and on the color and texture of the surface of the material used. The fraction of heat lost to the outside depends on the temperature and the air speed and on the cloudiness. A glazing placed before the wall reduces these losses by limiting convection and radiation from the wall surface. This is the "greenhouse effect" (See 1.3: Greenhouse Effect).

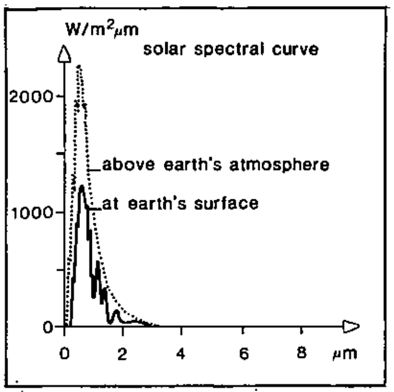
The diagrams below show the temperature variation on the surface of different south-facing external walls and of a floor located behind south-facing double glazing, on December 15, under a clear sky and with a wind speed of 4m/s. (latitude 51°N). Higher temperatures indicate more positive heat flows to the interior; lower temperatures indicate heat losses. The complete temperature profile is shown in Section 2.1.



1.3. GREENHOUSE EFFECT

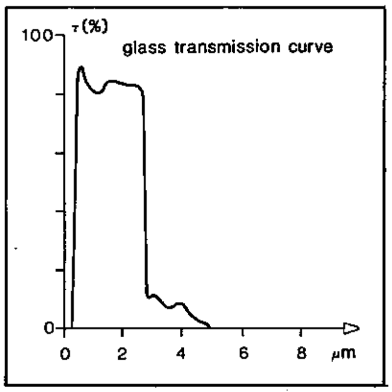
As described briefly in the previous section, the greenhouse effect is the principle of the solar collection through any glazing element which admits solar energy at a faster rate than it loses energy to the environment. The ability of a collection device to take advantage of the greenhouse effect is determined by its geometry, the choice of glazing material (fraction and spectral curve of energy transmission), the choice of opaque material (absorption and spectral curve of energy emission) and by the respective proportions of transparent and opaque materials. Performance is strongly influenced by climate via the outdoor air temperature and the quantity and direction of solar radiation.



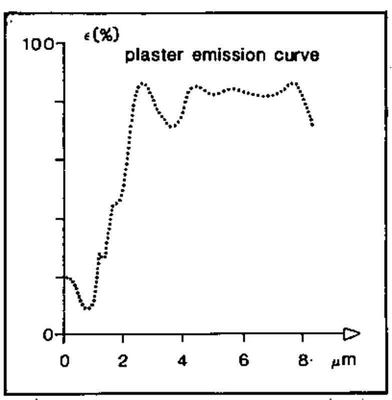


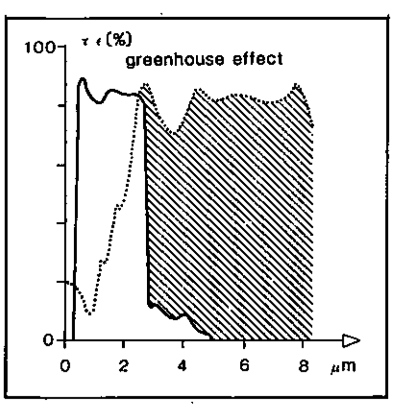
The solar radiation which reaches the earth is composed of ultraviolet (UV), infrared (IR) and visible radiation. The wavelengths of solar radiation range from 0.25 to 4 microns (1 micron = 10^{-6}m). The diagram opposite indicates the spectral distribution of direct solar radiation on a normal surface to the radiation at the confines of the atmosphere and at ground level.

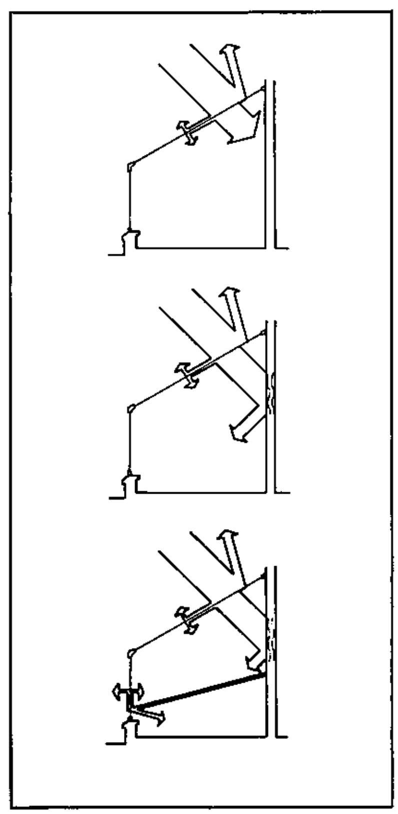
When the sun's rays strike glazing, much of the visible radiation and shortwave infrared is allowed to pass; however, glass is practically opaque to the infrared radiation of wavelenghts higher than 2.5 microns. The solar radiation passing through the glazing is then absorbed by the opaque surfaces of the building (walls, floor) which become warm. These surfaces lose heat through convection and longwave infrared radiation in all directions. Convective heat loss is partially blocked by the glazing surface. Similarly, when infrared radiation strikes a window it is partially reflected and partially absorbed. The absorbed fraction is re-emitted on either side of the glazing. Part of the radiation is therefore trapped, leading to an increase in the internal temperature. This is the **greenhouse effect**.



The opposite figure shows the spectral curve of the energy transmission of a 6mm thick clear glass, and the figure below shows the spectral curve of energy emission of plaster. The last figure superimposes the two previous curves, showing the trapped fraction of radiant energy in the shaded region.





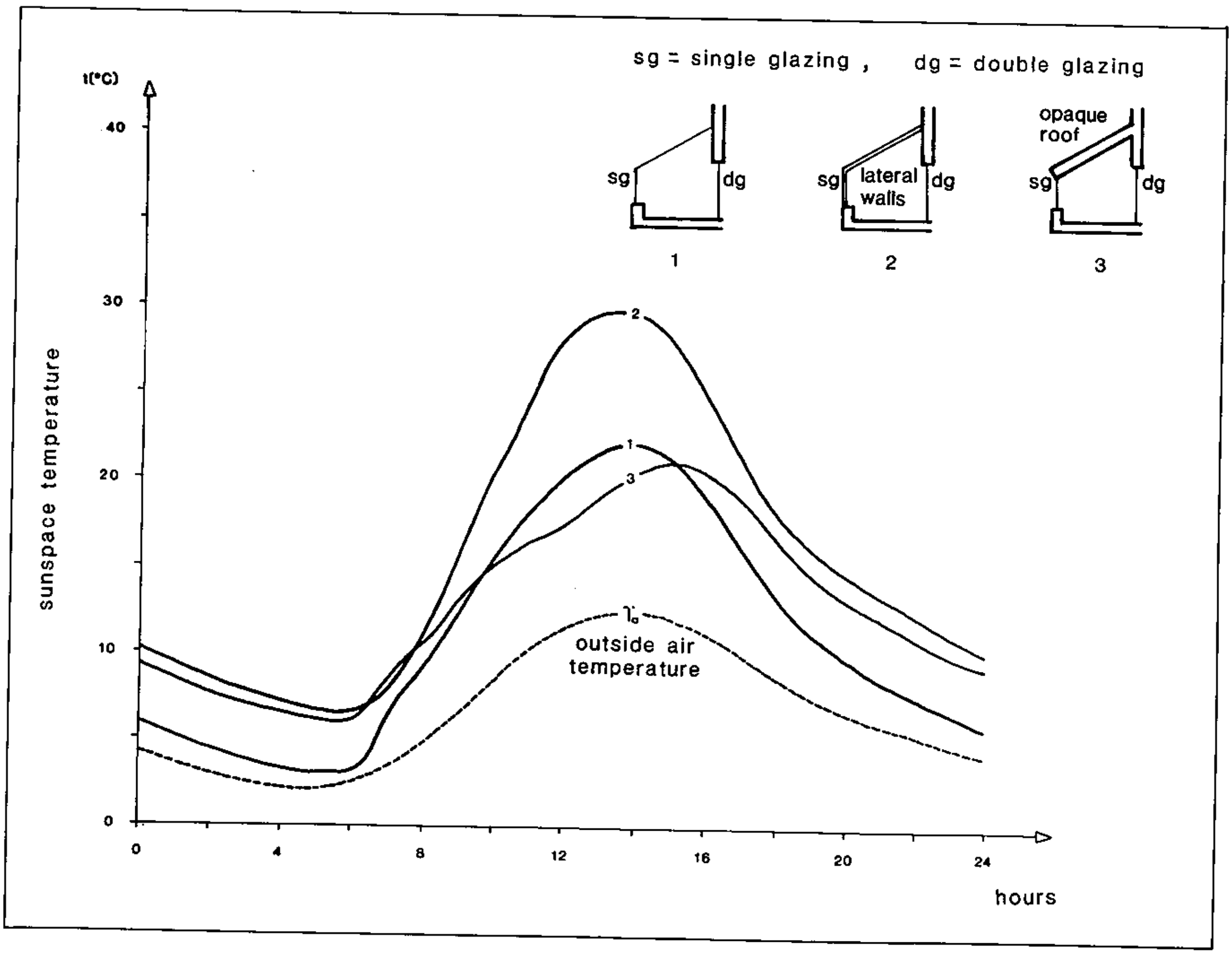


To illustrate the greenhouse effect, the interior temperature of a sunspace design with different wall and roof materials is shown below. A sunspace is a sun facing room adjacent to, yet physically separate from, a home's main living area. The sunspace temperature is allowed to fluctuate. Useful heat is delivered from the sunspace to the living area by conduction or through openings in the common wall or by a fan. See Booklet No. 2 for more information on sunspaces.

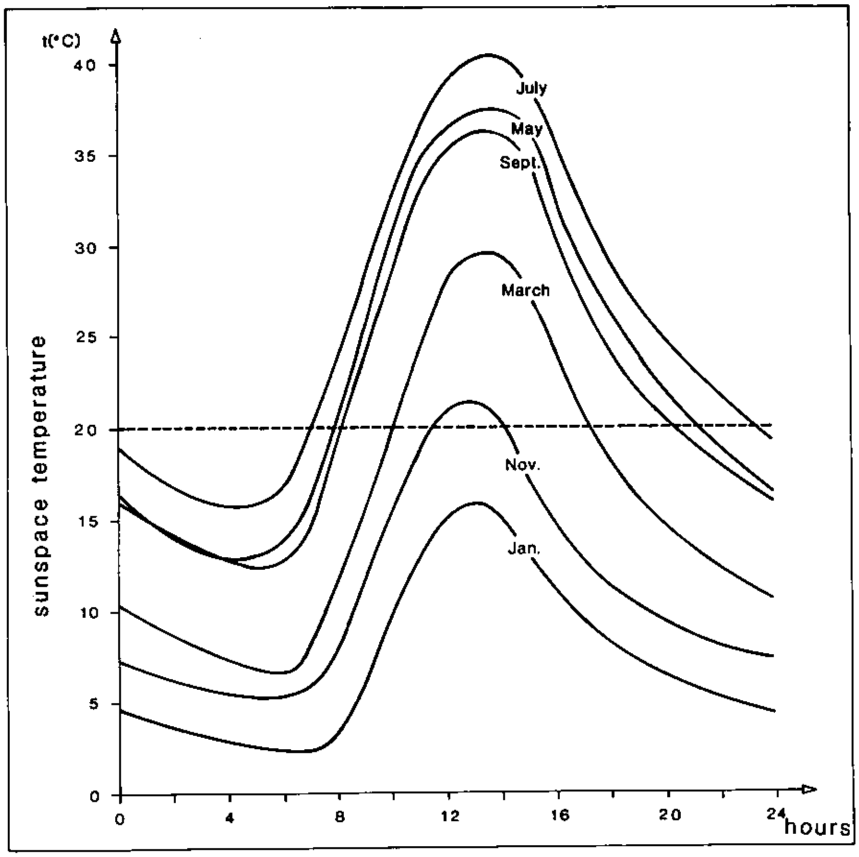
The reference sunspace is a south-facing sunspace unheated exposed to sunshine on March 15, (latitude 51°N), under a clear sky and with a wind speed of 4m/s. The floor area is 10 m², the volume 25 m³ and the ventilation rate is 0.7 ach. The sunspace abuts a 200 m² (450 m³) heated house, with 15 m² of south-facing glazing, 10 m² east, 10 m² west and 5 m² north. The average indoor temperature is 18°C all during the day. The results shown in the following diagrams are based on computer simulations.

The conductance or U-value is 0.4 W/m²K for the opaque roof and walls, 5.8 W/m²K for single glazing, and 2.9 W/m²K for double glazing.

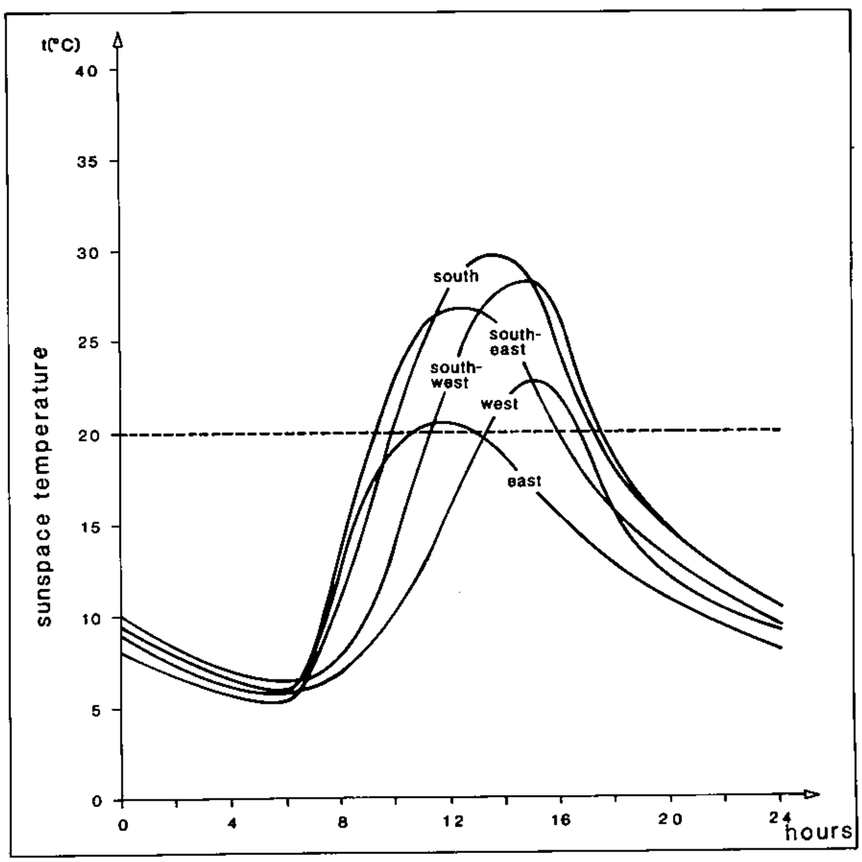
The diagram below shows the advantage of insulated, rather than glazed, roofs and east and west walls. Sunspaces 2 and 3 retain more energy and warmer temperatures into the evening than sunspace 1. Sunspace 2, with the glazed roof, overheats during the day, while sunspace 3 maintains comfortable temperatures for the most hours.

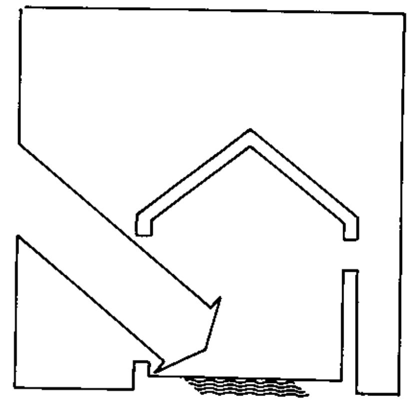


Temperature profiles are shown for the reference sunspace at the same location (latitude 51°N). External glazing is single, while that separating the sunspace from the living space is double and the lateral walls are opaque. In autumn and spring the temperature in the sunspace is high enough to deliver heat to the house. However, in summer the space overheats, and it becomes necessary to employ shading devices and also to manage ventilation apertures in the sunspace. As shown on the previous page, insulated roofs and east-west walls can moderate these temperature fluctuations and may reduce the need for summer shading and venting devices.

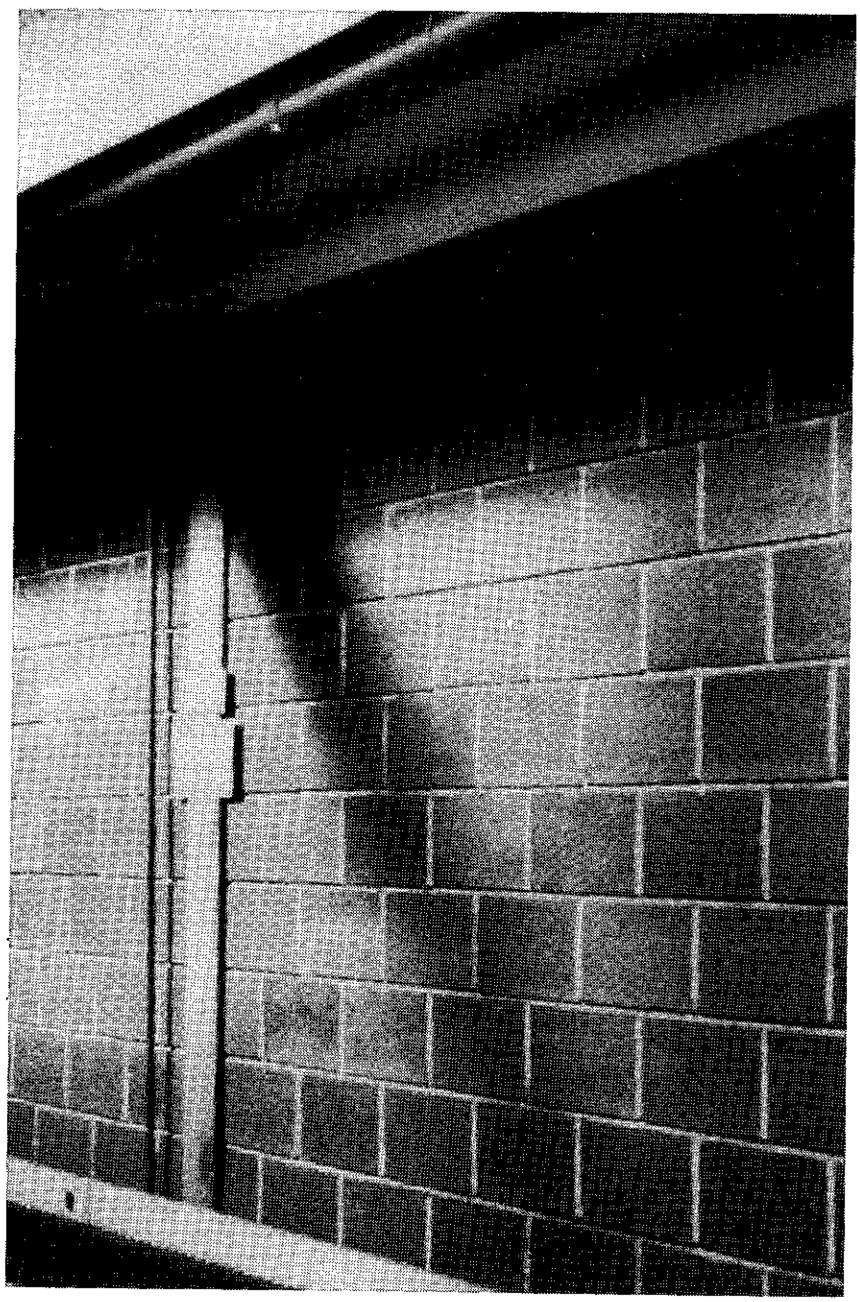


This diagram shows the influence of orientation on the sunspace temperature profile in the same sunspace, on March 15, (latitude 51°N). One can see that the decrease in temperature is smaller when the sunspace is oriented to the west than when it is to the east, although this effect is climate-specific.

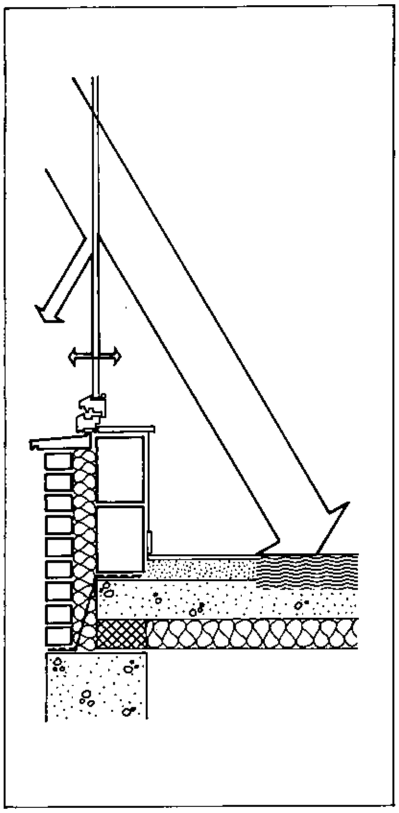




Solar radiation varies in diurnal and annual cycles. Because it is often not available when heating is required in a building, thermal energy storage is needed. The principle of storage is to collect and retain surplus heat in order to utilize it when needed at a later time.



2.1. DIRECT STORAGE



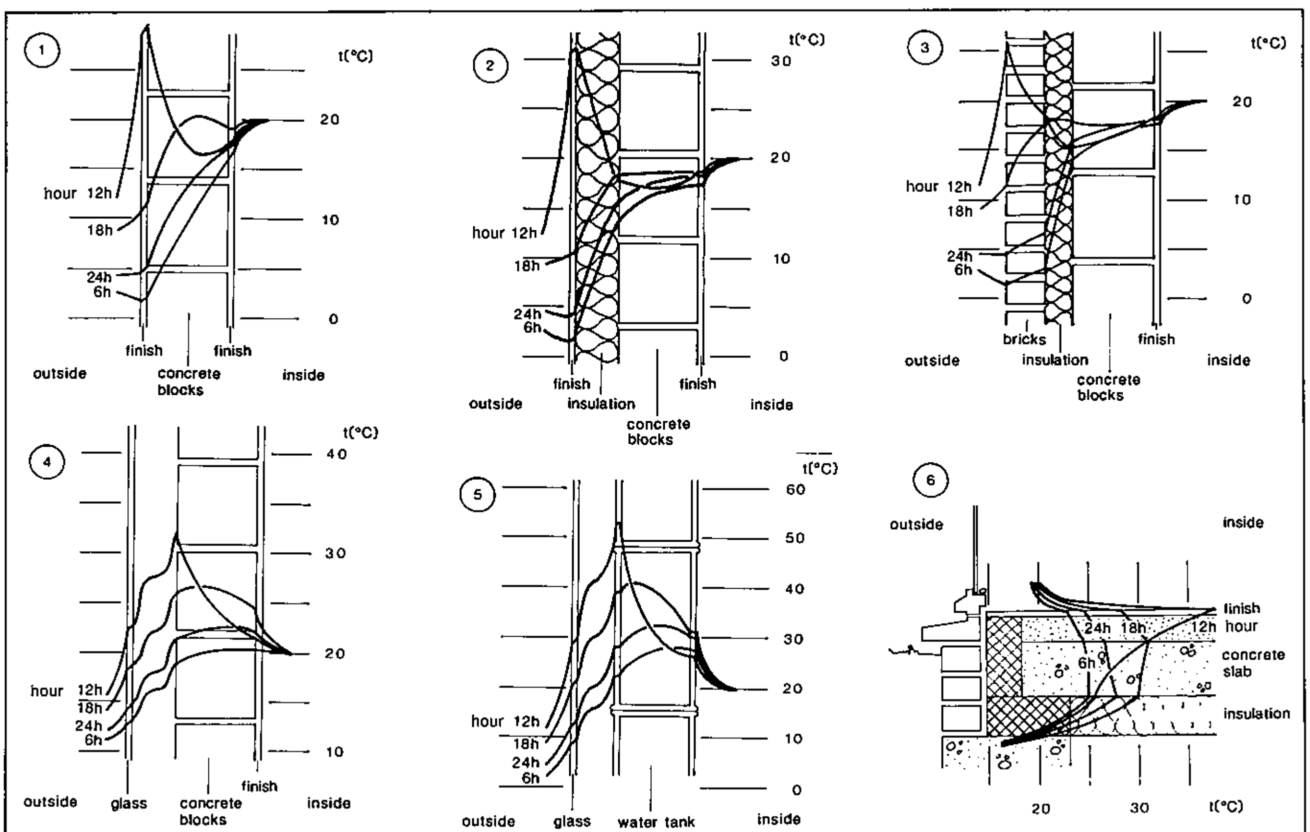
The solar radiation received by a material directly or after its passage through a glazed element is partly absorbed by the material and converted into heat. Thus an important property of a storage element is its ability to absorb and convert solar radiation, i.e. its absorptivity. A fraction of the absorbed heat is lost from the sunlit side by longwave radiation and convection. Another fraction is retained in the material which becomes gradually warmer by conduction.

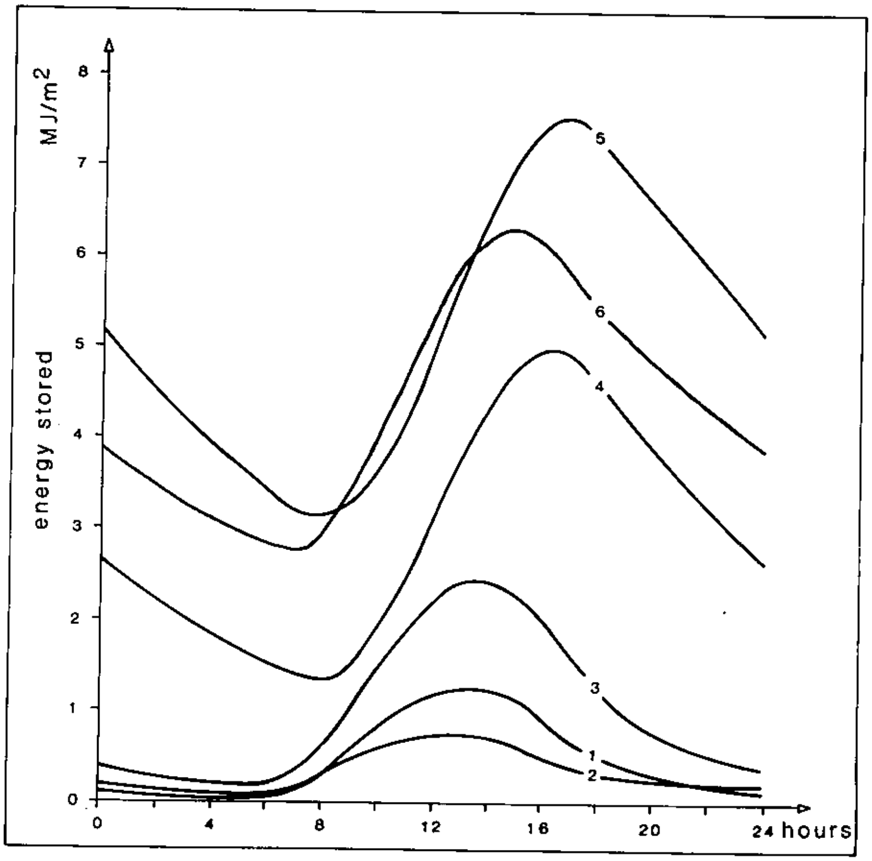
The rate of heat penetration is fast if the thermal diffusivity of the material is high. Thermal diffusivity increases if conductivity increases and if density or thermal capacity decreases. Heat diffusion through the material removes heat from the sunlit surface, preventing rapid temperature increase at the surface. Instead, the entire mass of the material increases slightly in temperature.

Thermal inertia is a concept which corresponds both to heat storage and to its re-emission with a time lag which varies according to the physical, dimensional and environmental characteristics of the storage building component.

This time lag is the time between the maximum temperature reached on the sunlit surface of the material and the maximum temperature reached on the opposite side. High thermal inertia could allow the absorption of heat during the day so as to re-emit it during the night.

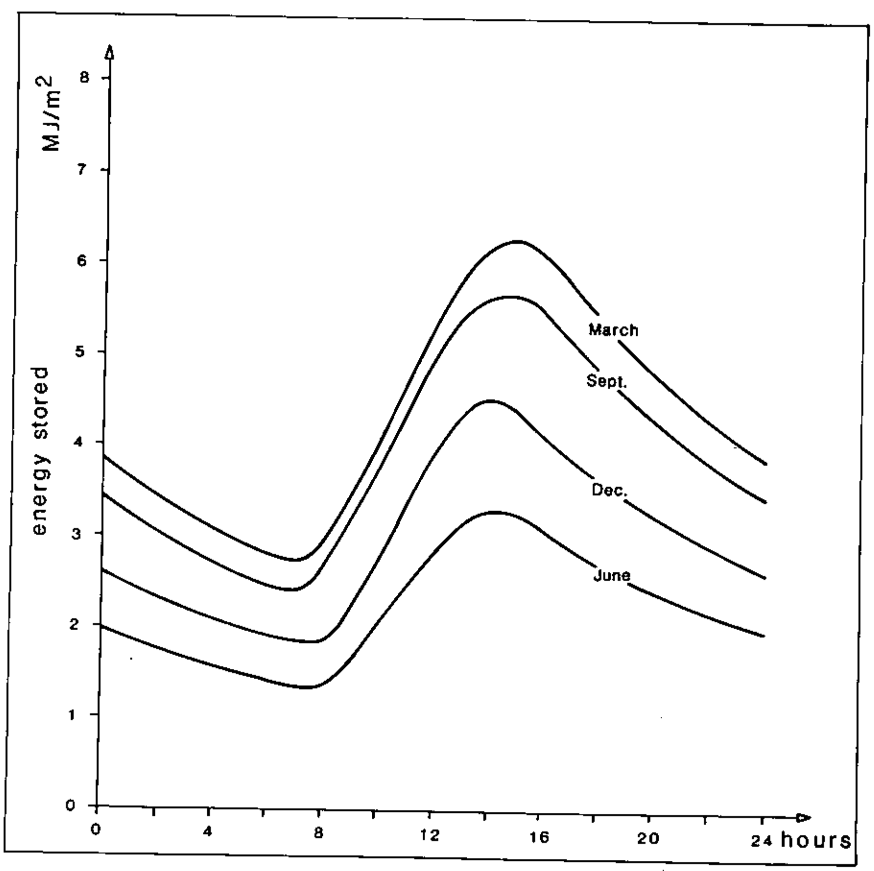
The graphs below show the daily temperature fluctuations for various south-oriented external walls, and for a floor under a clear sky and with a wind speed of 4 m/s on March 15 (latitude 51°N). The indoor temperature is fixed at 20°C. For the glazed walls in particular, the maximum interior surface temperature occurs several hours after the maximum exterior temperature. This illustrates the thermal benefit of placing massive wall materials, such as concrete or water, inside of insulation or glazing. Note, however, that on cloudy days the insulated wall will perform much better than the glazed wall.





Daily variation of the solar gains stored in the walls and the floor shown on the previous page, under the same conditions. The greatest heat gains occur about five hours after the maximum solar radiation, which occurs at mid-day.

1. concrete masonry wall
2. insulated concrete masonry wall
3. insulated concrete masonry wall with bricks
4. concrete masonry wall behind exterior glass
5. water tank wall behind exterior glass
6. concrete slab behind glazing

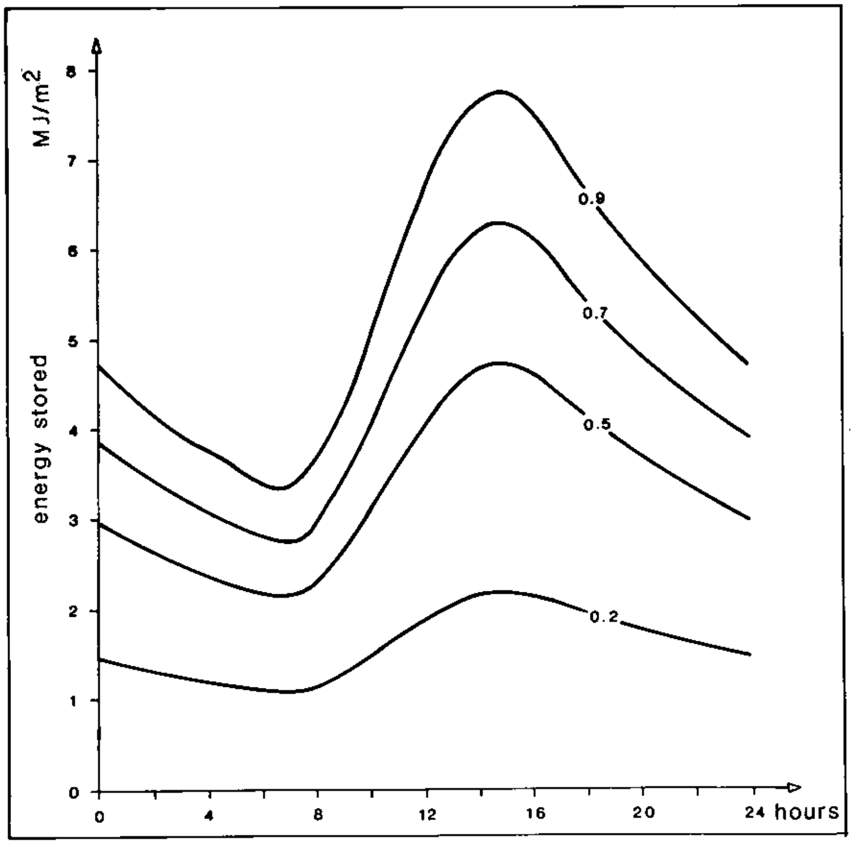


Daily variation of the solar gains stored in the floor shown on the previous page, for different months. March and September receive the most solar gains because there is more radiation available than in December, and the sun angles are lower than in June.

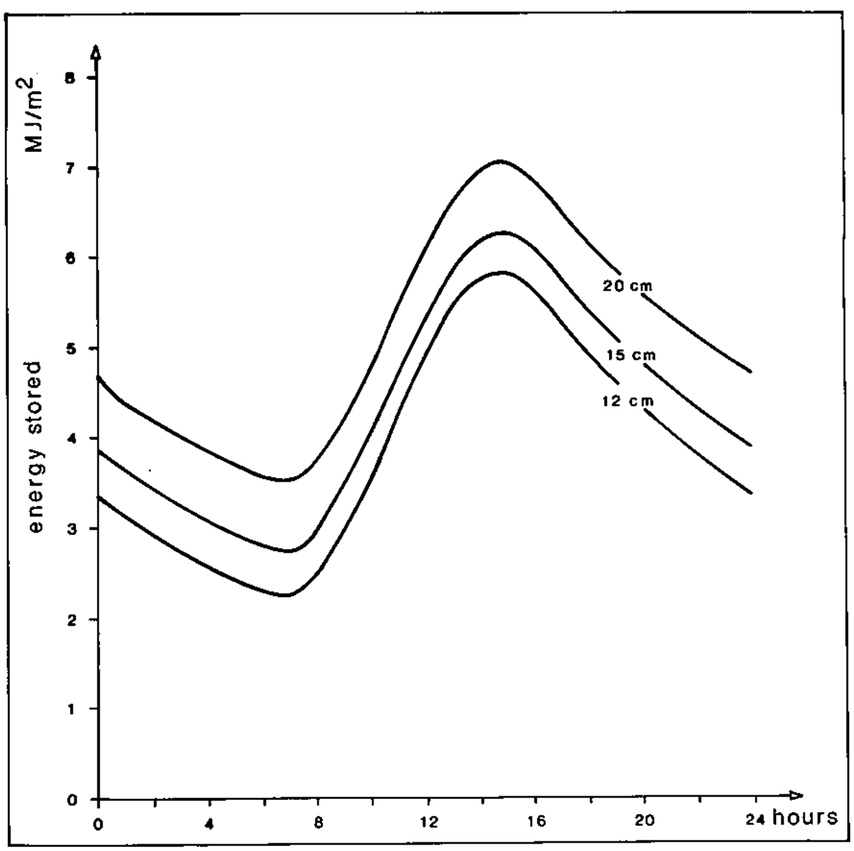
Storage of solar energy on March 15, under a clear sky (latitude 51°N) in the floor of the previous figures for different colors of the concrete surface. The absorptivity varies by each color as follows:

α = 0.9: black
= 0.7: red and brown
= 0.5: gray
= 0.2: white

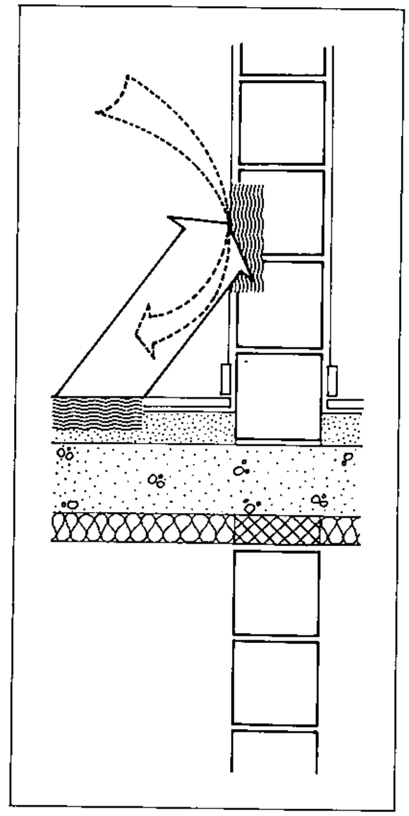
The indoor temperature is fixed at 20°C, and under the floor at 13°C. It is clear that surface color has a strong effect on the amount of solar radiation which can be stored in floor thermal mass.



Storage of solar energy on March 15, under a clear sky (latitude 51°N), in the same floor, but with a variable thickness of concrete. The indoor temperature is fixed at 20°C, and under the floor at 13°C. A thicker storage material stores more heat, but at a decreasing rate. While the 20 cm floor requires 67 percent more material than the 12 cm floor, it only stores about 30 percent more energy. In fact, most of the material's heat storage potential is satisfied by the first 10 cm.



2.2. INDIRECT STORAGE



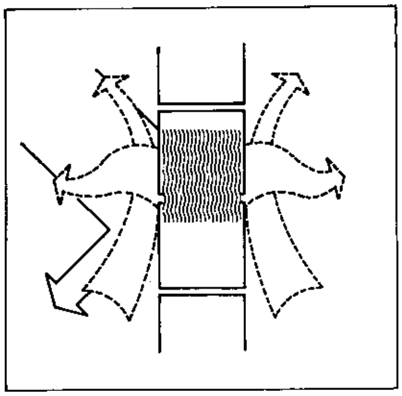
A building element can store energy by absorbing longwave infrared radiation from other walls or floors having a higher temperature. Similarly, if the air is warmer than a wall this wall can gain heat by convection. Both types of energy storage are indirect.

Indirect storage by longwave infrared radiation is influenced by the temperature difference between the surfaces, their relative position and their emissivity. Unlike shortwave (visible) radiation, infrared radiation absorption is not influenced by the surface color but by its smoothness. Indirect storage by convection is influenced by the temperature difference between the air and the wall, the air speed along the wall, and the roughness of the wall surface.

This exchange of heat between masses of different temperature is spontaneous because it obeys the second principle of thermodynamics aiming at thermal equilibrium between masses. This phenomenon permits storage of heat supplementary to that already stored by the direct storage. Moreover, the tendency towards the temperature equilibrium of the walls leads to an increase in the occupants level of comfort.

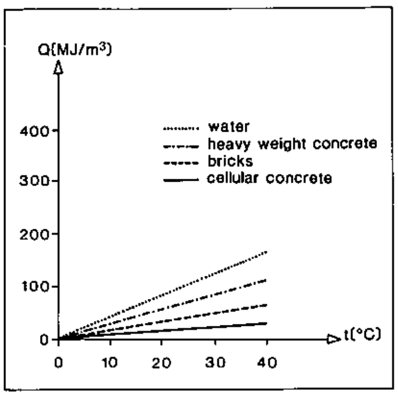
If a space is overheating, the energy of the hot air can be transferred by fan and ducts to a separate storage. This method of storage is aimed at balancing the availability of heat in a controlled way. The storage, such as hollow core concrete blocks or a rock bin, is only effective when correctly dimensioned and carefully insulated, and when the air passing through it is warm enough to increase the storage temperature significantly. Because the temperature differences are usually rather small, this is difficult to achieve. Remote thermal storage by hot air circulation should be considered as a comfort control strategy, rather than a significant energy saving feature.

2.3. STORAGE MATERIALS

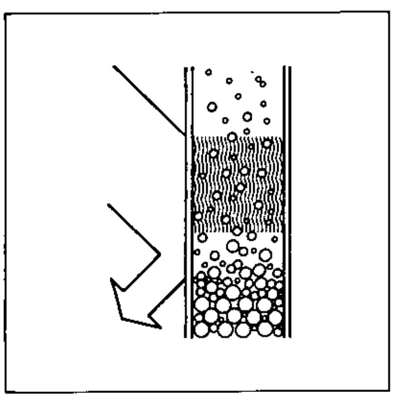


The thermal storage capacity of a material depends on its specific heat and density. This property expresses a material's ability to store heat per unit volume for a 1°C temperature rise. Materials which have a high thermal conductivity allow heat to penetrate rapidly. Heat is usually stored in dense building components, such as concrete or brick.

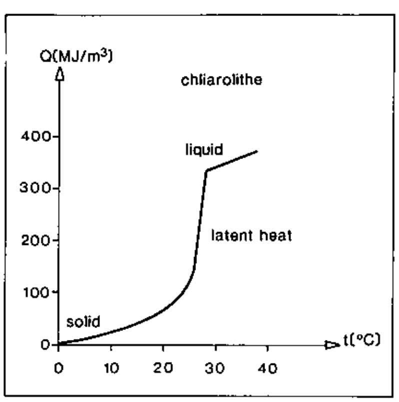
The storage capacity of solid materials generally used in construction ranges from 735 kJ/m³K for cellular concrete to 2825 kJ/m³K for heavy-weight concrete.



Other materials which have a high storage capacity are also used when it is desirable to increase the mass already provided by the building walls and floors or in lightweight construction. Water is the least expensive storage material, and its thermal storage capacity, 4165 kJ/m³K at 20°C, is very high.

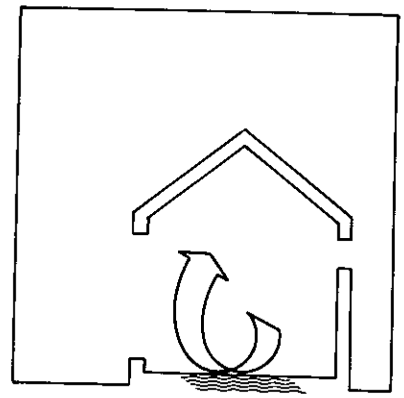


Contrary to conventional means of storage which use sensible heat (i.e. the heat flow which results from a difference in temperature), phase change storage makes use of latent heat. This is the amount of heat required to change the state of a substance, for example from solid to liquid. This change of state occurs at a constant temperature according to the material, generally between 2°C and 50°C. Compared to sensible storage, phase change materials can store large quantities of heat (from 140 000 to 380 000 kJ/m³ at the moment of phase change). Consequently phase change storage materials require smaller volumes than sensible heat storage.



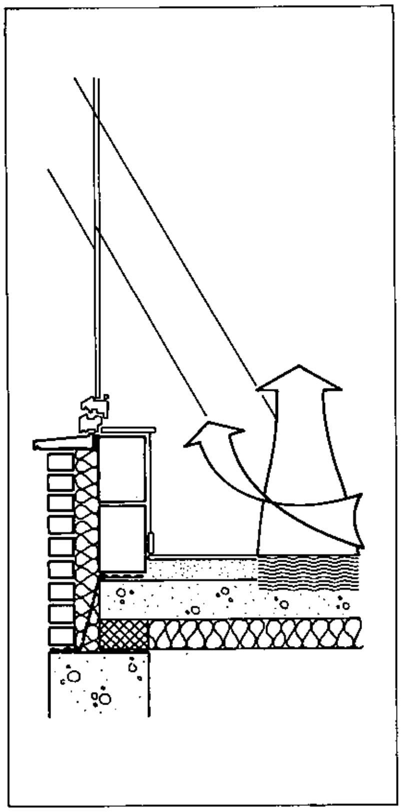
The performance of liquid and phase change storage materials depends on the kind of containers and, if they are many, on the way they are connected. Also, these materials are subject to various problems related to the quality of their containers, risks of freezing or expansion, and the persistence of their physical or biological qualities over a period of time.

HEAT DISTRIBUTION 3.0



To be useful, stored heat must be released when needed from the storage material, and distributed to the living space.

3.1. HEAT DISCHARGING

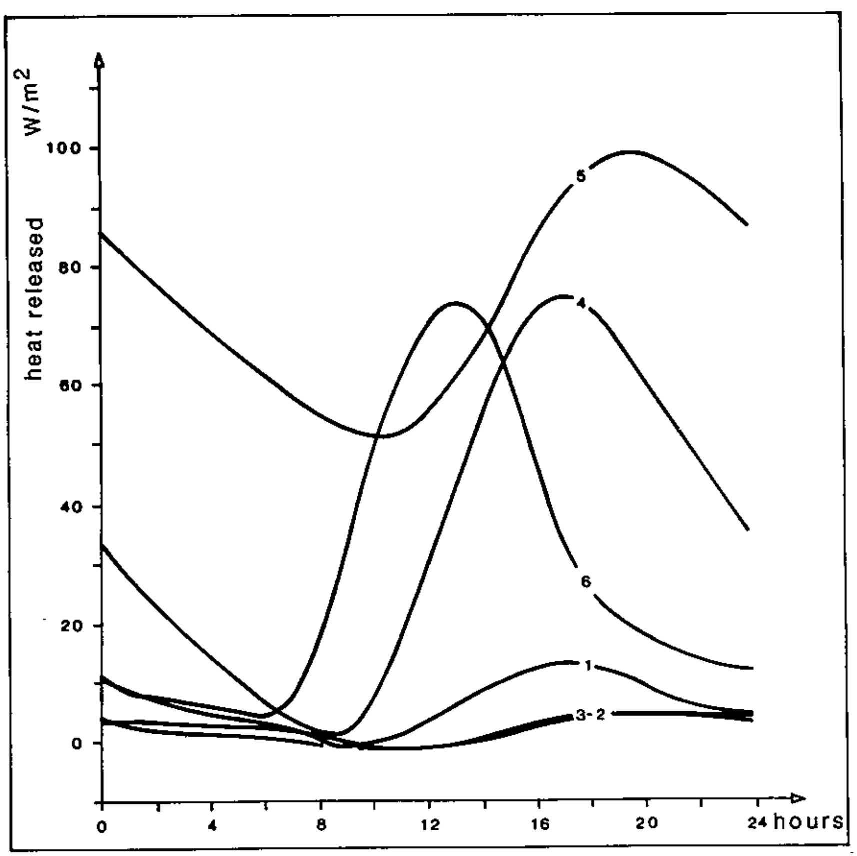


The heat stored in a material is released naturally by convection and radiation. Convection occurs as soon as the surface temperature of the material is higher than the temperature of surrounding air, while radiation in the form of longwave infrared radiation occurs when the surface temperature of the material is higher than the surface temperature of other surrounding objects.

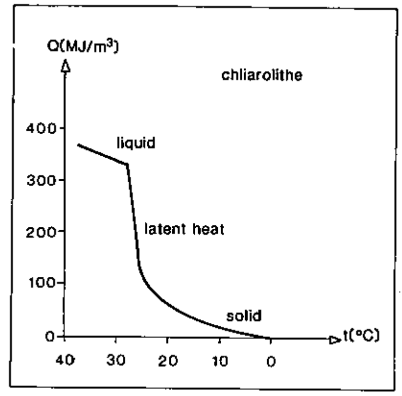
Since raising the temperature of the storage element drives heat distribution, energy release from a building surface begins almost instantaneously when the surface receives direct sunlight. However, on the opposite surface energy release is only possible after a time lag sufficient to allow enough heat conduction to raise the surface temperature.

The diagram opposite shows the amount of heat released per square meter of surface for the walls and the floor described in Section 2.1 (March 15, clear day, latitude 51°N). The indoor temperature is fixed at 20°C, and under the floor at 13°C.

1. concrete masonry wall
2. insulated concrete masonry wall
3. insulated concrete masonry wall with bricks
4. concrete masonry wall behind exterior glass
5. water tank wall behind exterior glass
6. concrete slab behind glazing



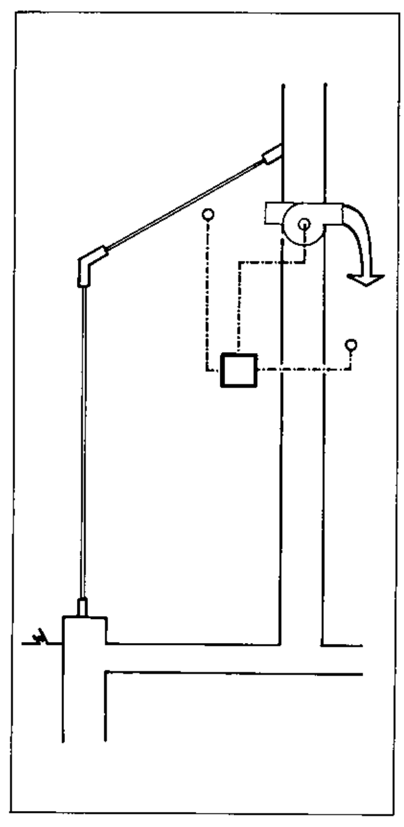
Phase change materials release most of their stored heat with a slight temperature change when changing phase. Afterwards they behave like other materials, releasing sensible heat proportional to temperature difference.



3.2. DISTRIBUTION OF WARM AIR

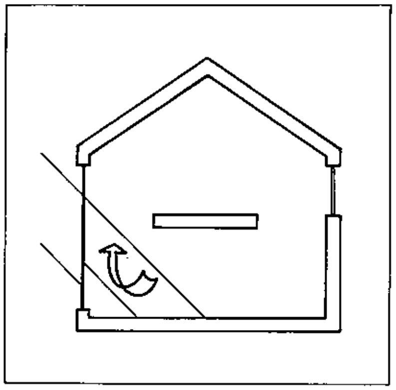
MECHANICAL DISTRIBUTION

Mechanical air circulation can distribute heat during times of solar collection. Using fan and ducts, it is possible to deliver warm air from sunlit spaces to remote spaces, or from the top of the space to the bottom, preventing temperature stratification. Another possibility is to remove hot air from a sunspace and use it to charge a storage component, such as hollow core concrete block or a rock bin. Mechanical heat distribution of this type is most reliable if controlled by a temperature differential thermostat.

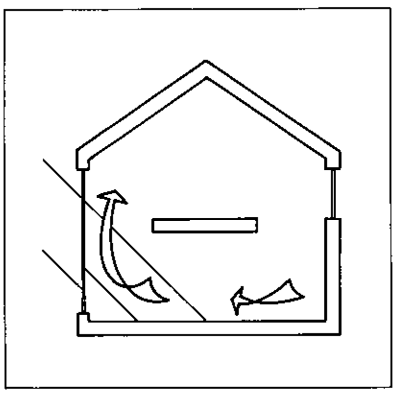


THERMOCIRCULATION

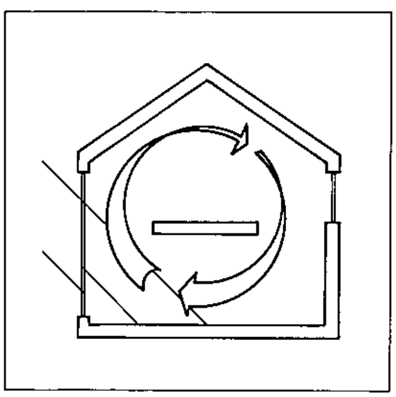
When a volume of air is heated, its density decreases and consequently this air moves upwards. A judicious organization of spaces takes advantage of this effect to distribute heat via the warm air. Thus, the solar energy is distributed by solar generated warm air.



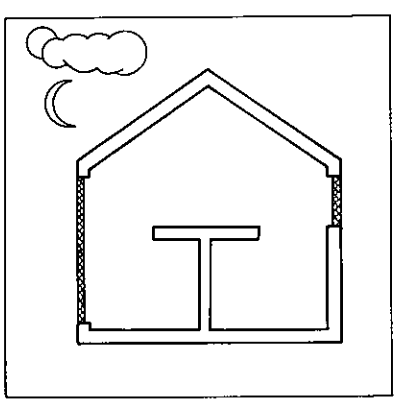
As solar radiation heats an interior surface, the surface begins to release its stored heat into the surrounding air by convection.



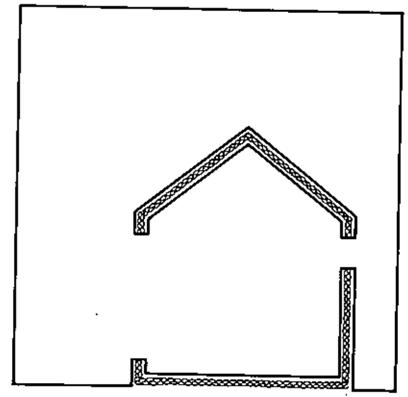
Then the air becomes lighter and moves upwards causing a downward draft of cooler air.



A circulation of air is created between the sunlit and remote zones, if permitted by the arrangement of the spaces and the openings between the spaces. This movement is air thermocirculation. It can be controlled by opening or closing internal doors or windows to encourage or block the air flow.



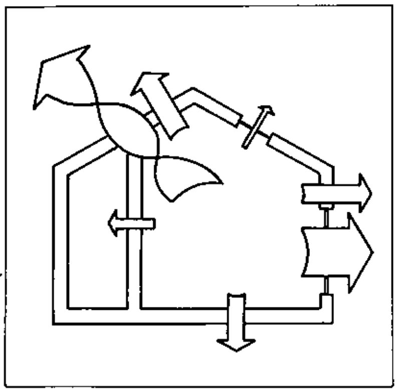
During cloudy or nighttime periods the air close to the glazing cools quickly. There is then a risk of creating reverse circulation and further cooling. This can be minimized by closing off spaces or using some form of tight-fitting movable insulation to prevent air circulation.



The building envelope design plays an important role in minimizing heat losses. Whether the heat comes from solar energy, free heat gains or auxiliary heating, it is necessary to try to keep as much as possible in the building.

There are two primary heat loss mechanisms: heat loss by transmission through the envelope and then by convection or radiation to the outside, and heat loss by infiltration and ventilation.

4.1. REDUCTION OF TRANSMISSION LOSSES



The heat losses by transmission are expressed by the heat flow rate through a material or combination of materials, which is the amount of energy passing through in unit time (measured in W = J / s). Heat flow rate depends on the temperature difference across the building element and on the thermal resistance of the materials. To a lesser extent it is influenced by surface roughness, wind speed, moisture presence and thermal lag. Because of the number of parameters related to transmission heat losses, there are different ways to decrease these losses.

- The most common is to increase the building envelope **resistance** by means of **insulation** which is a barrier to conduction through a building element.

- A barrier to radiation heat flow can decrease heat exchange between two buildings components by **reflection** of longwave infrared radiation.

- The magnitude of heat losses can also be reduced by decreasing the **area** through which heat flows. This means making the building more compact and by decreasing the total exposed surface area.

- Another approach is to reduce heat loss by reducing the indoor **temperature**, and thus the temperature difference which drives the heat loss.

THERMAL RESISTANCE

The thermal resistance R of a building element is equal to the sum of the thermal resistances of its component materials, including the sum of film coefficient between one surface of that element and the adjacent air. The higher the R-value, the greater the resistance to heat transfer through the envelope.

- The **thermal resistance** of a layer depends on the thermal conductivity (k) of its component material and its thickness. The thermal conductivity is the heat flow rate through a unit area and a unit thickness of that material, when there is a unit temperature difference between its surfaces. Resistance is expressed in W / mK.

- The **film coefficient** expresses the rate at which heat conducted through a material can be transferred by convection to the air. It depends on fluid characteristics (temperature, velocity, specific heat, density, viscosity) and on building component characteristics (temperature, shape and roughness of the surface, conductivity, configuration of the system, temperature of the other surfaces, emittance, absorbance) and the direction of heat flow.

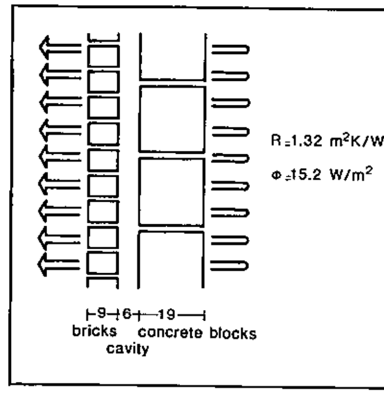
Insulation is the most common and cost effective way to increase the thermal resistance of the building envelope. Materials used for this purpose act as a barrier to conduction heat flow and must therefore have a low thermal conductivity.

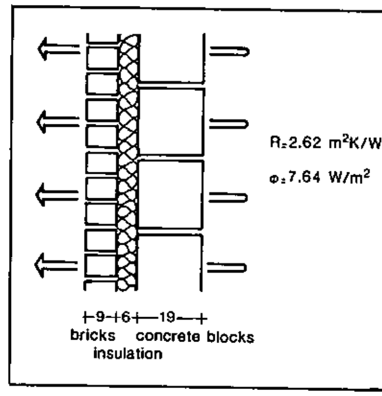
The most efficient common insulator is air, as long as convective movement is prevented. Thus, a material with a porous structure including many still air bubbles will have a good insulating effect. Common insulating materials include glass fiber, mineral wool, and cellulose.

Attention should be paid to keep such insulating material dry. As water fills the pores of the insulator, its conductivity increases rapidly (k-value of air = 0.026W/mK, k-value of water: 0.58W/mK).

The major factors influencing the thermal conductivity of a material are its density, its water content, the size of air pores and the nature of the solid matter which contains the air.

INSULATION

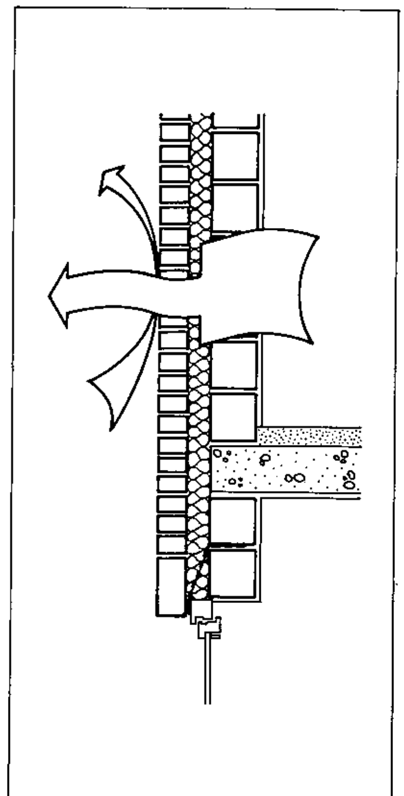




As an example the graphs opposite illustrate the difference between heat flow through an uninsulated cavity wall, and through an insulated cavity wall. The figures are given for a surface of 1 square meter, for a 20°C temperature difference across the wall and assuming that the walls are not exposed to sunshine.

In order to minimize heat losses due to transmission, the walls and ceilings should be equipped with a permanent insulation which compensates for the thermal weakness of load-bearing materials. Insulation also improves comfort by keeping the inner surfaces of the envelope at a higher temperature than those of uninsulated buildings.

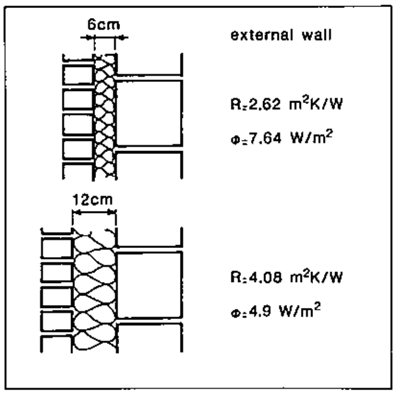
OPAQUE ELEMENT

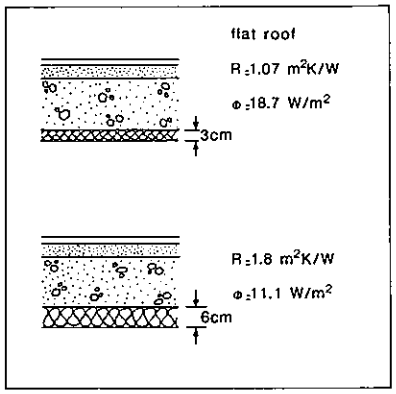


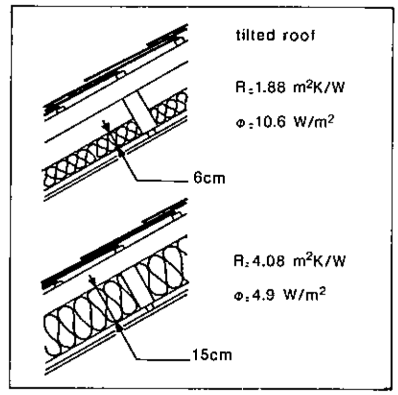
Insulating materials can be placed in different ways in a wall (on the external face, on the internal face or within the wall) without influencing the quality of the wall thermal insulation but substantially influencing the risk of condensation and the inertia of the building.

Insulation in an opaque element is generally permanent, but movable insulation is also possible.

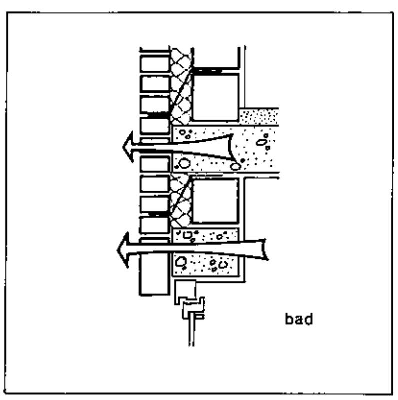
The graphs below give the thermal resistance (R-value) of different walls, floors and roofs, and the heat flows through these, for a surface of 1 square meter, a 20°C temperature difference, a wind speed of 4 m/s, and assuming that they are not sunlit.

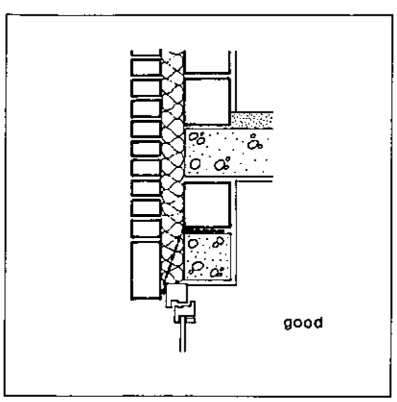






THERMAL BRIDGES

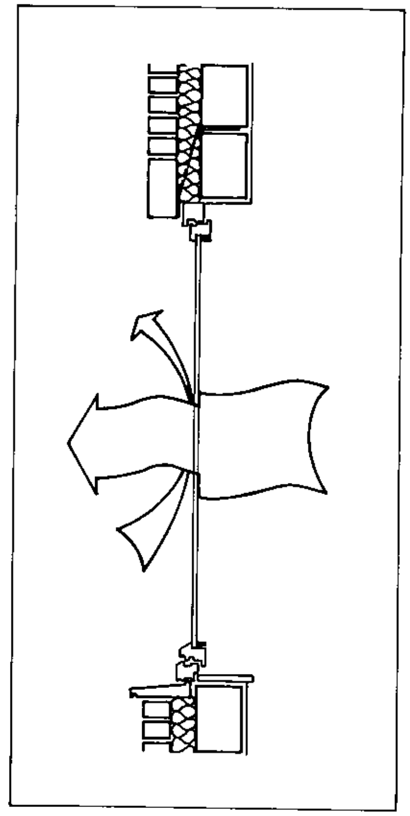




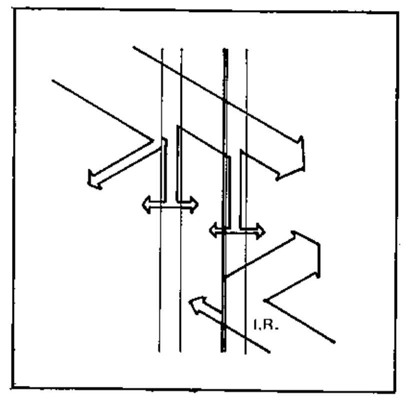
In the design of the envelope, thermal bridges should be avoided. A thermal bridge is a direct link of highly conductive material between the interior and exterior sides of a wall. This allows more heat transfer than elsewhere and reduces the temperature of the interior surface of the wall. A large thermal bridge can significantly reduce the performance of an otherwise well insulated wall. There is a risk of thermal bridge at any junction between building components. The diagram opposite illustrates a good and a poor design.

Windows are the weak element of the building envelope. This weakness results from the nature of glazing materials and the frames designed to support them. In order to provide better insulating capacity, transparent walls are composed of two or three layers. The air between two glazing layers provides a 50% reduction in thermal transmission compared to single glazing. A third layer reduces transmission to 30% that of single glazing.

GLAZING ELEMENT



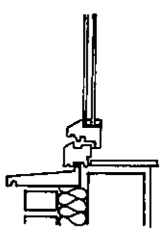
Heat loss through windows can also be reduced by a special treatment of the glazing itself. A thin metal oxide layer is placed on the interior glass of a double glazed window, on the cavity side. This low emissivity layer acts as a barrier to longwave infrared radiation by reflecting it back to the interior while allowing most of the sun's rays to penetrate the building. The heat loss through this type of "low-e" window is about 30% that of ordinary single glazing, or approximately equivalent to that of triple glazing.



Another way to improve the thermal resistance of windows, although perhaps not as reliable as multiple or low emissivity glazings, is the use of supplementary protection from curtains, shutters and other movable insulating devices. These movable insulation components also make it possible to protect against the summer sun and to prevent overheating.

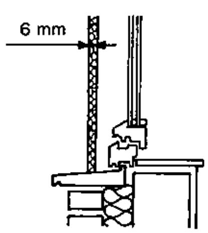
The graphs below show the thermal resistance and the heat flow per square meter through various window components with and without insulating shutters. The wind speed is 4 m/s, the temperature difference between the inside and the outside is 20°C and the walls are not sunlit.

double glazing



R=0.29 m^2K/W

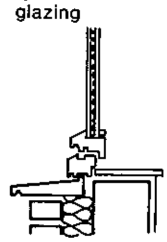
Φ=68 W/m^2



R=0.6 m^2K/W

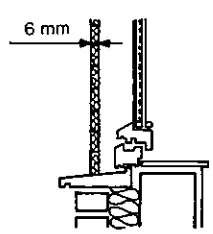
Φ=33.5 W/m^2

special double glazing



R=0.63 m^2K/W

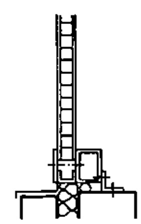
Φ=32 W/m^2



R=0.94 m^2K/W

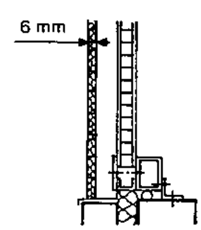
Φ=21.3 W/m^2

polycarbonate



R=0.26 m^2K/W

Φ=78 W/m^2

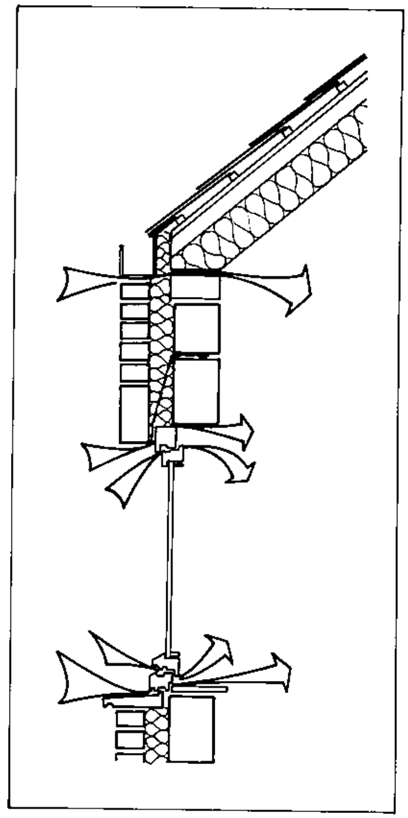


R=0.57 m^2K/W

Φ=35.1 W/m^2

4.2. REDUCTION OF INFILTRATION

It is necessary to ventilate a house in order to remove stale air, smoke and odors, and to maintain proper humidity. The minimum hygienic ventilation rate is generally set at 12 to 25 m³/h per occupant, depending on the country and on the type of occupancy. The ventilation is usually expressed in terms of number of air changes per hour, (ACH), i.e. the volume of fresh air introduced expressed as a multiple or fraction of interior volume of the space. The rate allowed is between 0.25 and 2 air changes per hour depending on the country and the type of climate.

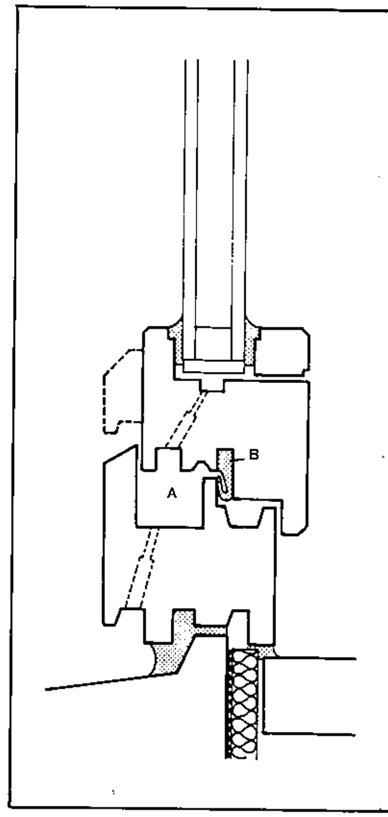


Infiltration can, of course, provide part of the necessary ventilation. However, minimizing infiltration makes control of the ventilation rate simpler and more certain.

The infiltration rate depends on the wind velocity and on the difference between indoor and outdoor temperatures. Thus external windbreaks and reducing the indoor temperature can réduce heat loss.

Infiltration occurs from openings in the envelope (chimney, ventilation duct, etc.), from cracks between building elements (walls and roof, for example), and from joints of the movable parts of doors and windows. The quality of the workmanship during the construction process is especially important in limiting infiltration. Effective measures include proper design of details such as joints, windows, doors, closing systems, at sensitive points.

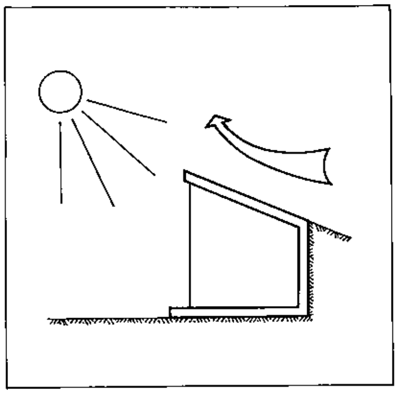
Infiltration through windows can also be reduced by making joints airtight and by applying insulating devices such as shutters. One large window instead of two little ones reduces the total length of joints. The section opposite shows weatherstripping devices in a window frame: (A) decompression zone and (B) tight joint.



Since air leakage depends on the windspeed and the temperature difference across the envelope, it is extremely difficult to estimate the air infiltration rate in a building, but it is possible to measure it after construction.

4.3. MANAGEMENT OF THE TEMPERATURE DIFFERENCES

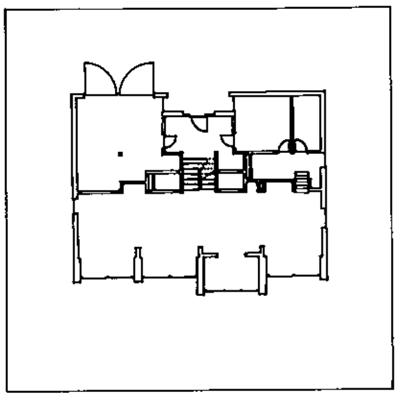
A large temperature difference across the building envelope increases the heat losses, whether by transmission or by infiltration.



The exterior surface temperature increases when exposed to solar radiation and decreases when exposed to strong wind. The designer can take advantage of this by reducing the areas of the envelope facing north and prevailing winds.

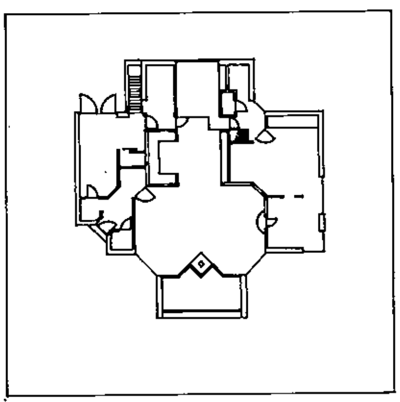
In case of strong wind and low ambient temperature, earth sheltered buildings reduce heat loss by infiltration and also by transmission because of the relatively undisturbed temperature distribution of ground. The earth gives an additional thermal resistance to the envelope and therefore reduces the average thermal load. The internal side of the envelope should be protected by additional insulation.

Good interior temperature management is relatively easy to achieve. Of course each room must maintain comfort conditions, but the temperature required depends on the activities of the occupants and on the use of the room. In addition, some rooms are occupied only a few hours a day while other rooms such as a kitchen take advantage of substantial internal heat gains.

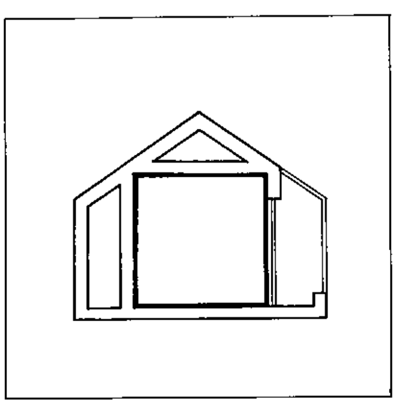


Thus, proper building organization, placing the rooms with higher heat demands facing south and the others toward the north, allows a rational distribution of heat and reduces heat loss by placing cooler rooms to the north. This organization is called thermal zoning.

Another possibility is to organize the building as a hot core surrounded by concentric circles of rooms of decreasing temperature needs.

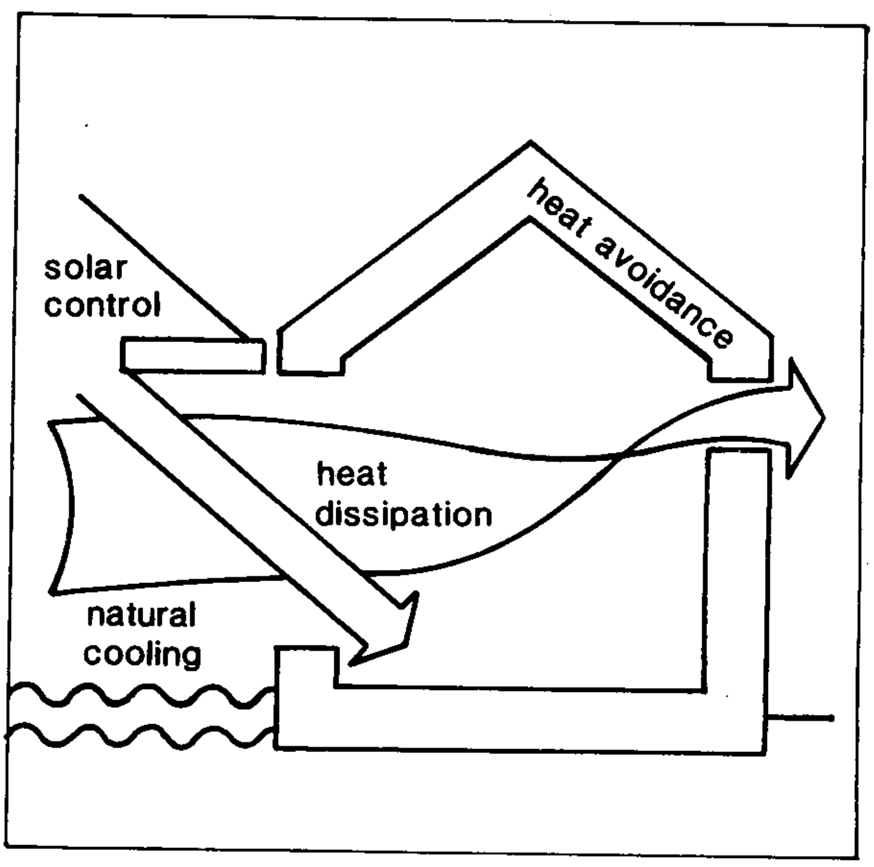


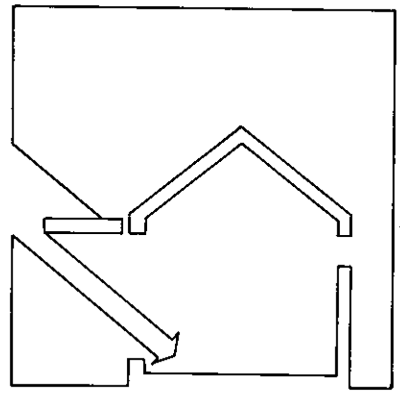
The same idea is also applied when unheated spaces like carport, storage room, laundry, etc. are placed along north walls in order to protect the building as buffer spaces. Cellars and attics are also buffer spaces.



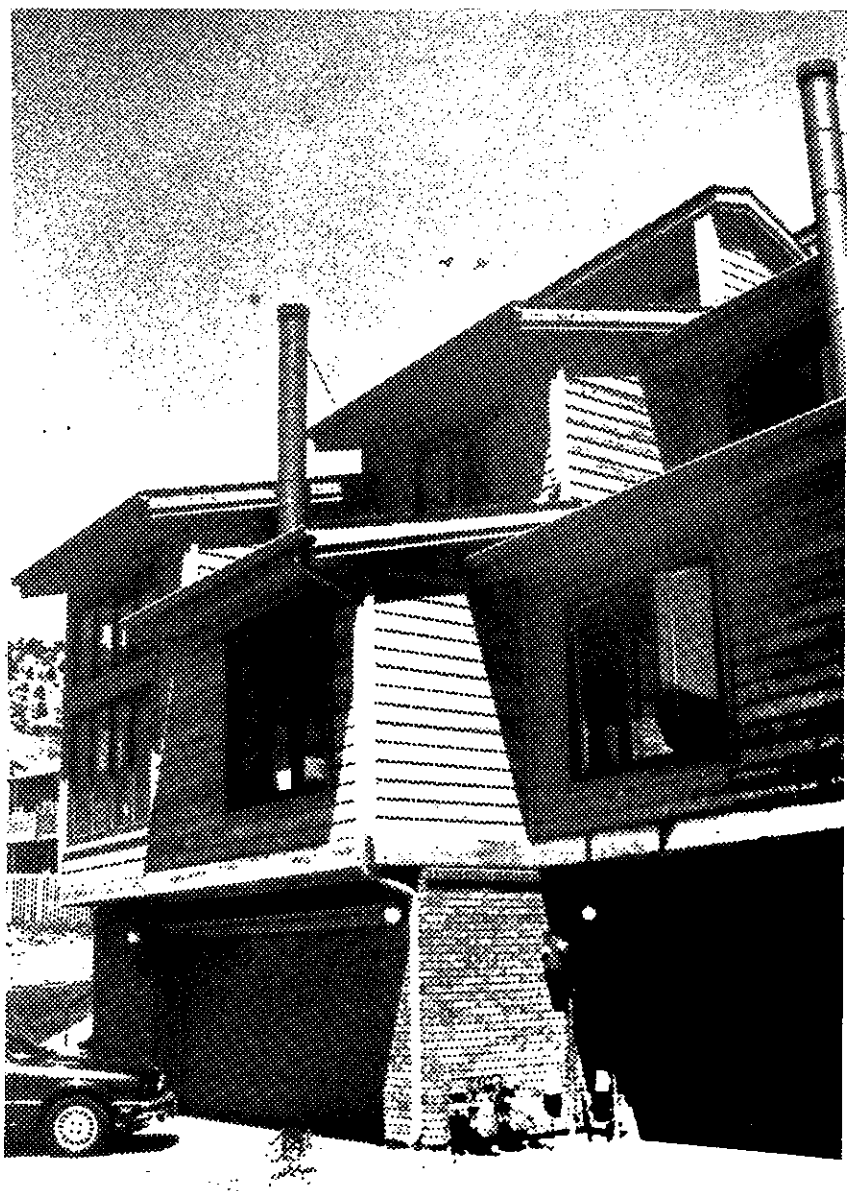
COOLING STRATEGY

The primary cooling strategy is to avoid or remove the sun's energy in order to keep the inside temperature comfortable. The first goal is to keep the sun's rays from reaching and entering the building (first principle: solar control). Protection against heat conduction through the building envelope and against hot air infiltration is also necessary (second principle: heat avoidance). Despite the observance of these two principles the building can overheat, partly because of the internal gains (appliances and people). The hot air must be removed and replaced by cooler outdoor air if the outdoor air temperature is comfortable (third principle: heat dissipation). Some natural ways of cooling can also be used to decrease the temperatures of the envelope and the inside air (fourth principle: natural cooling).

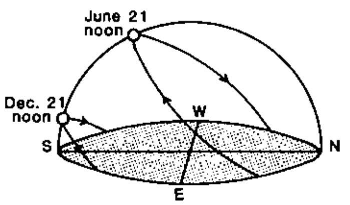




During some periods of the year or in warm climates solar heat gains through glazing elements create discomfort by raising the interior temperature above the comfort zone. It is then necessary to limit solar gains by keeping the sun's rays from entering the building. Solar control means can be permanent, seasonal or movable.



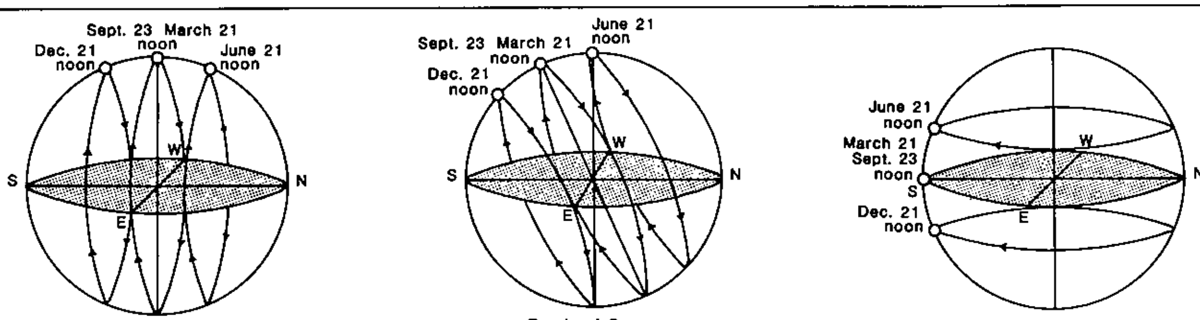
5.1 SOLAR GEOMETRY



Apparent movement of the sun at the solstices (lat. 51°N)

The most effective and least costly way to keep the sun's energy out of a building is to shade windows, walls and roof surfaces. The shading effect depends on the sun's position and the geometric characteristics of the shading device in relation to the element being protected.

In northern latitudes, the summer sun is high in altitude when it is in the southern sky (around mid-day). Therefore relatively little solar radiation reaches the south windows, and they are easily shaded. East and west windows, however, present a more difficult summer shading problem. The summer sun is low when it is in the eastern or western sky. As a result, incident solar radiation is greater during the summer on east and west windows than on south windows. The first step in a passive cooling strategy is to minimize east and west windows.

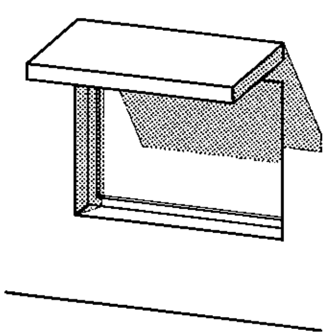


Equator

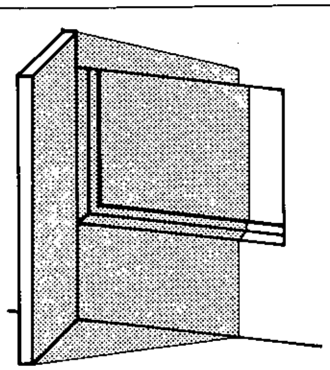
Tropic of Cancer

North Pole

Apparent movement of the sun above the horizon



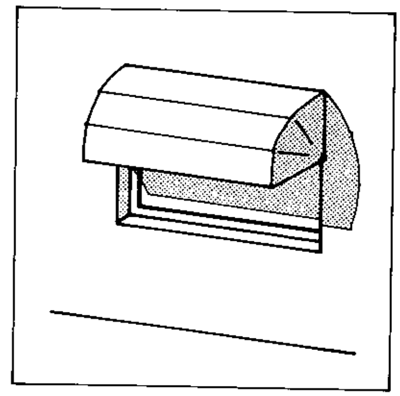
South windows can be shaded by overhangs above the glazed element. Summer shading requirements must be balanced with the need for solar heating during the winter through south windows. A balanced design is difficult for a fixed overhang that is placed immediately above the top of the window. It is possible, however, to admit the low winter sun and block the high summer sun with a fixed overhang if it is placed 30 to 50 cm above the top of the window.



East and west windows are difficult to shade because of the low and variable sun angles. Vertical movable devices are most effective, but can be expensive and difficult to maintain.

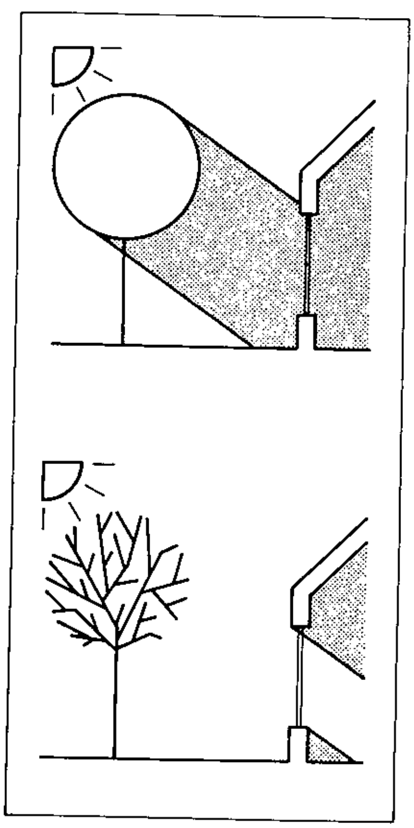
When sizing permanent shading devices it is important to consider the overhang depth in relation to its distance above the window and the window height and the overhang length in relation to the breadth of the window. For vertical projections, consider their height and their depth, respectively. By determining those two geometric characteristics, the shading conditions and the surfaces shaded can be calculated.

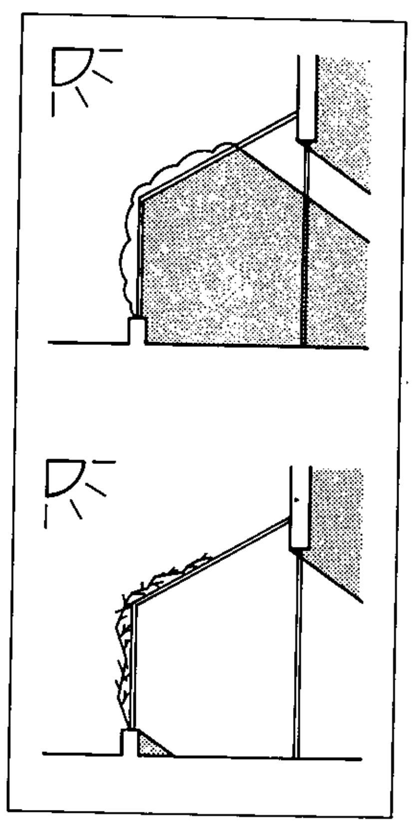
Because the solar altitude and azimuth vary hourly and seasonally, the shade created by a screen or awning will vary in the same way. The problem with fixed overhangs is that the shadow variation follows the seasons of the sun rather than the climatic seasons, which are always somewhat behind. For instance, in moderate climates an optimal shading on August 15, when the weather is warm causes the same shadow on April 27, when solar heat gains are welcome.



For this reason movable shading devices like awnings or movable vertical louvers are better in climates with significant heating seasons. However, such devices attached to the outside of buildings are sometimes difficult to operate and maintain.

Deciduous vegetation more closely follows the climatic seasons. However, even when the foliage is dense some sunlight will pass through and when the tree is completely bare of leaves, it still blocks 20 to 40 percent of the sun's direct radiation, reducing solar gain proportionately.





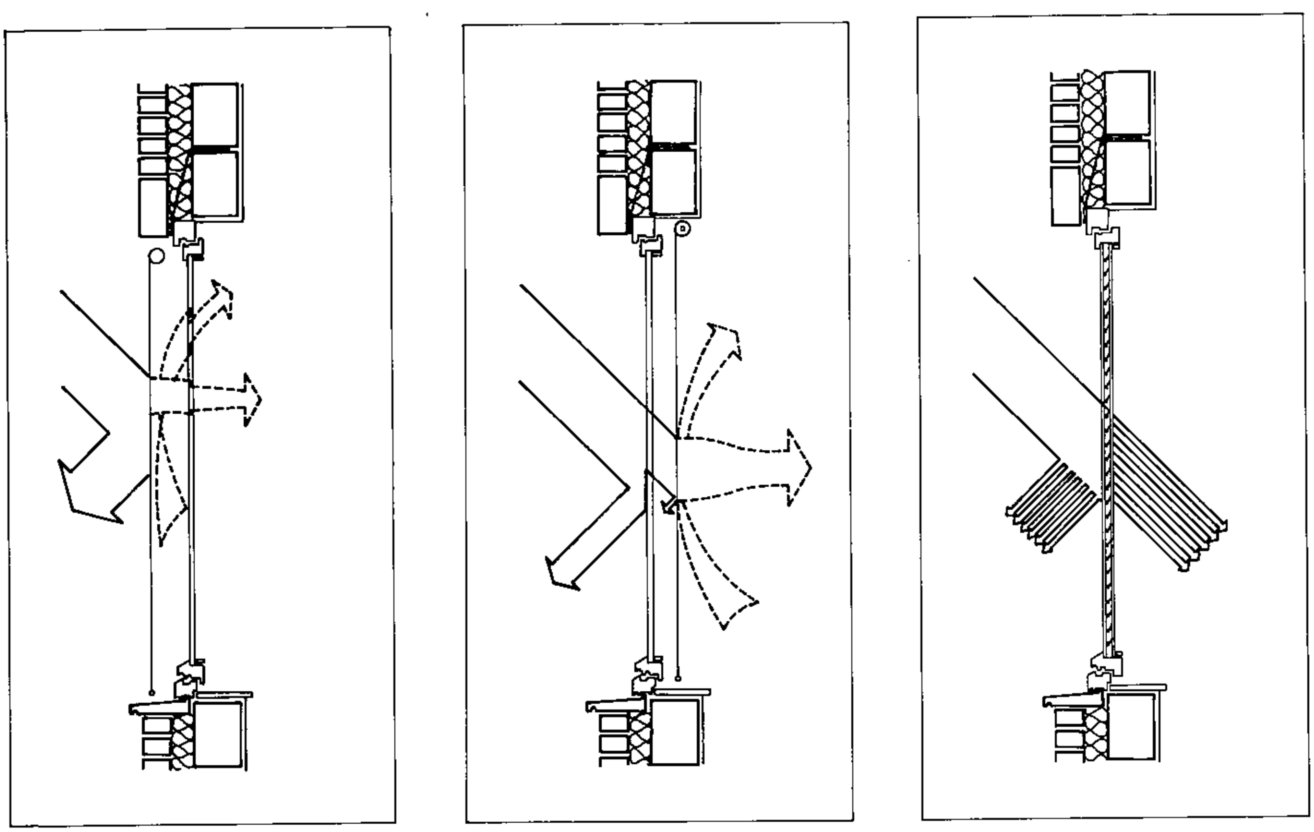
5.2. WINDOW SCREENS

The effectiveness of window screens is not as strongly dependent on the sun's path. The effectiveness of shading is defined by the shading coefficient, which is the ratio between the quantity of solar energy passing through the protected window and the energy passing through an unprotected reference window, usually simple single glazing (this definition may vary by country).

A shading device allows a reduction of solar gains, but should never darken living spaces and force its occupants to use artificial lighting. Screens which permit some diffused light to be transmitted are preferable.

Window screens can be operable like shutters, blinds, persiennes, shades and curtains, or fixed, like louvers and lattice-work screens. Movable devices can be used more flexibly than fixed elements and can fill several functions. For example, in winter they can be used as complementary thermal insulation if their thermal resistance is sufficient.

Shading devices are better placed on the exterior of the glazing. Such a location allows the reflection of the major fraction of incident solar radiation before it even reaches the building. Interior screens are less effective since they stop the sun's rays only after they have entered the building. In that case, the air layer between the glazing and the shading device as well as the device itself becomes warmer. This disadvantage is less important in the case of a highly reflective device. Reflective shades are effective almost anywhere. Shading devices can also be placed between two layers of glazing. A good example is a Venetian blind of which the slats can be tilted to reflect summer radiation and yet allow the winter sun to penetrate through the window. This design is more effective than interior blinds, and it avoids the maintenance problems of the exterior devices.



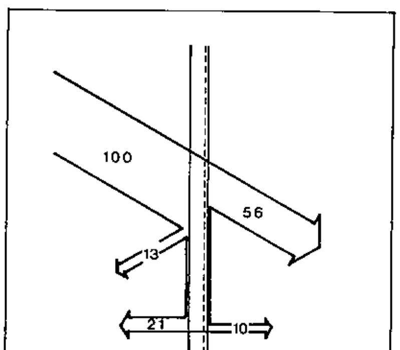
5.3. SPECIAL GLAZING

Because east and west windows are difficult to shade, special glazing can be used when view and light are important and solar gains are unwelcome.

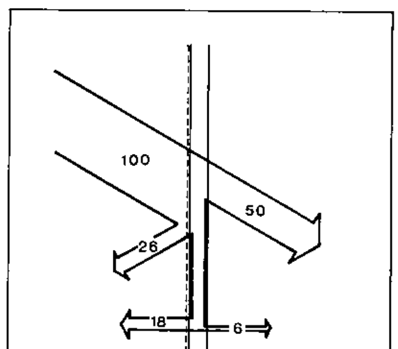
Absorbing glass decreases the total transmission of the glazing by decreasing direct transmission and increasing outward re-emission after absorption.

Reflecting glass is made by lining the glass with a thin highly reflective metal oxide layer. This layer is better placed on the outer face of the glazing, but is then difficult to maintain. When placed on the inward glass of a double glazing, facing the cavity, the temperature in the cavity increases excessively and explosion could occur. The best placement is on the cavity side of the outer glass.

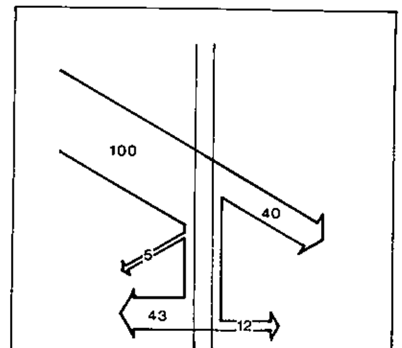
Absorbing and reflecting glass is recommended only in east and west windows. These products are not commonly used in residential applications, but they appear promising, especially in warmer climates.



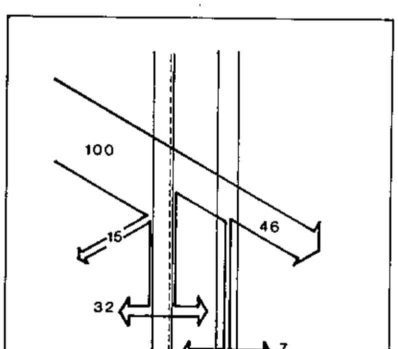
reflecting glass 6mm



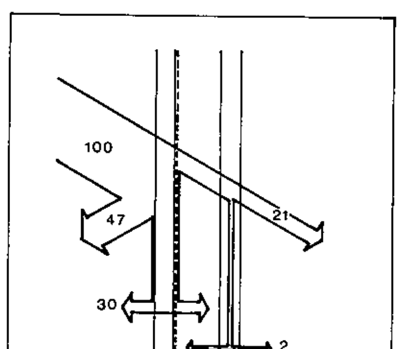
reflecting glass 6 mm



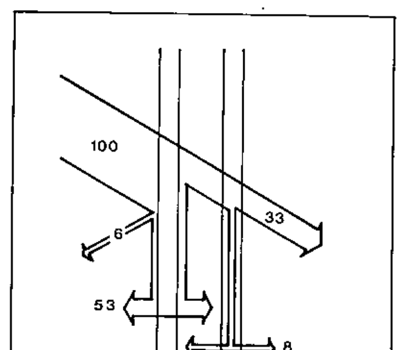
absorbing glass 6mm



reflecting glass 6mm-clear glass 6mm



reflecting glass 6mm-clear glass 6mm

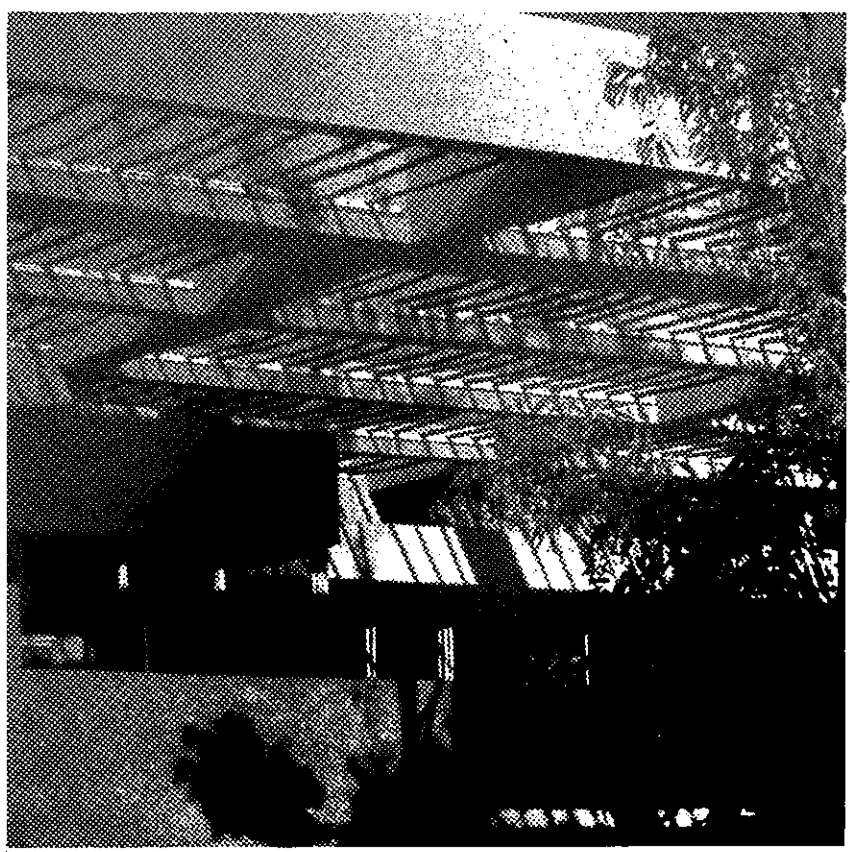


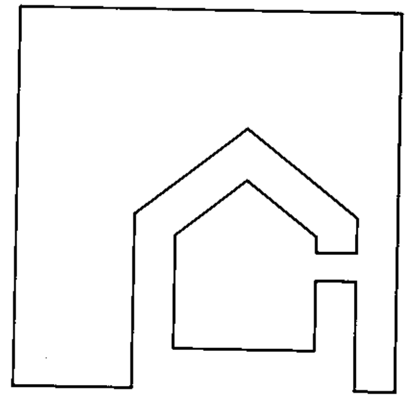
absorbing glass 6mm-clear glass 6mm

5.4. BUILDING PROTECTION

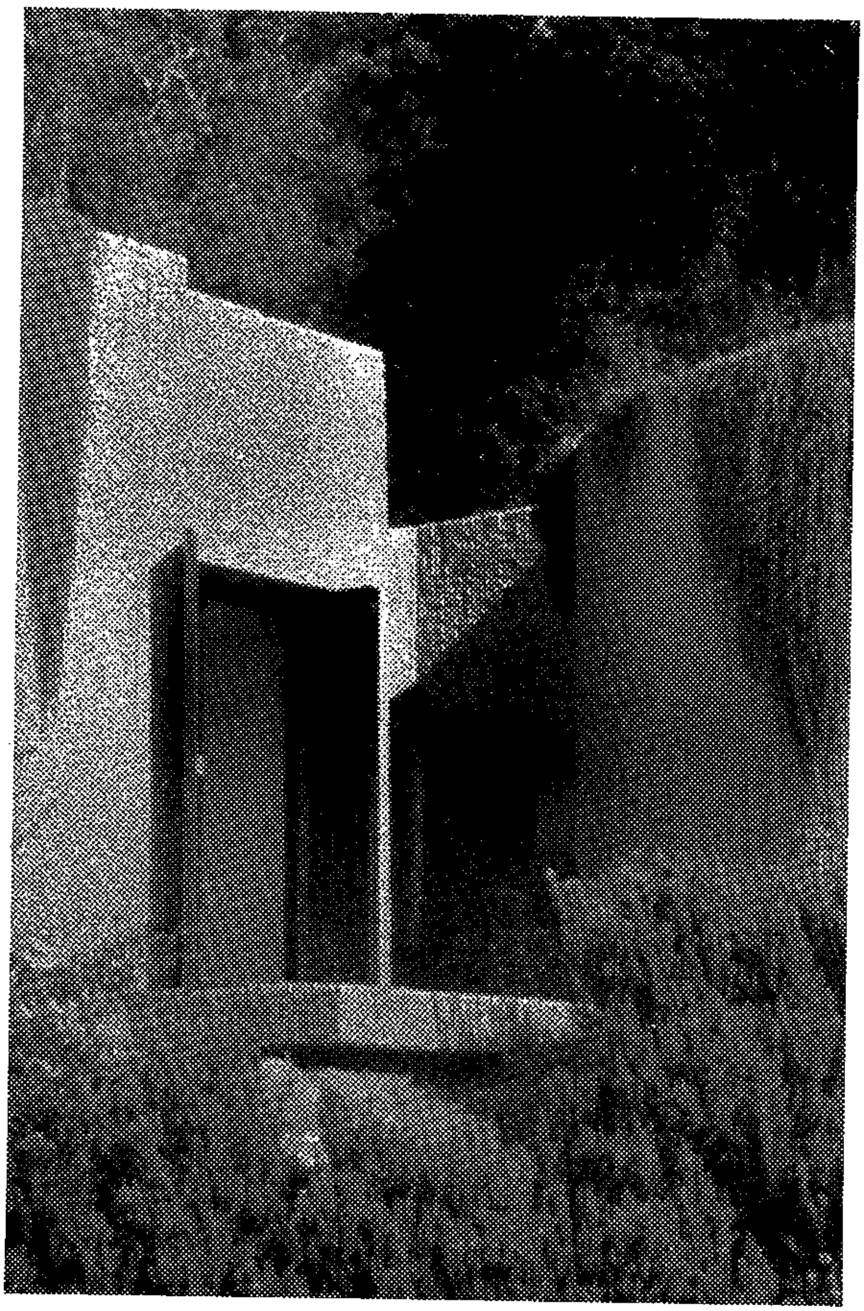
Building shading is hard to achieve in many hot climates. Neighboring buildings and trees can cast some shadows and landscaping can also help. Many well known cave dwellings, dug into vertical hill-sides, have the advantage of being completely protected against summer sun.

Modern building designs have used this concept with an exterior lattice structure above the roof or above courtyards, or with large roof overhangs that shade the walls. Such devices allow natural cross ventilation and avoid the summer sun, an ideal cooling combination for hot climates.





As shown in the previous section, the building envelope is heated directly by the sun's rays if not well shaded. It is also heated by external warm air through convection. In both cases, the heat flow rate through the envelope must be reduced.

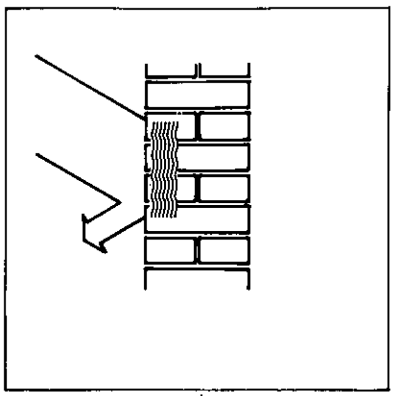


6.1. REDUCTION OF THE TRANSMISSION GAINS

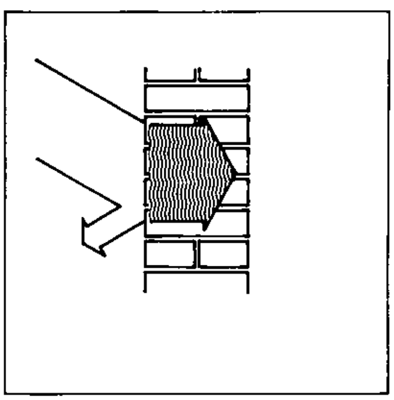
Contrary to the wintertime condition, heat flow through the building elements during the summer comes from the outside to the inside of the building. A well insulated building, one that conserves thermal energy, is also well designed for heat avoidance. The principle of insulation has been explained in Section 4.1. High levels of insulation are more often found where the heating season is relatively severe, but insulation is also necessary in warmer climates.

Two other ways to reduce heat flow can be used in hot climate. One takes advantage of the time lag caused by thermal storage,and the other uses a barrier against thermal radiation. The relative advantage of these two options depends on the specific climate and location.

THERMAL INERTIA AND TIME LAG

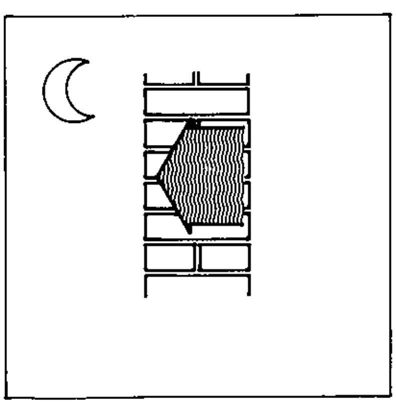


Thermal inertia is only useful where there is a wide diurnal temperature variation, and where the average ambient temperature is within the comfort zone. This is characteristic of the hot dry climates. This method of reducing heat flow makes use of the thermal capacity of heavyweight construction and the resulting thermal time lag. When the sun's rays strike an opaque element, the exterior surface absorbs a part of the radiation and converts it into heat. Some of the heat is immediatly lost and the remainder is conducted into the element at a rate that depends on the thermal diffusivity of the material.



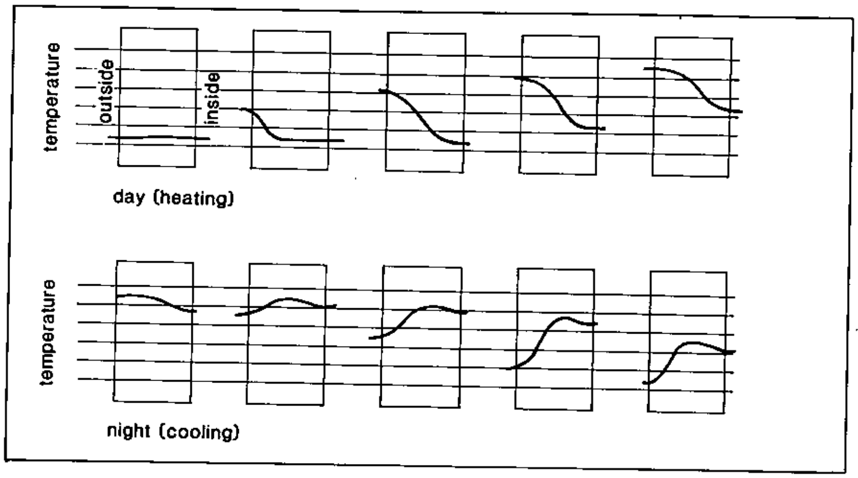
If the temperature difference across the element is kept constant, a temperature gradient develops across the element, creating heat flow proportional to the temperature difference and the U-value of the material.

On the other hand, if there is a daily temperature variation and if the building element has sufficient mass that the heat absorbed at the exterior surface has not already reached the interior side when the exterior surface temperature decreases, some of the heat stored begins to flow outward. Thus, at this time heat is emitted on both sides.

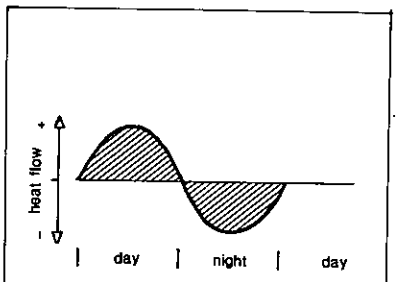


During the night the interior air temperature is higher than the ambient temperature. Outward heat flow continues, and the temperature of the building element gradually decreases. In addition, the inner side of the envelope can be cooled by nighttime ventilation (See Section 8.3).

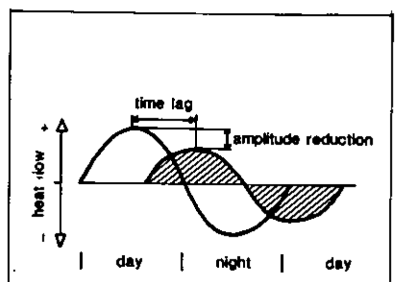
Using the effect of thermal inertia does not change the total heat flow between the building and the environment. However, by dampening the diurnal temperature fluctuation, thermal mass can provide comfortable indoor temperatures, particularly in dry climates. This effect has limited value in cold climates, because heating season temperatures are too low to provide any usable energy. Mass is useful in the heating season only when it is used to store solar energy. Thus, insulation remains the primary means of heat conservation and heat avoidance in cold climates.



The figure opposite shows the temperature gradient within a heavyweight wall over a 24-hour cycle. The crest of the temperature "wave" never reaches the interior surface. During the day, the interior temperature rise is much smaller than that of the exterior. At night, heat is released to the cool exterior surface. Comfort during evening hours can be further enhanced by ventilation.

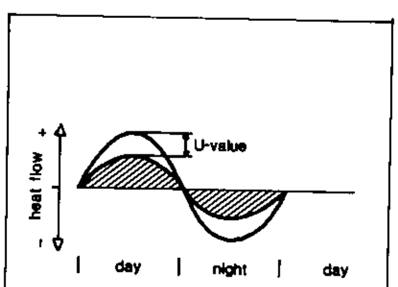


perfectly conductive wall

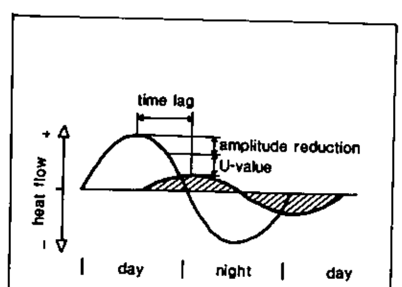


effect of thermal mass

The diagrams opposite show the effect of thermal mass and insulation on the heat flow passing through a wall.

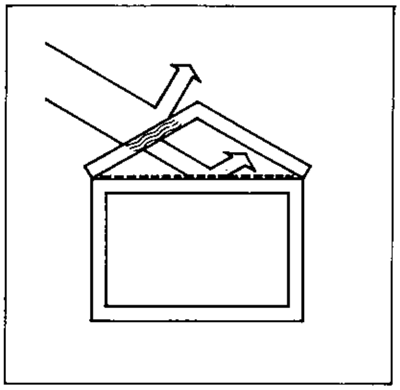


effect of insulating value



compound effect

HEAT FLOW REFLECTION



In a cavity where the air is still and convection is reduced, the primary heat transfer mechanism is radiation. Radiative heat flow can be reduced by lining each face of the cavity with a highly reflective foil, such as aluminum foil. A similar effect is obtained by hanging a foil sheet at the center of the cavity, as long as there is no contact allowing conduction between the foil and another material. Also, a single foil sheet placed adjacent to an insulation element, with an air space between, increases its thermal resistance.

This method to decrease radiative heat exchange is especially effective when heat flow is downward, such as in the roof during the summer or in the floor during the winter. A radiation barrier can augment the thermal resistance of floor insulation, but subfloor moisture may cause rapid deterioration of foil materials.

Radiation barriers in the roof are recommended in warm humid climates where buildings are lightweight and heat avoidance is difficult. Reflective foils placed on the underside of the roof and above the ceiling can reduce heat transmission from the sun-heated roof by as much as 90 percent.

THERMAL BRIDGES

As described earlier relative to heat conservation, thermal bridges must be avoided for an optimal performance of the envelope (See Section 4.1.).

6.2. REDUCTION OF INFILTRATION

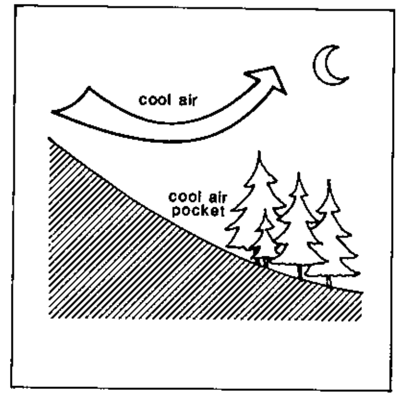
In hot dry climates where there is a wide daily temperature variation, air infiltration must be avoided during the day and the building should be well ventilated at night. In warm humid climates when a mechanical cooling system is necessary, infiltration should be minimized at all times, even when the cooling system is not in use, to prevent excess moisture accumulation.

Air-tightness keeps the interior cool and prevents an increase in humidity which can lead to moisture condensation due to lower temperatures inside the building than outside. The principles of air- tightness are the same as those described earlier relative to avoiding infiltration heat losses (Section 4.2.).

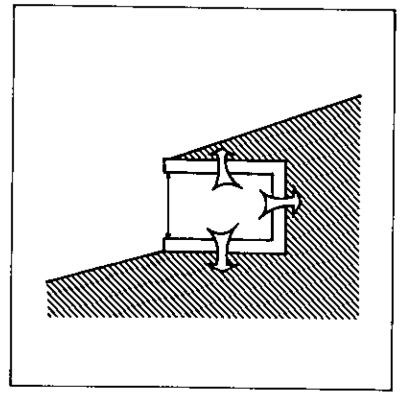
Nevertheless, reduction of infiltration is not a concern during the summer in many temperate climates, where ventilation is welcome.

6.3. MANAGEMENT OF TEMPERATURE DIFFERENCES

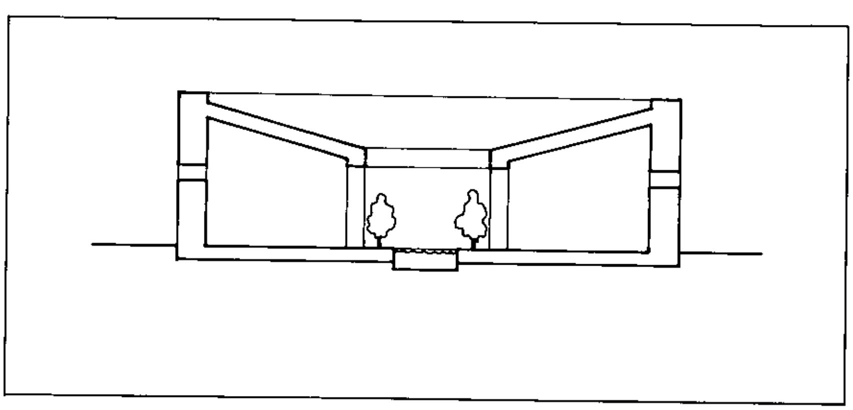
It is often possible to take advantage of natural cooling effects to reduce the air temperature around a building. At night, cool air from higher elevations flows down through valleys and fills the depressions in the ground. Landforms and vegetation help to keep the cool air trapped. In addition, the presence of water can provide a cooling effect. These three elements are generally found in an oasis. They maintain a more comfortable temperature even in the middle of the desert.



In hot climates the temperature of the ground is nearly always cooler than the air. In such climates, earth contact will decrease heat gains. The parts of the envelope that are below grade should remain uninsulated, but should be waterproof in order to avoid condensation on cool inside surfaces. In temperate climates where there is a significant heating season, the entire envelope should always be insulated.

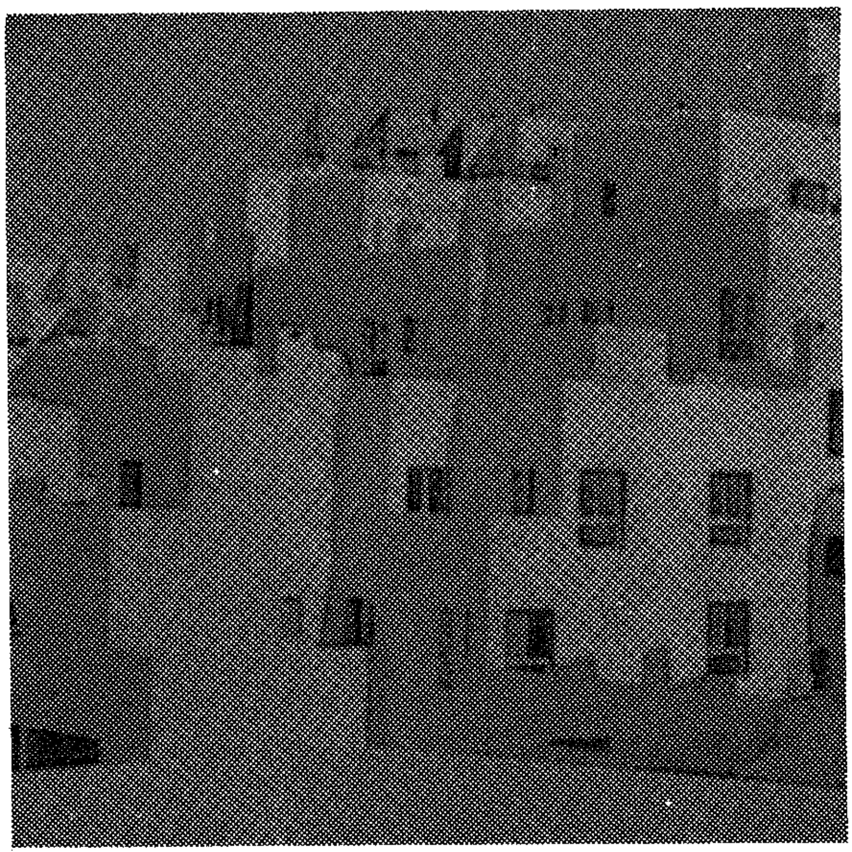


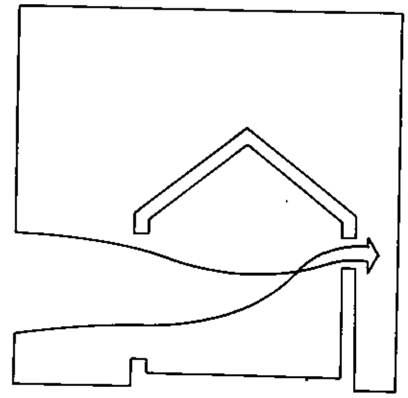
Thermal zoning and ventilated south-facing buffer spaces also help to keep the living spaces cool. The cool core principle is illustrated by courtyard houses, which are common in warmer climates.



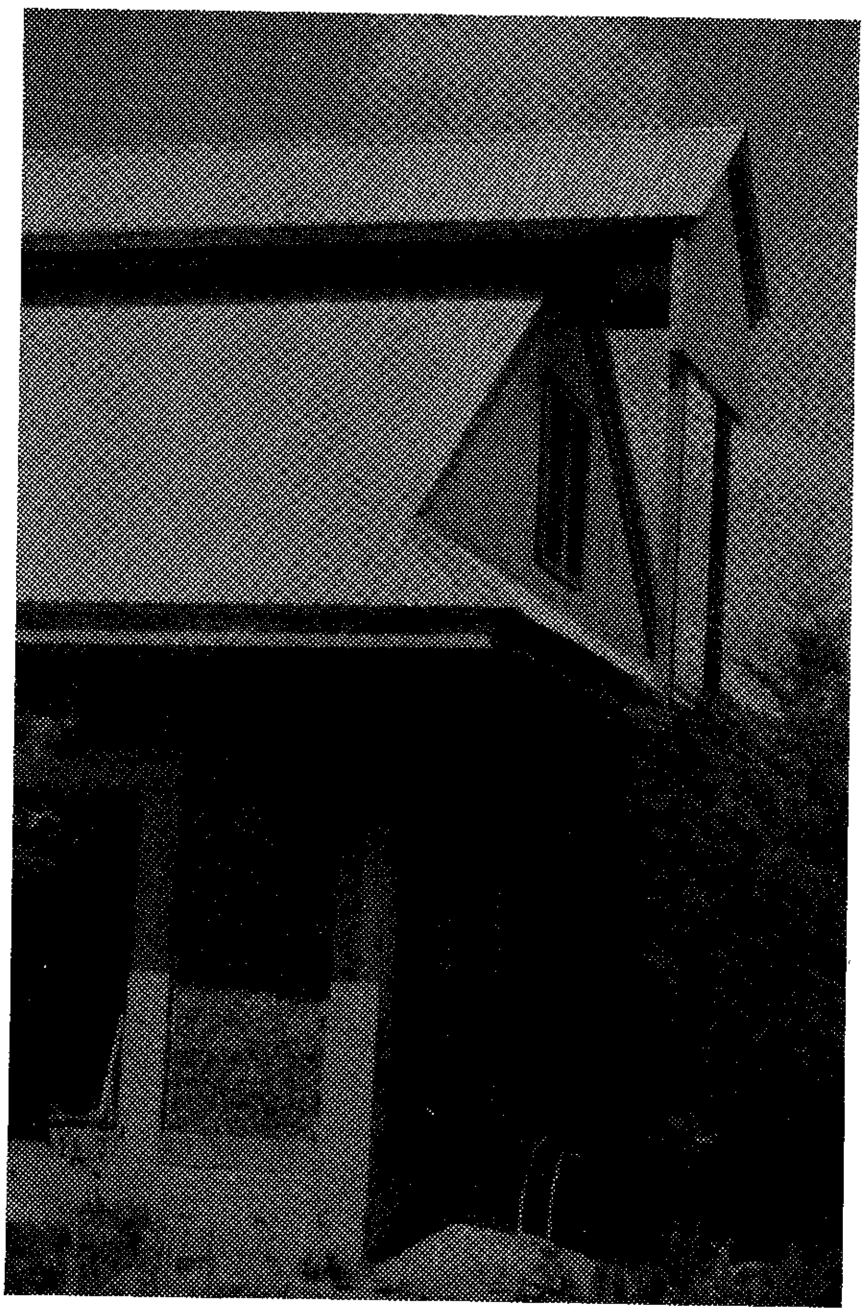
6.4. COMPACTNESS

In hot dry climates, cities are traditionally very compact in order to keep cool and also to shade buildings by the neighboring ones.



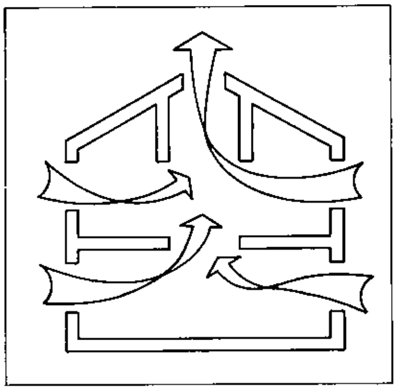


There are many hours during the summer when the interior temperature, due to solar and internal heat gains, is warmer than the ambient temperature. During these hours, natural air circulation can be used to remove warm air from the building and replace it with cooler air from the outside. Natural ventilation can be driven by temperature differences or by wind.

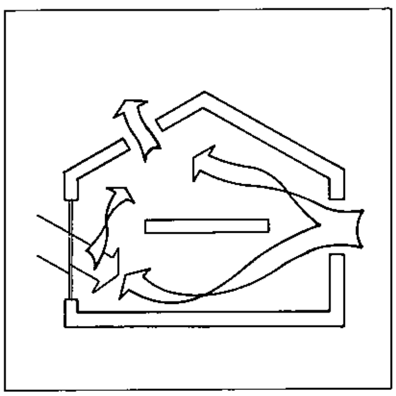


7.1. TEMPERATURE GRADIENT EFFECT

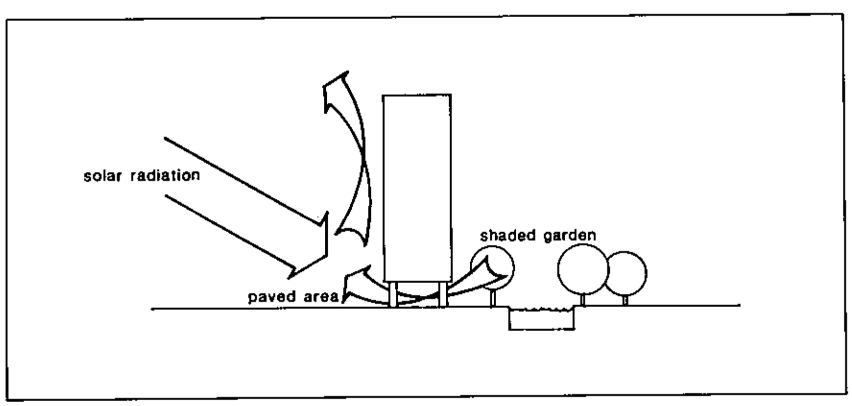
When two air masses have different temperatures, their densities differ as well. This density difference induces air movement, as the warmer air rises and the cooler air falls.



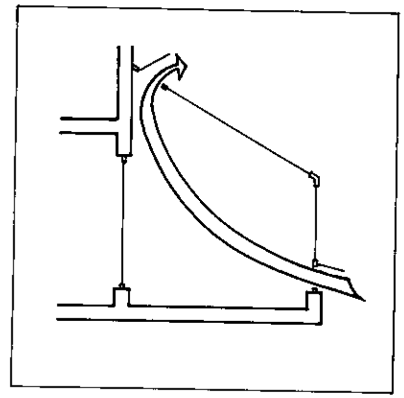
If sufficient air passages are present to allow it, warm air masses rise naturally in the building and escape through high openings, while low openings allow the entry of cool outdoor air. This is the "stack effect". This physical phenomenon explains why ventilation is more effective when there is a vertical difference between window openings and when openings are vertical.



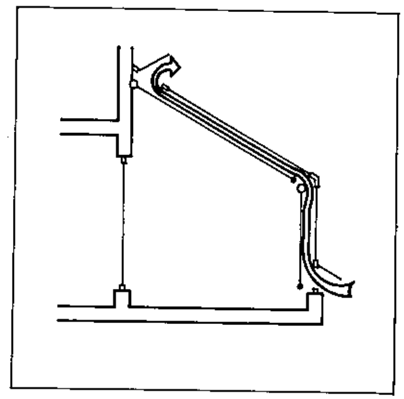
The same effect can be used to induce cross ventilation. Cool air pockets are created in the building shadow, while air becomes warmer near the sunny side of the building, especially if the surfaces are light colored. The warm air rises and cool air will flow through the building toward the sunny side.



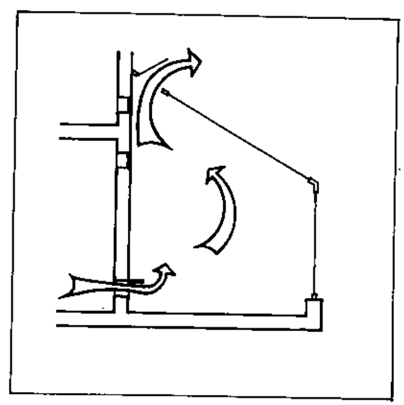
The figure opposite shows the apertures located in a sunspace to allow efficient heat dissipation by solar induced stack ventilation.



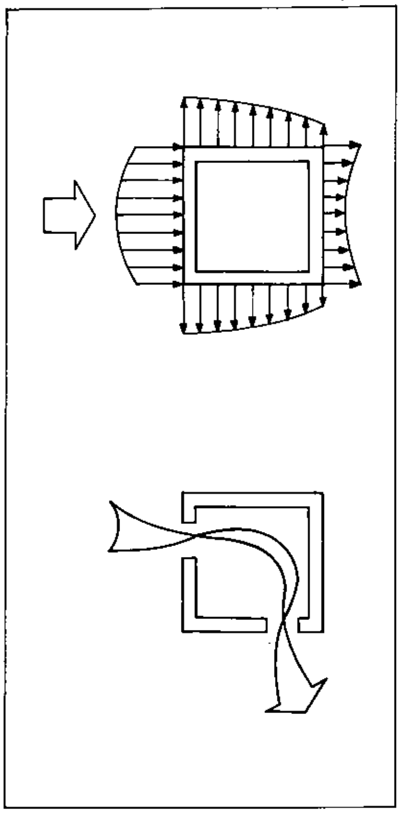
The shading device in the sunspace shown opposite creates a solar chimney effect between the glass and the blind.



The air movement in a sunspace can create a draft of indoor air, increasing the heat dissipation from the building. To provide ventilation only when needed, the aperture at the bottom of the wall separating the sunspace from the living space must be properly managed.



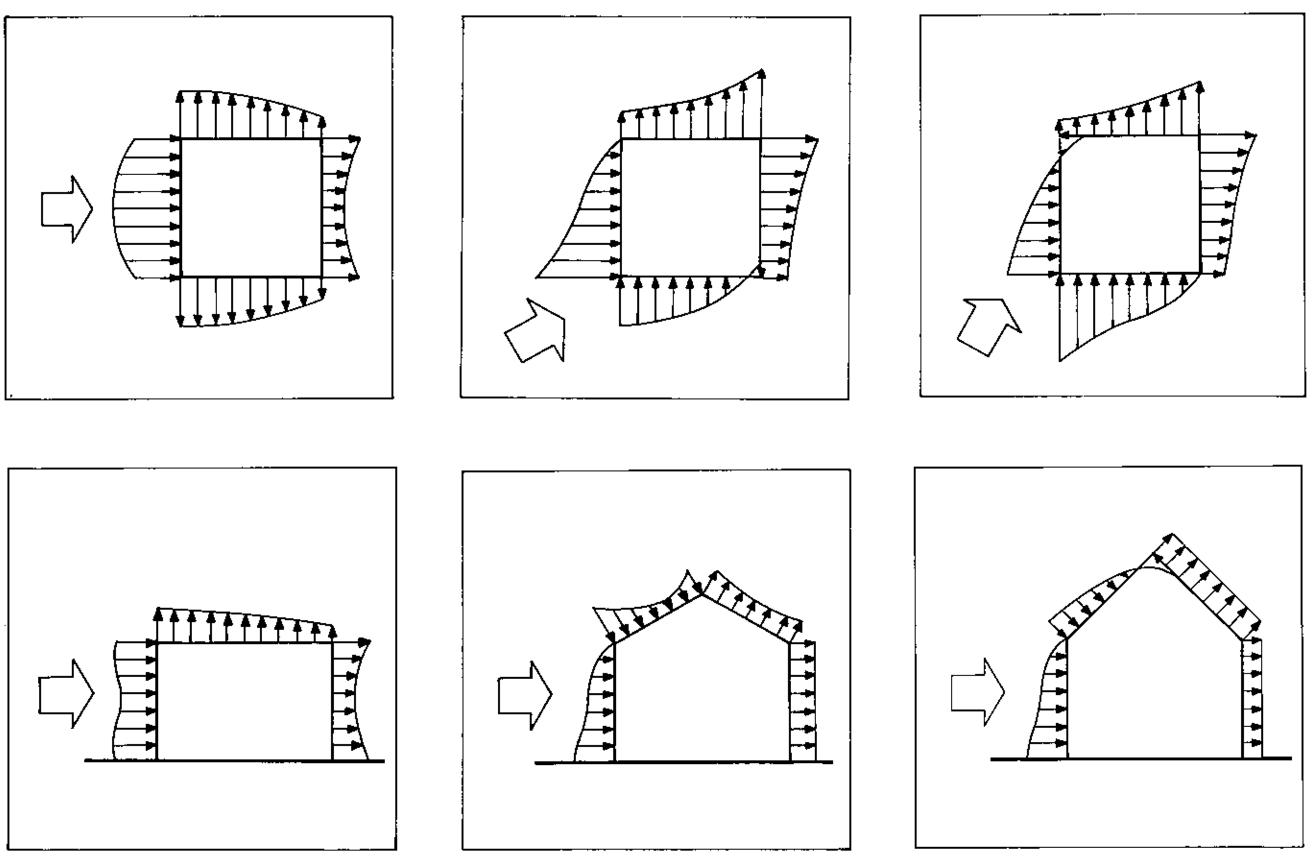
7.2. WIND PRESSURE EFFECT

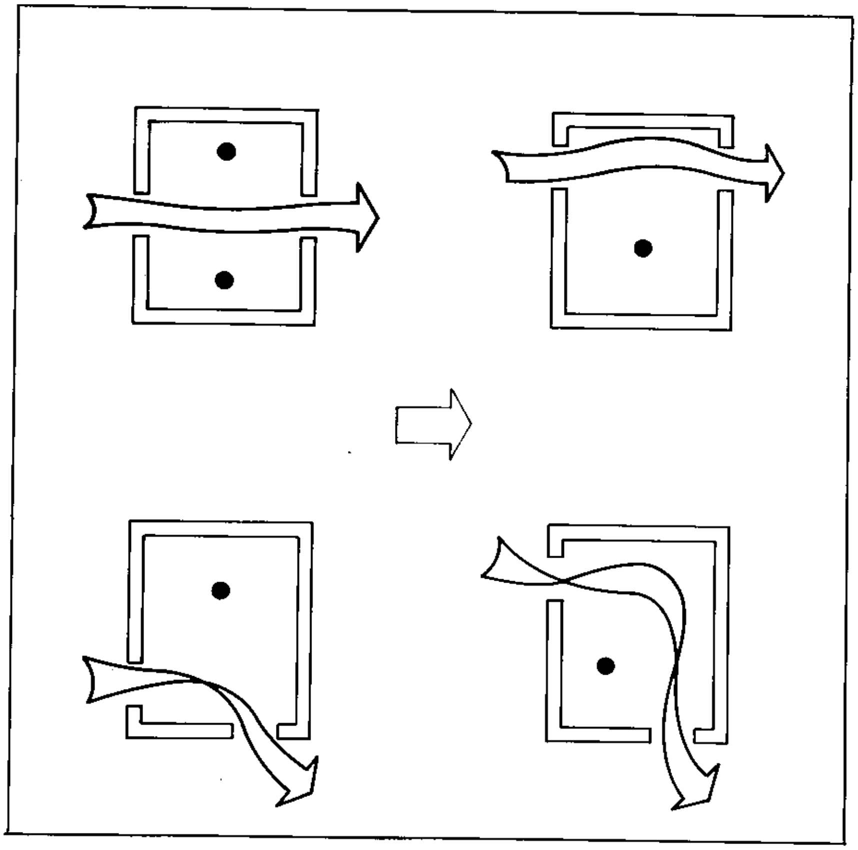


Heat dissipation can be accelerated by making use of the wind. When the wind strikes a building it creates high pressure on the exposed surface and low pressure on the opposite face. It is the direction of the local wind which determines the behavior of the pressure differences on the walls of the building. In most locations, wind speed and direction vary considerably over time and may not be reliable enough to be a basis for design.

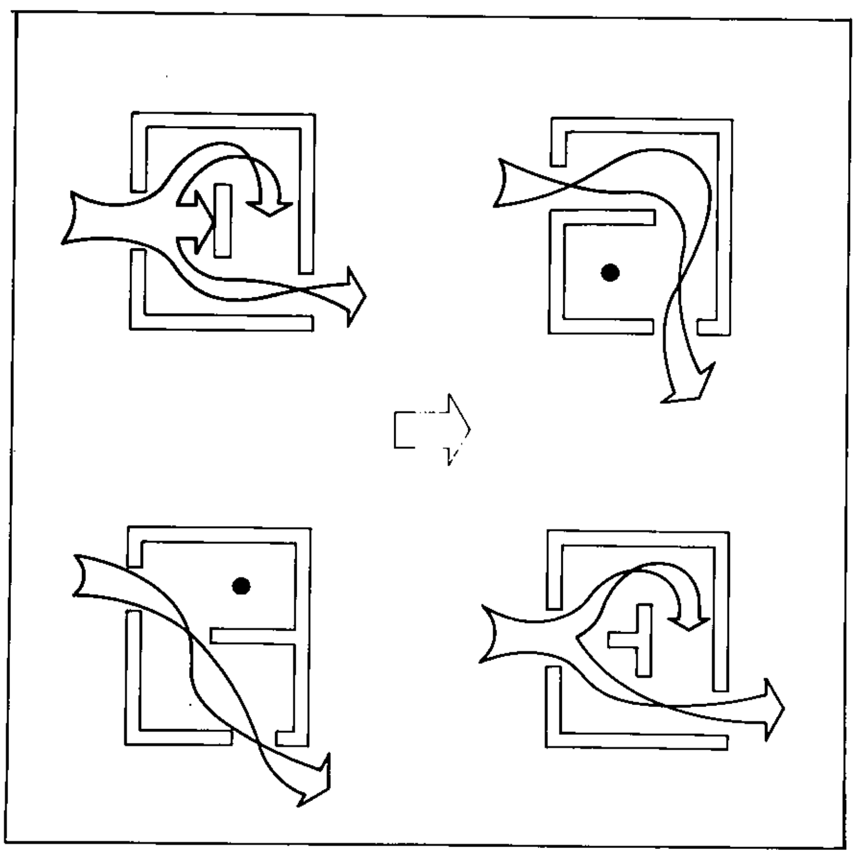
The air flow goes from high pressure areas to low pressure areas through openings in the building envelope. The size and location of openings determine the speed and the intensity of the air flow in the building. The air flow velocity will be at its maximum if air outlets are higher than inlets. The distribution of ventilation in a building is better when windows are arranged diagonally and when the air flow through the building is not hindered by partitions, furniture, etc.

The examples below show the high and low pressure areas around a building of simple shape as a function of the wind direction.



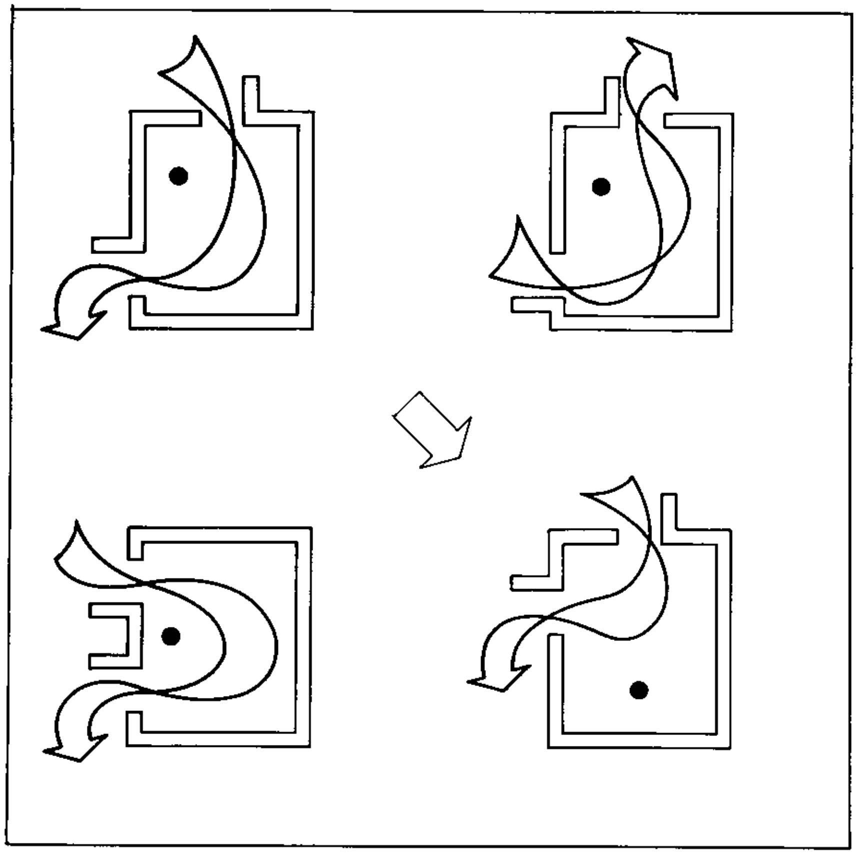


The location of openings determines the airflow path through the building. Unventilated areas are marked with the solid dot. The arrow in the center of the four diagrams indicates the prevailing wind direction.

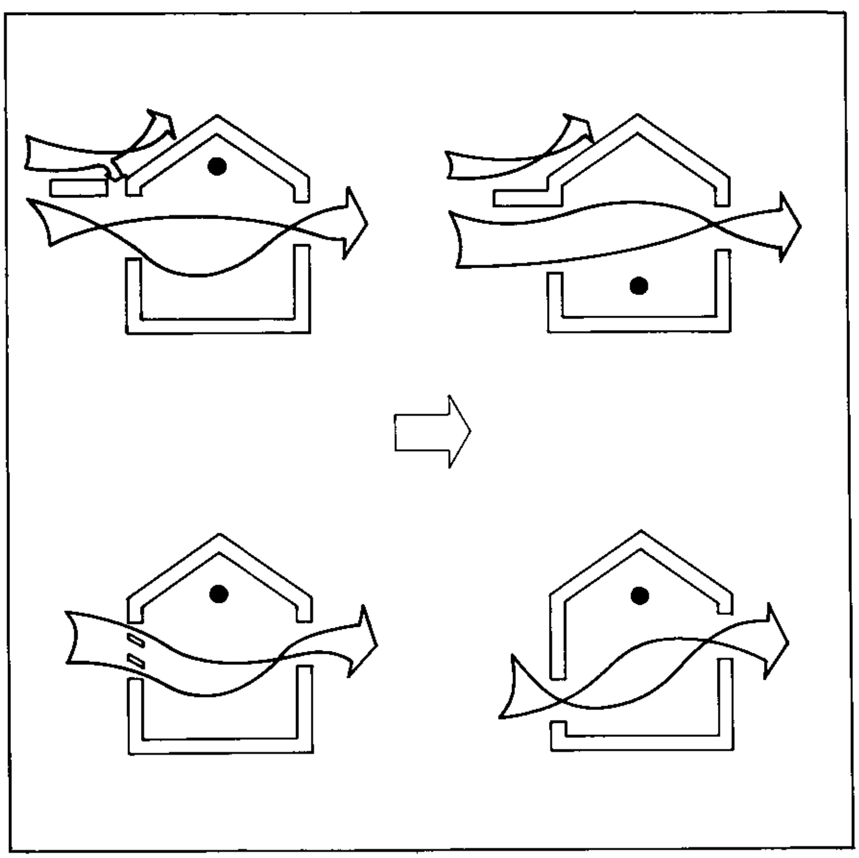


Partitions influence the airflow. Unventilated areas are marked with the solid dot.

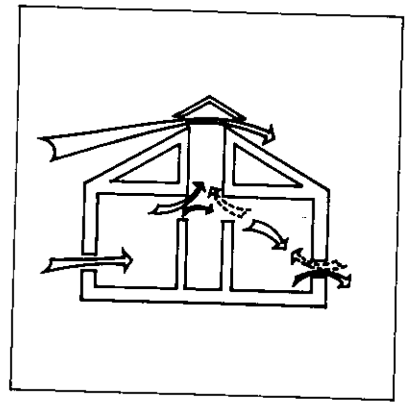
The diagrams opposite show the effect induced by wind deflectors. Sometimes open casement windows can serve as wind deflectors. Their use makes it possible to reverse pressures through openings and consequently to choose the area vented by the airflow. Proper placement of wind deflectors requires a thorough understanding of seasonal local wind patterns.



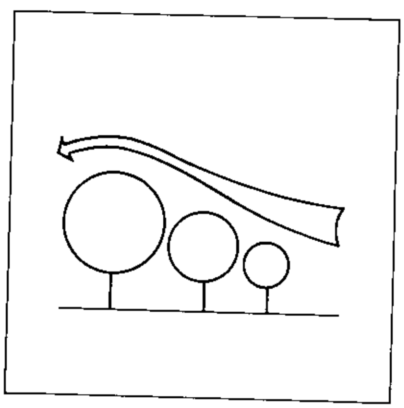
The revolving blades shown below make it possible to cause the airflow to deviate as desired. Unventilated areas are marked with the solid dot. The arrow in the center of the four diagrams indicates the prevailing wind direction.

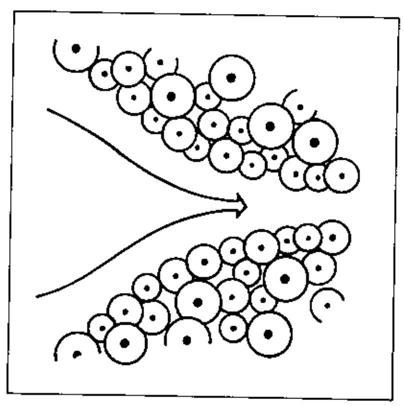


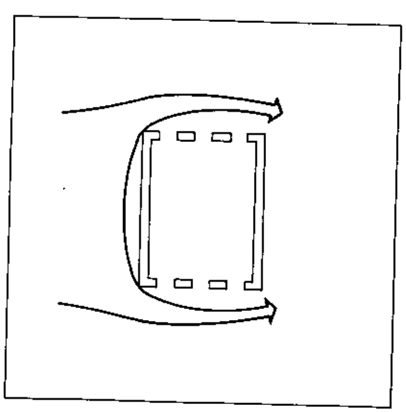
One can also make use of wind by creating a Venturi effect. The figure opposite shows the wind passing below the upper detached part of the roof to induce a draft of inside air and accelerate the heat dissipation.

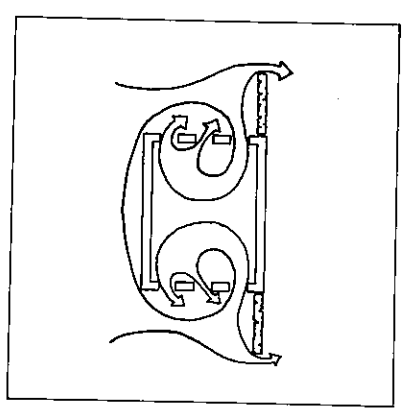


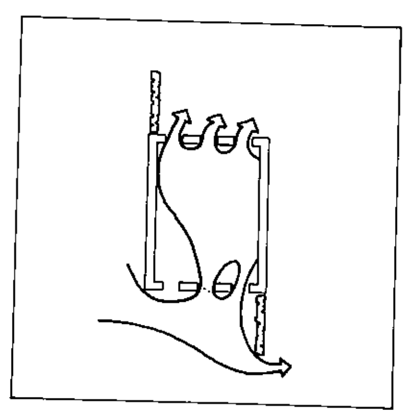
When the best position for ventilation openings contradicts the best strategy to achieve solar control, it may be possible to funnel the wind outside the building by means of fences, hedges or shrubbery.



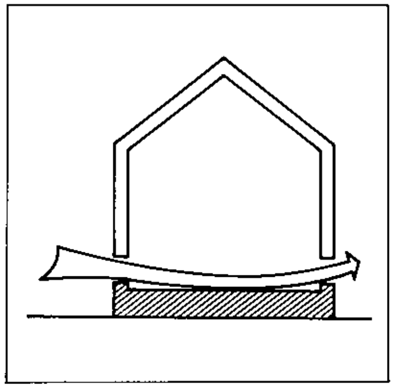


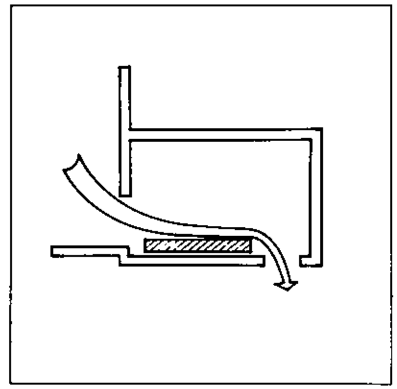




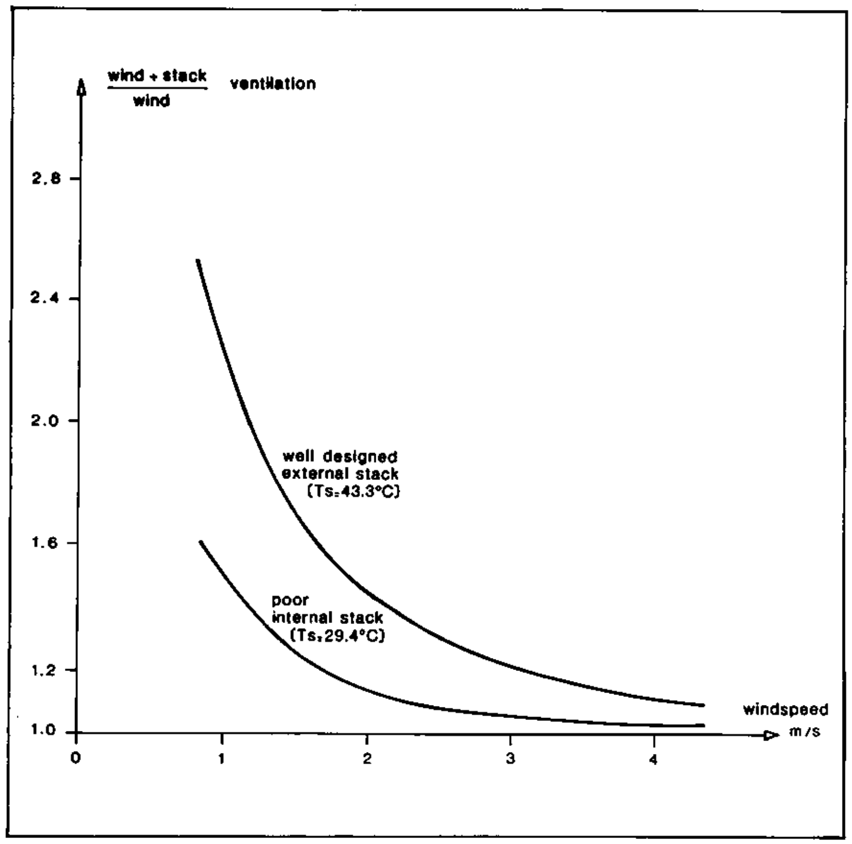


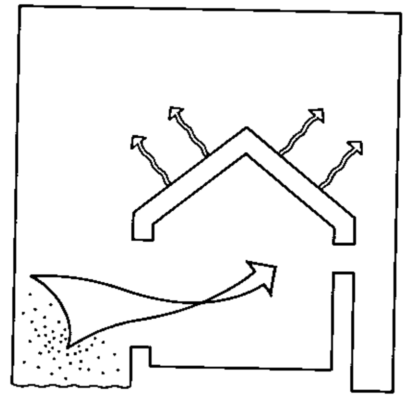
In order to effectively cool the thermal mass elements and benefit from their thermal inertia, it is necessary to channel the flow of ventilation air so that it passes across the mass surface. Mechanical fan back-up may be necessary to accomplish this.



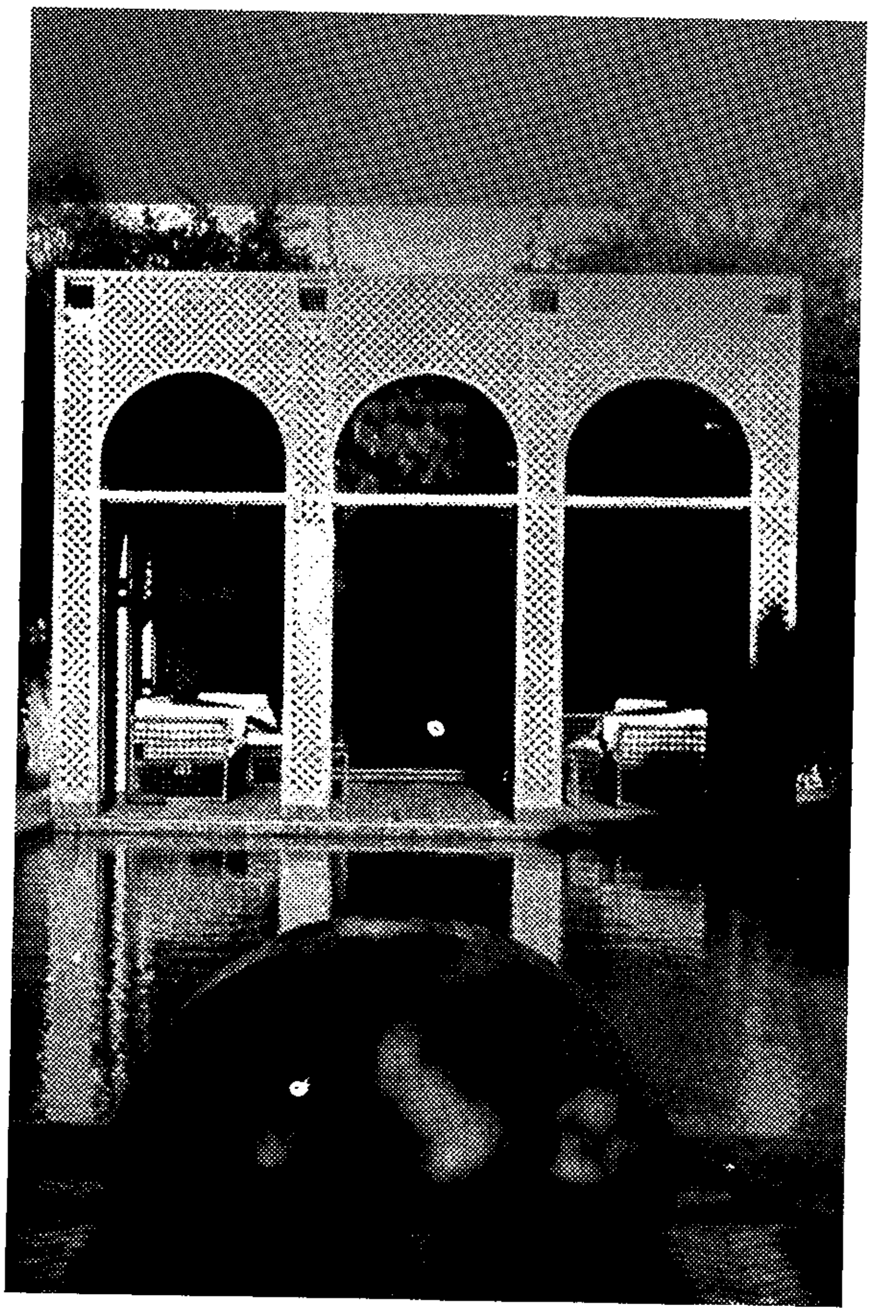


The diagram shows that, at windspeeds lower than 4m/s (which is a moderate windspeed), the stack effect is dominant, compared to the wind effect, in heat dissipation.

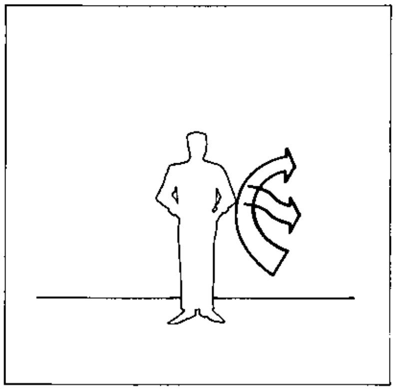




In addition to the avoidance and dissipation of heat, some natural processes can be used to decrease the temperature of the air or the building envelope. These techniques are properly called natural cooling. They may not all be possible or necessary in every warm climate.



8.1. PHYSIOLOGICAL COOLING

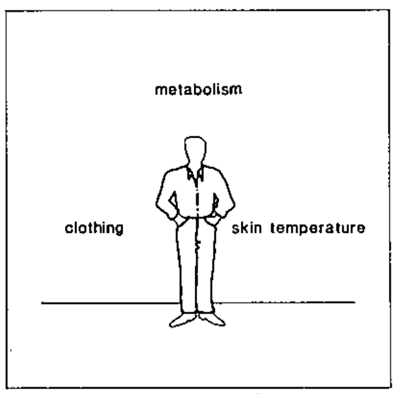


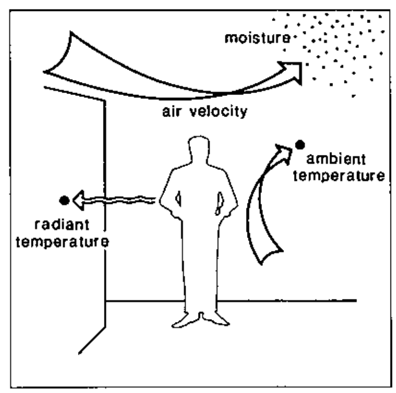
The feeling of comfort depends on many parameters. Three of them are physiological in nature: metabolism, clothing and skin temperature (which in its turn depends on the metabolism). Four are related to the environment: ambiant temperature, moisture, radiant temperature (i.e. the temperature of the surrounding surfaces) and air velocity.

Similar comfort levels can be obtained by different combinations of those parameters. An action upon one or more of them can provide physiological cooling. For instance, air movement of reasonable velocity increases human comfort without any change in temperature. As long as the air temperature is less than the skin temperature, air movement activates heat loss from the skin by convection.

Physiological cooling is also provided by acceleration of skin evaporation. Air movement breaks the saturated air envelope surrounding the body, which allows for efficient evaporation. This cooling effect is achieved by natural ventilation or by room fans.

During the summer and in warmer climates, internal and solar heat gains can cause interior temperatures to become too high. If it is not possible to store enough thermal energy to keep the interior temperature within the comfort limits, excess heat must be dissipated by ventilation and replaced by external air. Although the temperature may still be too warm for comfort in still air, the physiological cooling from the air motion may provide a feeling of greater comfort.





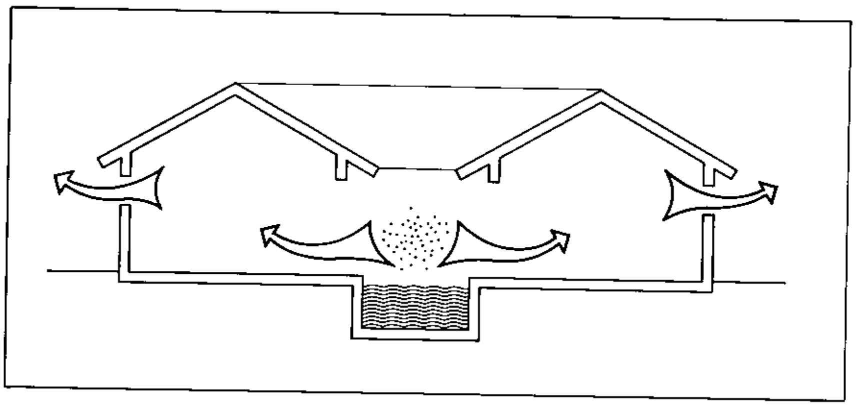
8.2. AIR COOLING

EVAPORATION

To change state from liquid to vapor, water needs a certain amount of energy called the latent heat of vaporization. The temperature of warm air decreases by supplying the latent heat to vaporize a quantity of water. This is evaporative cooling. The decrease in temperature is associated with an increase in moisture.

The evaporative cooling effect is enhanced by large water-to-air surface contact as well as relative movement of water and air. This can be observed near the surface of a pond, or from a breeze around a water fountain, spray, or waterfall. Cooled air flows downward due to the temperature gradient effect or the flow can be directed by placing the cooling device in the ventilation stream.

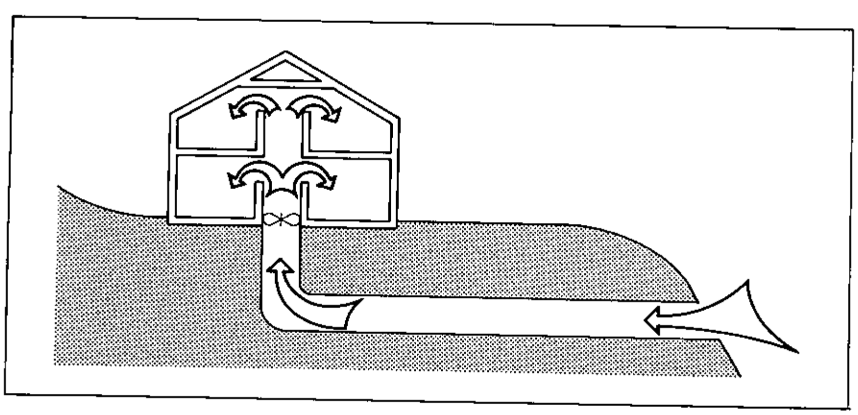
This cooling technique is not as efficient in humid climate where the air is already near saturation.



EARTH COOLING

In addition to the underground protection discussed in Section 6.3, the earth can provide a cooling effect by lowering the local air temperature. Underground tunnels can duct air into the earth and decrease its temperature by convection. If the earth is wet, an evaporative cooling effect occurs also.

The problem with this system is that, depending on the air input temperature, it is sometimes necessary to duct the air long distances before obtaining a cool enough temperature. There are also potential problems caused by organic decomposition inside the ducts or emission of pollutants, such as radon, from the earth.

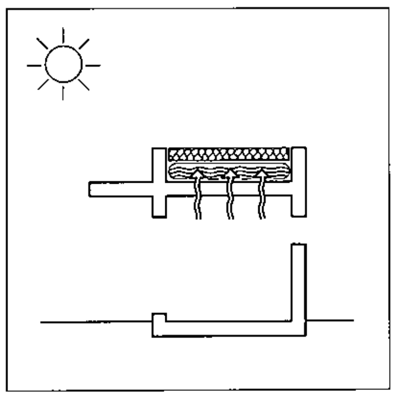


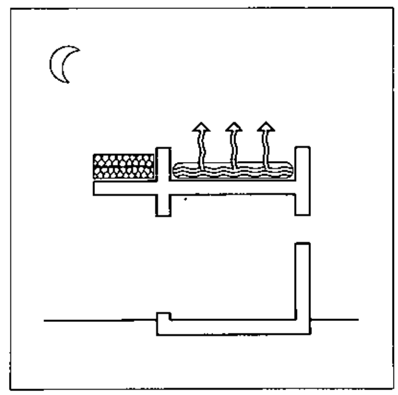
8.3. ENVELOPE COOLING

NIGHTTIME RADIATION

Radiative exchange of heat occurs continuously between masses of different temperature which face each other. The warmer gives its heat to the cooler. A clear night sky is very cold even during hot weather and a substantial quantity of stored daytime heat can be radiated to the night sky. This phenomenon allows the night cooling of heavyweight building elements or of water.

A typical example is roof ponds. During the day internal heat is collected and stored in the roof, which is protected by an external insulation. At night the insulation is removed and the stored heat is radiated to the sky. The performance is diminished by any kind of obstacles between the building and the sky. This effect is less effective in humid climates, because humid air is significantly less transparent to infrared radiation than drier air.





WIND

In addition to heat dissipation, wind also has a cooling effect on the building envelope by accelerating the heat loss by convection. Cross ventilation in the basement and the attic of a lightweight building keep its floor and ceiling cool. This is especially recommended in warm humid climates.

In hot dry climates, where the nighttime temperature is relatively low, nighttime ventilation of the building is an efficient way of cooling and the necessary complement of the heat avoidance by thermal storage (See Section 6.1). For maximum effectiveness, wind must be preferentially circulated past masses of high inertia in order to remove stored heat.