ABSTRACT

Sensitivity Analysis in Energy Responsive Design

by
Bratati Biswas

Energy responsive design involves the conscious use of climatic elements and natural processes in the design of spaces. Buildings are designed to react favorably with the environment to produce balanced comfort conditions. Passive solar building design utilizes this concept to heat or cool a building by natural means. In this approach, building components and materials are articulated to make maximum use of solar radiation and climatic elements producing energy responsive spaces.

The purpose of this research is to help designers to design with energy in mind. Energy related decisions are required during conceptual design and is not an add-on item to be imposed after the design is completed. A sensitivity analysis of various energy-related design parameters is presented. These provide a basic framework and aid in the design process, and also enable designers to get a quantitative feel of the different impacts. Designers are aware of the consequences of their design decisions and are able to make suitable trade-offs to design energy efficient spaces. Broad guidelines are articulated for four different climates with respect to exterior environment, building layout, and building elements.

SENSITIVITY ANALYSIS IN ENERGY RESPONSIVE DESIGN

by
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SENSITIVITY ANALYSIS IN ENERGY RESPONSIVE DESIGN

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CHAPTER 1

INTRODUCTION

The function of buildings has evolved over centuries to satisfy the changing needs of man. In ancient times, a building provided shelter from natural calamities. Now it serves dozens of complex functions. On the whole, the underlying principle of design has been to optimize the built environment for human comfort.

The concept of energy responsive design is rooted in ancient civilizations. Many traditional cultures have used energy conserving features in their architecture, which used solar energy beneficially. With the advent of modern technology, the climatic approach to design began to be de-emphasized. Designers built structures that relied increasingly on mechanical means, consuming significant amounts of energy to provide an optimum interior environment. Structures ignored the geographical and environmental factors, and were conditioned artificially to create closed systems.

Since 1973, rising fuel costs, prospective fuel shortages, and the imposition of governmental energy performance standards have made energy an extremely important consideration in building design. Society has turned to an alternative energy, i.e., solar energy, which can provide an inexhaustible source of energy for the future. In recent years, the trend in design has been to integrate natural and auxiliary energy issues. The principle of energy responsive design is to plan buildings that interact favorably with the climate and harness the forces of nature. The resulting spaces achieve higher levels of balance and are economical, providing comfort and enhancing the working ability of the people.

Energy responsive design encompasses the principle of passive solar design. A "passive" solar design involves the use of natural processes for heating or cooling to achieve balanced interior conditions. The flow of energy in passive design is by natural means: radiation, conduction, or convection. In most cases, a passive system is intimately integrated into the architecture of the building. Passive solar design involves the process of consciously designing to take the advantages of environmental energies and natural processes. This approach can be employed for heating, cooling, and daylighting. Since these are highly energy intensive functions, use of natural energies is economical.

The purpose of the thesis is to provide guidance to architects and designers who are not energy experts. Energy-related decisions have to be made during the conceptual and schematic design phases, and cannot be deferred to a later stage in the design process. A building cannot be made energy efficient after it has been designed. Energy conserving features are not add-on items that may be implanted on the building by engineers. It is for the architect to determine the characteristics of the design that have implications for energy performance. The aim is to provide information on energy conscious design in a format that will educate designers about the energy consequences of their design decisions and will be useful during the design process.

In the first stage of research, an understanding of energy conscious building design is essential. This is done through background study. The origin and developments of this approach and its integration into the design of buildings is investigated. Next, a sensitivity analysis is performed on various energy-related design parameters. These provide a basic framework and aid architects in the design process. Designers are able to understand the essence of energy conscious design without going into complex calculations. Finally, broad guidelines are presented on the incorporation of energy conserving strategies for four different climates with respect to exterior environment, building layout, and building elements.

CHAPTER 2

BACKGROUND STUDY

2.1 Energy Conserving Features and Building Systems

"The major objective in the design of buildings is to provide an environment that supports and enhances the ability of people to do whatever it is that the building is designed for." (Anderson 1990, 7) Heating and cooling are viewed as producing conditions that provide "human comfort" levels that people need to accomplish their tasks. Buildings consist of a collection of spaces enclosed by walls, roofs, windows, and other architectural elements. The organization of these elements, and their shape, size, and properties leads to a design which may or may not be energy responsive. These very components and their organization contribute to the "passive" design of a building. In energy conscious design, the building components are organized so that they interact favorably with the climatic elements and provide a good, working, environment.

Energy responsive design is not a special trade or industry; rather it is an approach to building which uses the natural energies for achieving a balanced environment. In winter, the entire house acts as a solar energy system and its components have dual functions; both the traditional function of providing a quality enclosure and the solar function of collecting, storing and distributing heat (Franklin Research Center 1979, 2).

Windows not only let light in and allow a view, but collect heat as well. Walls which subdivide and enclose space can also store and radiate heat. Components whose functions were primarily structural, spatial, or aesthetic may double as solar heating components. Often a traditional building component can be replaced by one with a dual solar function. The built-in nature of solar designs enables the builder to realize new economies in solar heating at minimum risk.

Environmentally conscious design includes the passive solar approach. The key to passive approach rests in the proper arrangement of common materials for residential construction. Passive designs require considerations of solar and heat flow in every detail and component. Floor plan layouts and circulation patterns, window location and the selection of wall and floor materials all effect how well a passive design will work. The passive approach to solar homes cannot be subcontracted to plumbing or solar equipment installers, for it is not an add on item.

2.2 Historical Perspective

The climatic approach to solar heating and cooling is not new. Deeply rooted in environmentally responsive building techniques, many cultures throughout the world have used passive features for centuries in traditional structures. The concept of using orientation and architecture to accept warmth from the sun in winter while denying entrance to excessive sunshine in summer was prevalent in ancient civilizations. Egyptians, Greeks, Persians and Indians all used the passive concept, so did the pre-Columbian Indians in North and South America. Much of the architecture of antiquity, following the teachings of Aristotle, Xenophon, and later Vitruvius was directed towards making use of sun and wind to ameliorate climatic extremes (Anderson 1990, 12).

The Greeks, nearly 2500 years ago, began orienting their buildings to best capture the sun's rays. The streets of Olynthus, for example, ran east to west to enable the houses to capture the sun. After the Greeks, the Romans advanced the technology further by using clear glass for windows. The Romans also constructed entire villages underground to take advantage of the cool earth. These underground dwellings also included central atriums and roof ponds for solar heating and cooling. As a result, the walls of these ancient dwellings remained below 75 degrees Fahrenheit throughout the summer (Schepp and Hastie 1985, 1). The Roman baths of Caracalla had large windows that transmitted heat and daylight deep into the interior spaces.

The Pueblo Americans of New Mexico purposely chose building sites that welcomed the winter sun, but rejected the summer sun. Montezuma's Castle, for example, was recessed within a south facing cliff. The overhanging ledge of the cliff above acted as an awning and provided summertime shade (Schepp and Hastie 1985, 8).

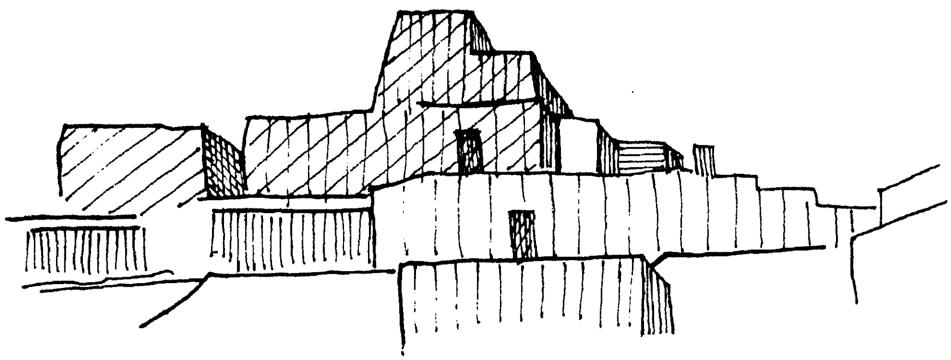


Figure 1 Native American Energy Responsive Architecture, Taos, New Mexico (Source: Schepp and Hastie 1985)

2.3 Modern Developments

As an endeavor towards energy responsive design, solar energy was introduced for space heating in this country in the 1930s. During that period, large hermetically sealed insulating windows became available at reasonable prices. Passive techniques began to enter residential architecture just before World War II. Among the pioneers were the Keck brothers of Chicago who were responsible for Solar Park, at Glenview, IL and for a solar home project at Rockford in the early 1940s (Paul 1979, 2-3).

Interest in solar heating began to revive in many parts of the US after the end of World War II. Most of the work was directed towards active systems such as those built and tested at Massachusetts Institute of Technology. There was little interest in passive systems, but fortunately work on fenestration carried out at the ASHRAE Laboratory in

Cleveland laid the foundation for procedures for calculating solar heat gains through windows (Paul 1979, 2-3).

The real awareness about solar as an alternative source of energy dawned after the 1973 oil embargo. Because of the energy crisis at that time, solar energy was taken seriously, with the government budget for solar research and development more than tripling between 1973 and 1974. The most important pieces of solar legislation passed by Congress at that time were the Solar Heating and Cooling Demonstration Act and the Solar Energy Research, Development and Demonstration Act. These two laws formed the basis of the national solar program (Schepp and Hastie 1985, 6).

Between 1974 and 1979, the federal government spent about $100 million to install solar systems on 12,000 houses, apartment buildings, and public structures. The earlier grants were for active systems, while the later grants were mainly for passive systems. California set the pace of an energy revolution. Due to Governor Jerry Brown's active support, California became the home to half the solar buildings in the United States (Schepp and Hastie 1985, 8).

Government support for solar energy has eroded badly since the days of the Reagan Administration (Schepp and Hastie 1985, 6-11). Today's stress on the environment, will perhaps generate renewed interest in this area. Every home will come with better insulation, energy conservation features, and passive solar will be an integral part of almost all houses.

CHAPTER 3

OBJECTIVE AND ASSUMPTIONS

In energy responsive design, decision making about design parameters is of vital importance. Often the designer is unaware about the significance of a design decision and how the efficiency of the building is affected. The issues often appear unimportant and are ignored, but may have serious consequences on the performance of the building. In this respect, sensitivity analysis serves as a guide in the design process. It brings out the relative significance of various design parameters and their preferred values.

The objective of this analysis is to provide designers with a basic framework on the performance of design parameters with respect to energy. By reviewing the charts and graphs, the designers will get a quantitative feel of the passive solar approaches. This will enable designers to design with energy in mind and make tradeoffs between energy issues and other issues, being aware of the consequences of their decisions.

The analysis has been performed for Temperate climate which is typical for New York-New Jersey area (40°N latitude). A black box, 40' long, 20' broad, and 10' high was considered as the experimental cell in order to establish a basis of comparison. Impacts are evaluated with respect to the experimental cell. This box may be used as a reference during schematic design. R-values of the walls and roof of the box are 19 and 30 respectively. Parameters considered may be broadly classified into building layout, building envelope, solar control measures, and building mass. Heat transmission and storage values have been calculated based on this cell. Winter performance is based on Jan 21 and summer performance on July 21. Both these days are near the extreme but not at the extreme, and are representative days in the winter and summer.

PARAMETERS CONSIDERED:

1. Building Orientation
2. Building Shape
3. Radiation Effects on N, S, E, W faces during Winter and Summer.
4. Color/Finish of Material.
5. Insulation.
6. Glazing: Amount of south glass.
7. Types of glazing.
8. Time Lag Characteristics.
9. Heat Capacity of materials.
10. Infiltration and Ventilation .
11. Cross Ventilation
12. Shading.
13. Landscape.
14. Interior Mass.

Heat gain and loss are calculated based on the "sol-air" approach for all parameters except south glazing, cross ventilation, infiltration, and interior mass. This approach recognizes both air temperature and solar radiation acting in conjunction on the building. Heat gain and loss would vary according to the combined impact of the sun and exterior air temperature.

Calculations for building orientation are based on data from Olgyay (1973). Method used for calculating heat gain and loss are described in detail by ASHRAE (1985). Data for building shape sensitivity analysis was also derived from Olgyay (1973). Calculations on the sensitivity of color and insulation are based on ASHRAE (1985). Winter heat gain through south glass is calculated using the Solar Load Ratio (SLR) method described by Balcomb, Jones, McFarland, and Wary (1984). This method correlates the monthly solar gain through south glass to the monthly heating load. Solar gain is calculated from the insolation, SLR coefficients and degree-days.

Calculations for glazing types is based on data derived from ASHRAE (1985). Data on time lag are obtained from Olgyay (1973). Data source for heat capacity calculations are from Balcomb, Jones, McFarland, and Wary (1984). Data on infiltration and ventilation were derived from ASHRAE (1985) and calculations used the method described by Stein, Reynolds, and McGuinness. Shading coefficients of shading devices and landscape elements were obtained from Olgyay (1973).

Concepts about interior mass are based on the research performed at the Los Alamos National Laboratory. Details about mass performance are yet to be researched. Although mass is a volumetric quantity, it has been expressed in sqft by the researchers. The thickness of the mass is predetermined based on performance and the remaining dimensions(= area) are ascertained later.

CHAPTER 4

SENSITIVITY ANALYSIS

4.1 Building Orientation

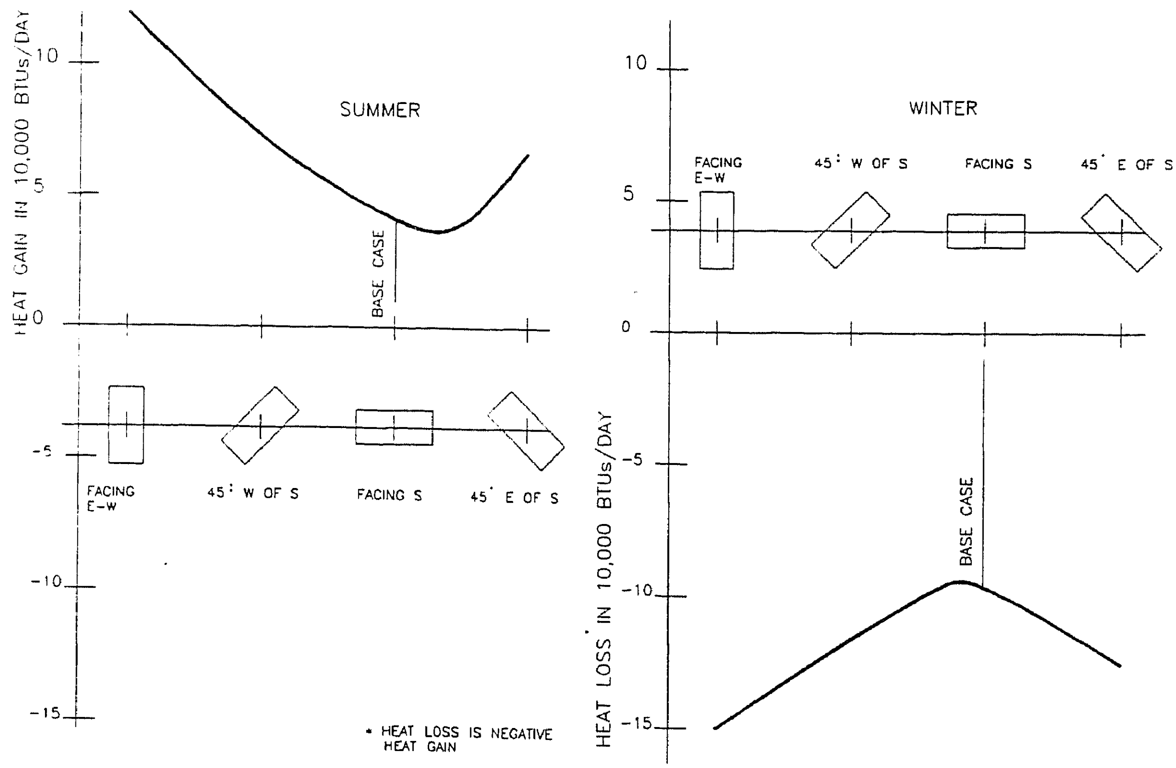


Figure 2 Sensitivity of Building Orientation (Based on Olgyay and ASHRAE)

Under ideal conditions, the building should be positioned to receive maximum radiation during the winter, while during the summer, the orientation of the building should minimize undesirable solar impacts. Windows are taken into account in section 4.6. Summer and winter performance is critical for the orientation facing E-W. Orientations facing true south receive 50,000 BTUs less in the summer than those facing E-W direction, and lose 40,000 BTUs less in the winter. Orientations 45° E or W of south are intermediate in both summer and winter performance. The optimum orientation is 17½° E of S which receives maximum BTUs in the winter and minimum in the summer.

4.2 Building Shape

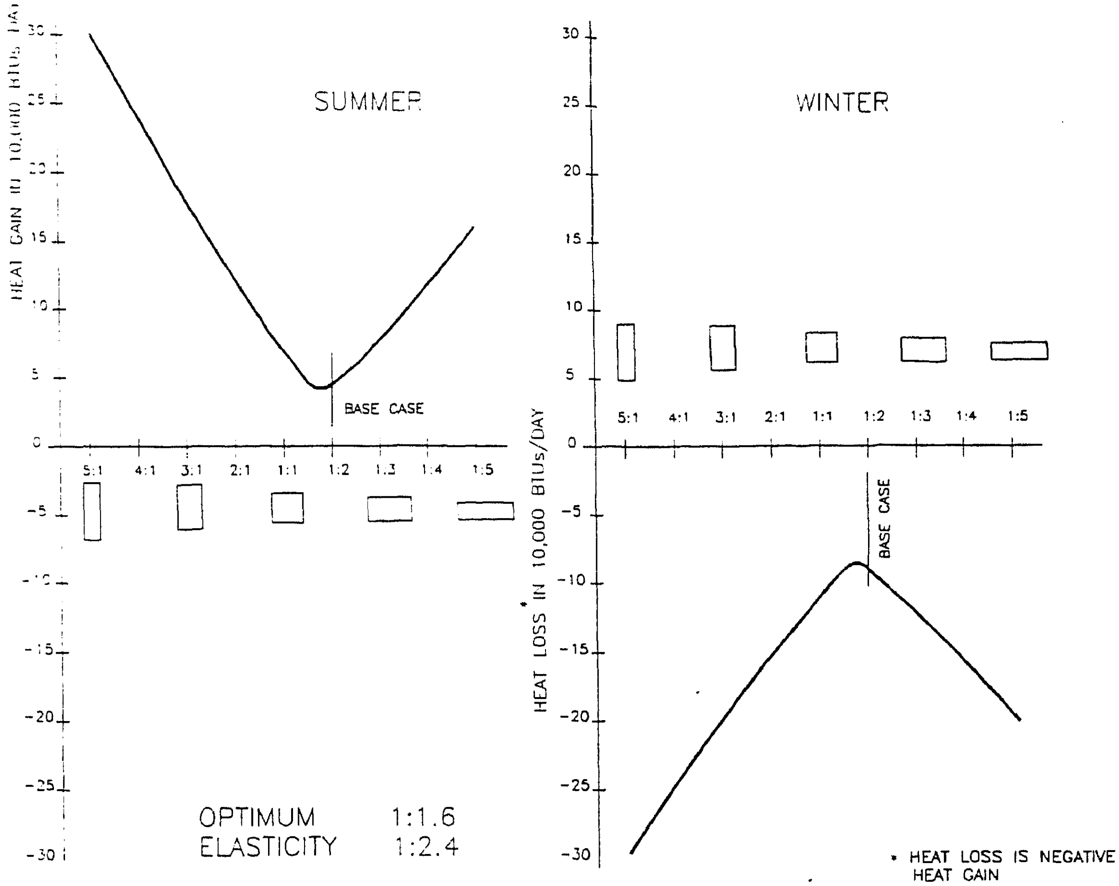


Figure 3 Sensitivity of Shape (Based on Olgyay)

Heat impacts on four sides of a building were calculated for different length breadth ratios, keeping the area of the test cell (800 sqft) constant. The different forms were elongated in an east-west or north-south direction. The shape with aspect ratio 5:1 performed the worst both in summer and winter. It gained 260,000 BTUs more than the base case (1:2) in the summer and lost 220,000 BTUs more in the winter. Shapes elongated in the E-W direction performed better than those elongated in the N-S direction, even with similar aspects. The optimum was a shape elongated along the east-west direction with an aspect ratio of 1:1.6, which lost minimum amount of outgoing BTU in winter and accepted the least amount of incoming BTU in summer. (Olgyay 1973, 88-89).

4.3 Radiation Effects on N, S, E, W Faces

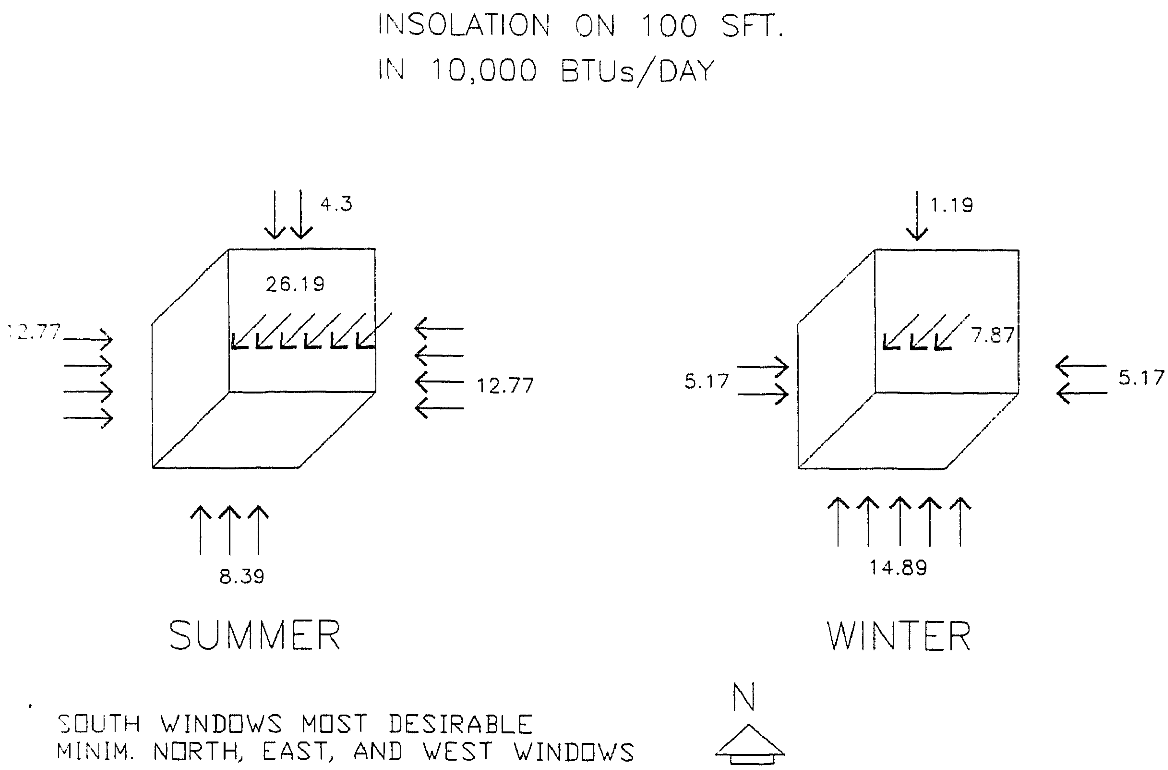


Figure 4 Insolation on Different Faces of a Building (Source: Olgyay 1973)

The various sides of a building receive markedly different insolation in summer and winter. Radiant heat gain is a function of insolation. East and west faces receive the maximum BTU in the summer, nearly 1.6 more than the south. On the west side high temperature impacts are increased by afternoon radiation effects. The south side receives moderate thermal impact in the summer, and maximum in the winter. Winter heat gain by the south is 3 times as much as the east or west. The north side receives only a small amount of radiation in the summer and loses significant heat energy in the winter. Comparing the summer and winter performance of the different sides, the south face is the only face that contributes positively to the heating/cooling needs of a building. It receives two times more radiation in the winter than in summer. East and west windows cause overheating problems in the summer and are difficult to shade.

4.4 Color/Finish of Materials

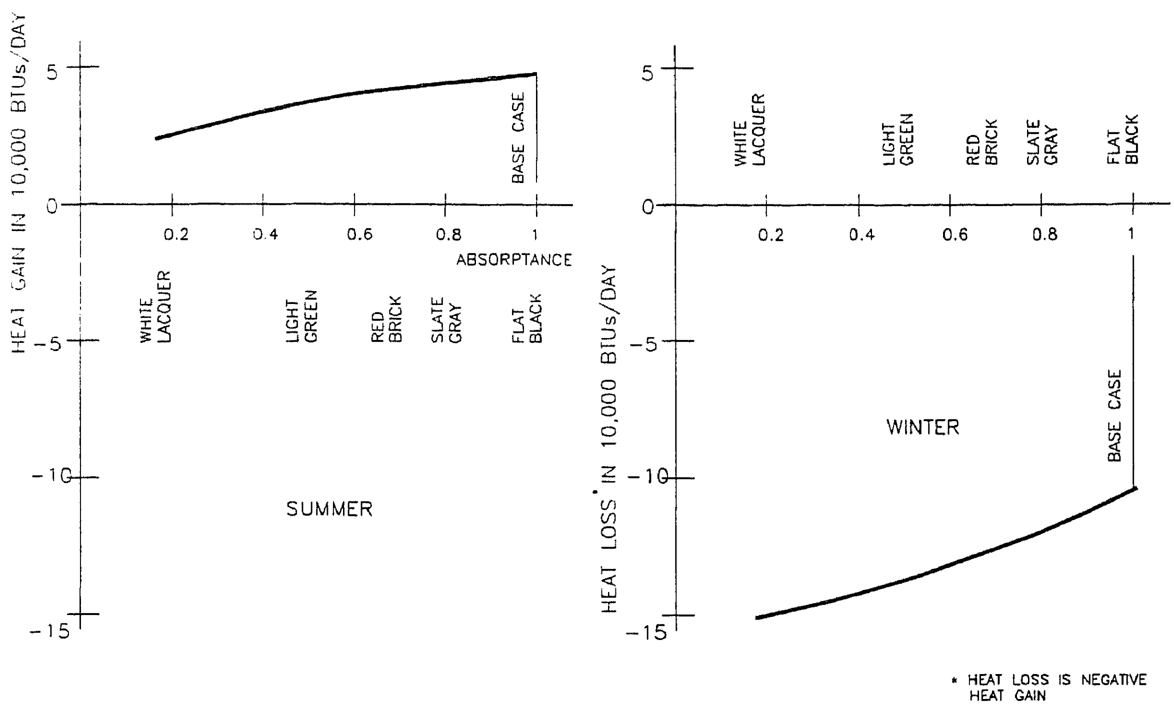


Figure 5 Sensitivity of Color/Finish (Based on ASHRAE)

Color and finish of the building envelope or mass surfaces directly influence the heat transmission and storage capacity. Light colored and glossy surfaces reflect the heat while dark colors and rough surfaces have good absorption values. Color and finish determine the "absorptance" of materials. Absorptance is defined as the fraction of incident solar radiation that is absorbed on striking a surface. Winter performance is improved with high absorptance values. The base case with the cell painted black absorbs 44,300 BTUs per day. By painting the exterior white, absorption is reduced to 26,400 BTU.

4.5 Insulation

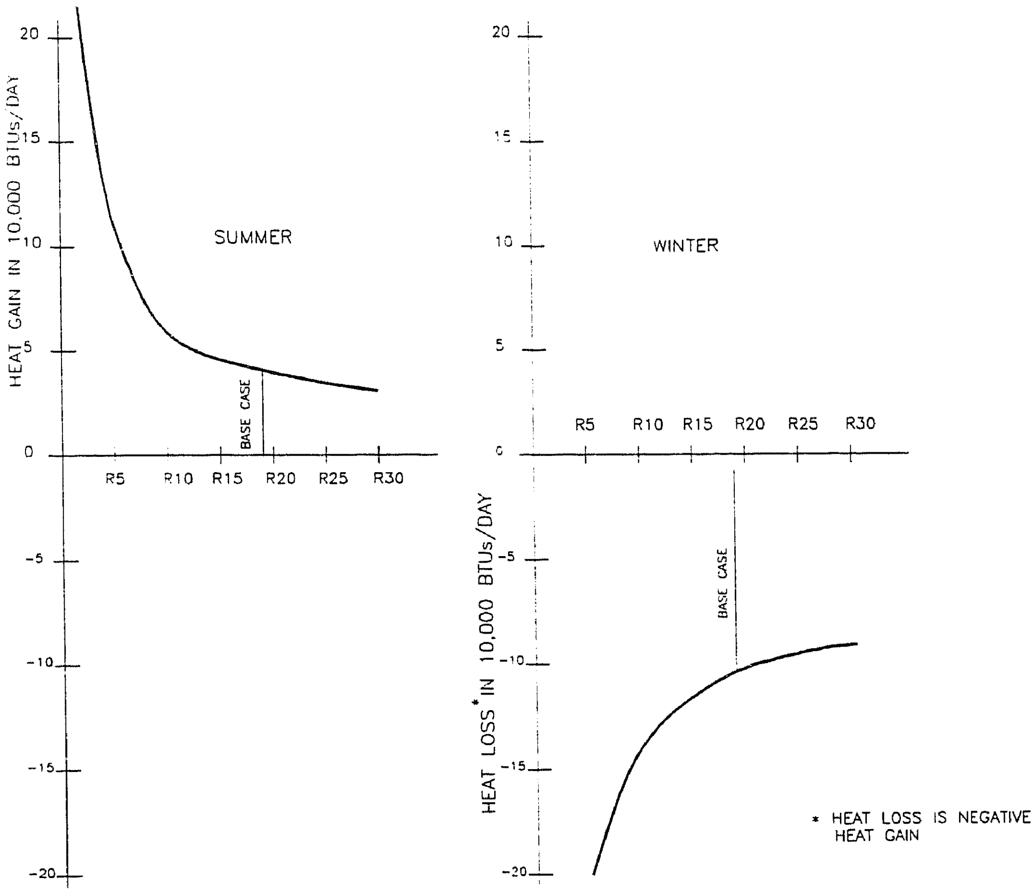


Figure 6 Sensitivity of R-values (Based on ASHRAE)

All materials have certain properties which offer resistance to heat flow. The thermal resistance of a building material is expressed by its R-value (h.°F. sqft/Btu). This measures the resistance to heat transmission of the building material and is the reciprocal of thermal conductance or U-value. The higher the R-value, the better the insulation effect. The base case with R-19 wall insulation transmits 44,300 BTU/day in the summer, and would have transmitted 116, 400 BTU with R-5 insulation. However, as indicated in the graph, the insulation value changes sharply between R-2 and R-10, gradually between R-10 and R-20, and insignificantly between R-20 and R-30. Materials with moderately high R-values are recommended for temperate climate so as to prevent the loss of interior heat of a building in the winter.

4.6 Glazing: Amount of South Glass

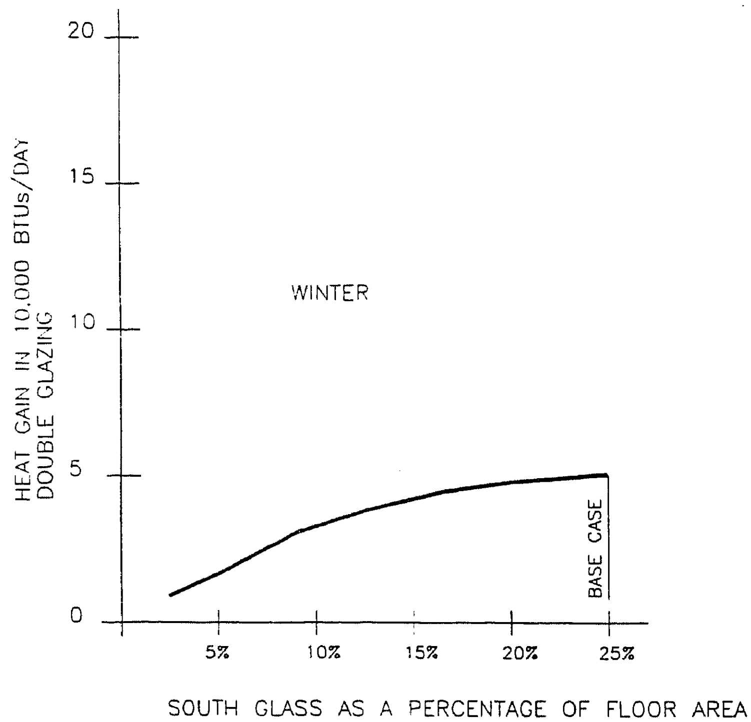


Figure 7 Sensitivity of South-facing Glazing (Based on Balcomb, Jones, McFarland, and Wary)

South-facing solar glass is a key component of any passive solar system. The amount of south glass is expressed as a percentage of the floor area of the building. A building must have enough south glass for good performance in winter, but not so much that the cooling performance in summer is compromised. There is a remarkable increase in the amount of useful solar energy transmitted by increasing the glass area from 5% to 15%. Between 15% and 20% there is a gradual increase, but between 20% and 25% the difference is negligible. Assuming south glazing of 200 sqft (25% of 800 sqft) for the test cell, the energy gained by the cell is 48,000 BTU per winter day. This gain is due to radiant heat and has been calculated based on the Solar Load Ratio method (Balcomb, Jones, McFarland, and Wary 1984).

4.7 Types of Glazing

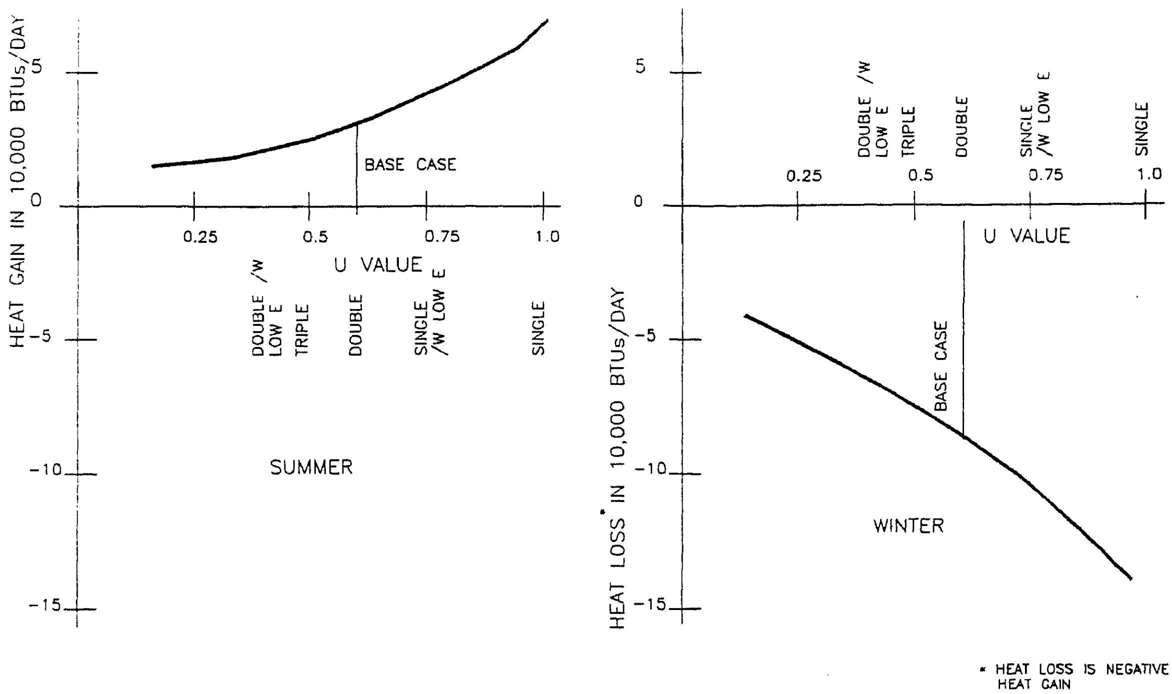
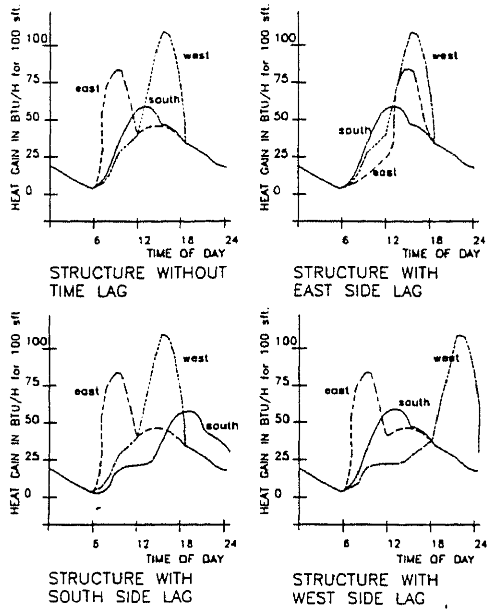


Figure 8 Sensitivity of Glazing Types (Based on ASHRAE)

The choice of glazing has a significant impact on the energy performance of a building. The heat transmitted by conduction through a glazing is dependent on its U-value. Glazings with low-emisivity (low-e) coatings have improved performance. Since air is a good insulator, double or triple glazings with air in-between resists heat transmission. Gas filled double and triple glazings are also being manufactured. The base case with 200 sqft of double glazing transmits 87,840 BTU/day in the winter and gains 38,064 BTU/day in the summer. Double with low-e glazing transmits 56,160 BTU/day in the winter and 24,336 BTU/day in the summer. Using different types of glazing for windows with different orientations should be considered. For example, use of heat-rejecting glazing on west windows, low U-value glazing for north windows, and clear double glazing on south windows.

4.8 Time Lag Characteristics



TIME LAG & R-VALUES

	Thickness (inches)	R-value	Time Lag (hours)
Stone	8	1.5	5.5
	16	2.1	10.5
Solid Concrete	4	1.2	2.5
	8	1.5	5.1
	16	2.1	10.2
Common Brick	4	1.7	2.3
	12	3.2	8.5
Face Brick	4	1.3	2.4
Wood	1	2.1	0.45
	2	3.3	1.3
Insulating Board	1	3.9	0.23
	2	7.1	0.77
	4	12.5	2.7
	6	20.0	5.0

Figure 9 Explanation of Time-lag showing R-value and Lag for Various Materials (Source: Olgyay 1973)

Time lag is the delayed heat flow phenomenon in materials. The rate of flow of thermal energy from the receiving surface to the opposite surface is dependent upon the density, specific heat, and thickness of the material. This results in a time lag between energy input from exterior environment and its interior effect. This enables the delay of night coolness to the day and day warmth to the nighttime, buffering the diurnal temperature changes and resulting in the heat balance of structures. Since the sun strikes the east, south, and west faces at different times of the day, it is possible to use different hours of lag to manage heat gain. The figure illustrates the consequences of a 6-hour lag on the E, S, and W sides of a building. With an east side lag, the heat gain reaches a peak at 3 PM and causes discomfort. With a south side lag, the afternoon becomes cooler, but the temperature rises after 6 PM. West side lag balances indoor heat by delaying heat transfer to the night when the structure has cooled.

4.9 Heat Capacity of Materials

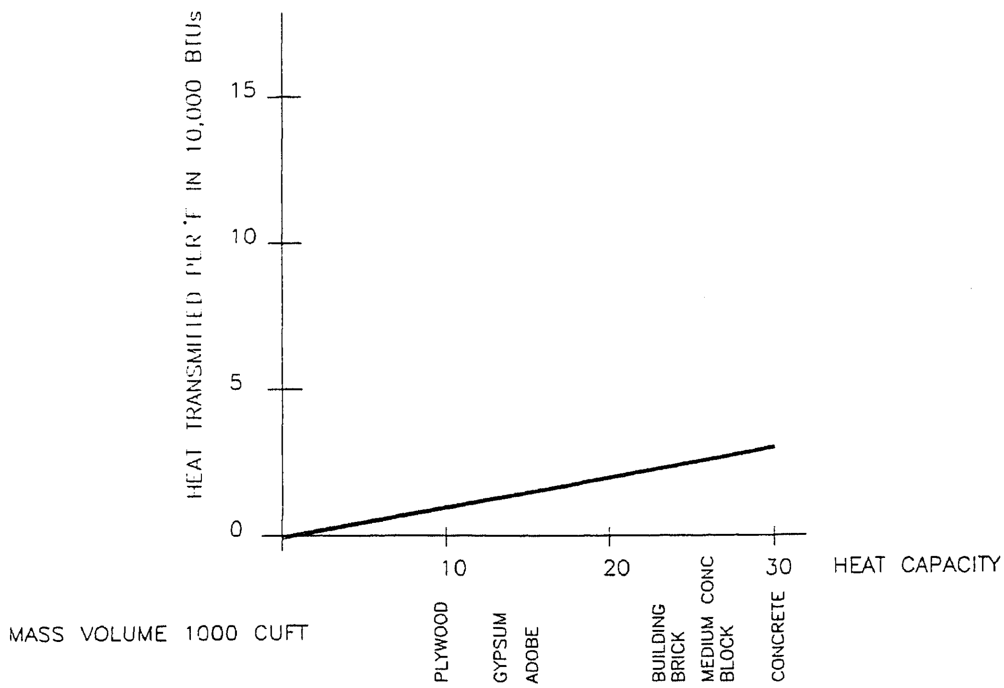


Figure 10 Sensitivity of Heat Capacity (Based on Balcomb, Jones, McFarland, and Wary)

Heat capacity is the ability of materials to store sensible heat per °F difference of temperature. In scientific terms it is the number of BTUs required to raise the temperature of 1 lb of material per °F (Btu/lb.°F). It is also expressed in volumetric terms, i.e., Btu/cu ft.°F. Concrete has the highest heat capacity, followed by building brick, adobe, gypsum, and plywood. The base case with 6" thick wall and roof has 1000 cu ft of material. With concrete as the material, for the temperature to drop by 1°F 30,300 BTU will have to be lost and 9,900 BTU for plywood. This implies that temperatures will fall much more for materials with low heat capacity, for the same number of BTUs lost.

4.10 Infiltration and Ventilation

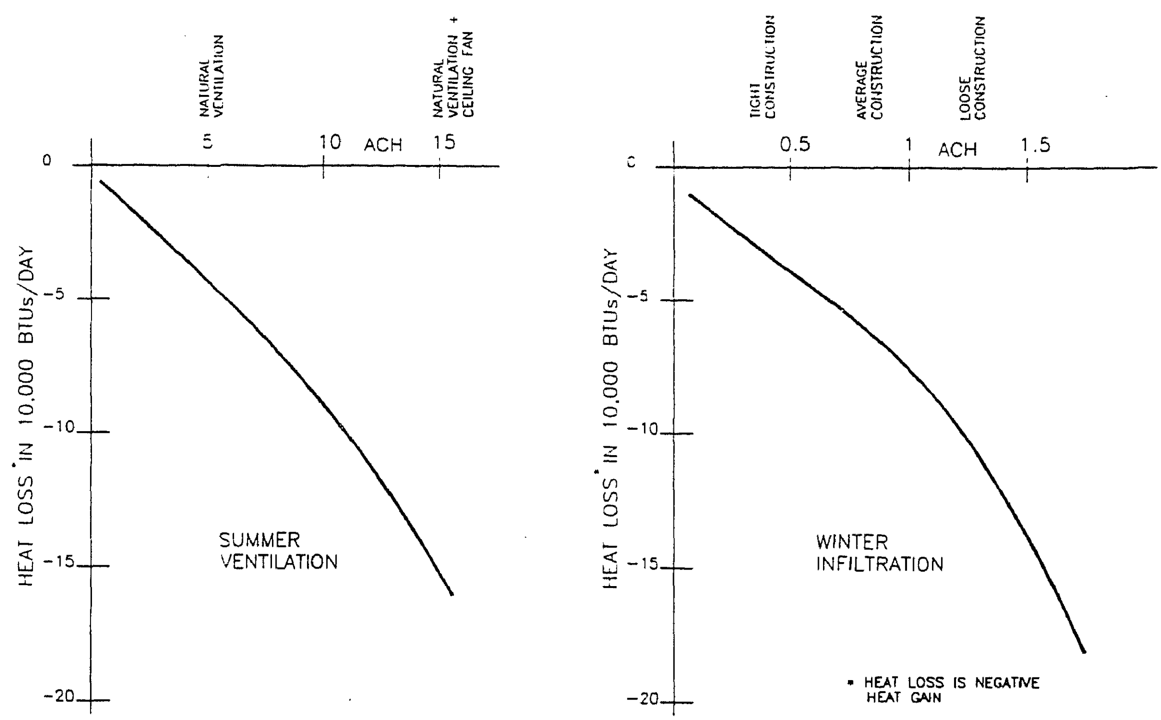


Figure 11 Sensitivity of Infiltration and Night Ventilation (Based on ASHRAE)

Infiltration is influx of outdoor air due to leakage through the building skin. Some amount of infiltration is desirable in the winter to maintain air quality and maintain odors. Heat loss due to infiltration is shown above. For tight construction (0.5 ACH), the heat loss is 45,000 BTU/day and for loose construction (1.25 ACH) the heat loss is about 98,000 BTU/day.

Ventilation is the deliberate introduction of air in the summer which helps in reducing air-conditioning loads. During the day the structure of the building absorbs heat. Ventilation is needed at night to flush out this heat, taking advantage of low nighttime temperatures. With natural ventilation (5 ACH) heat dissipated is 60,000 BTU compared to 185,000 BTU with ceiling fans (15 ACH). The building should be positioned to take maximum advantage of the prevailing winds.

4.11 Cross Ventilation

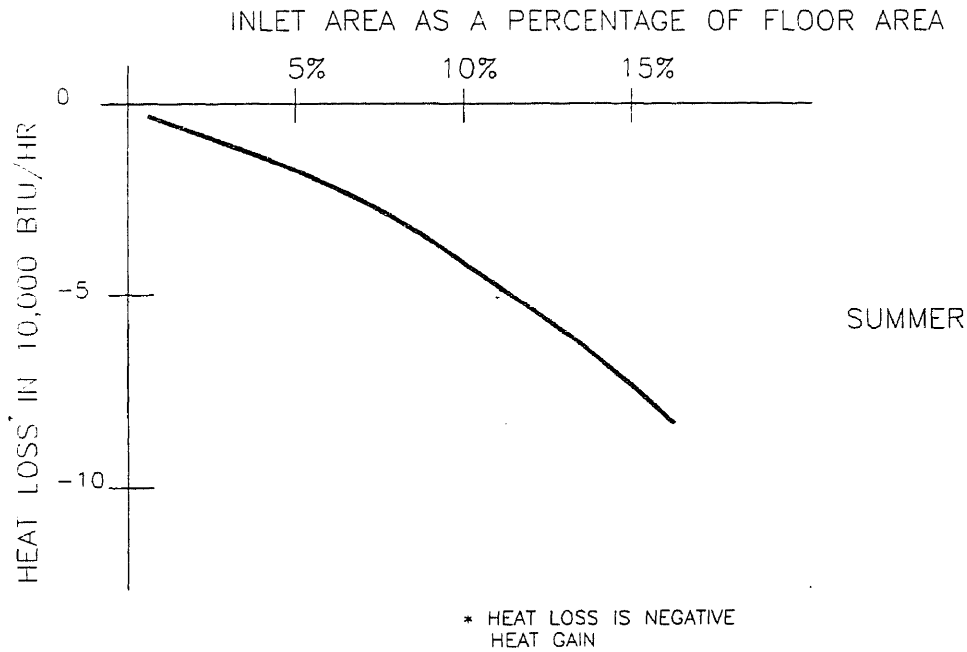


Figure 12 Sensitivity of Cross Ventilation (Based on Stein, Reynolds, and McGuinness)

Cross ventilation is a strategy that is used in the summer. This strategy is effective only at times the outside is cooler than the inside. The graph above shows the heat loss for different sizes of inlets for a wind speed of 5 mph assuming a temperature difference of 3°F. Inlets on the windward side should be slightly smaller than the outlets on the leeward side. For the base case, heat loss is 20,000 BTU/hr for an inlet size of 40 sqft (5% of floor area). Windows should be located for maximum cross ventilation in each room. Unobstructed openings or free vent area should be between 6-7.5% of the floor area.

4.12 Shading

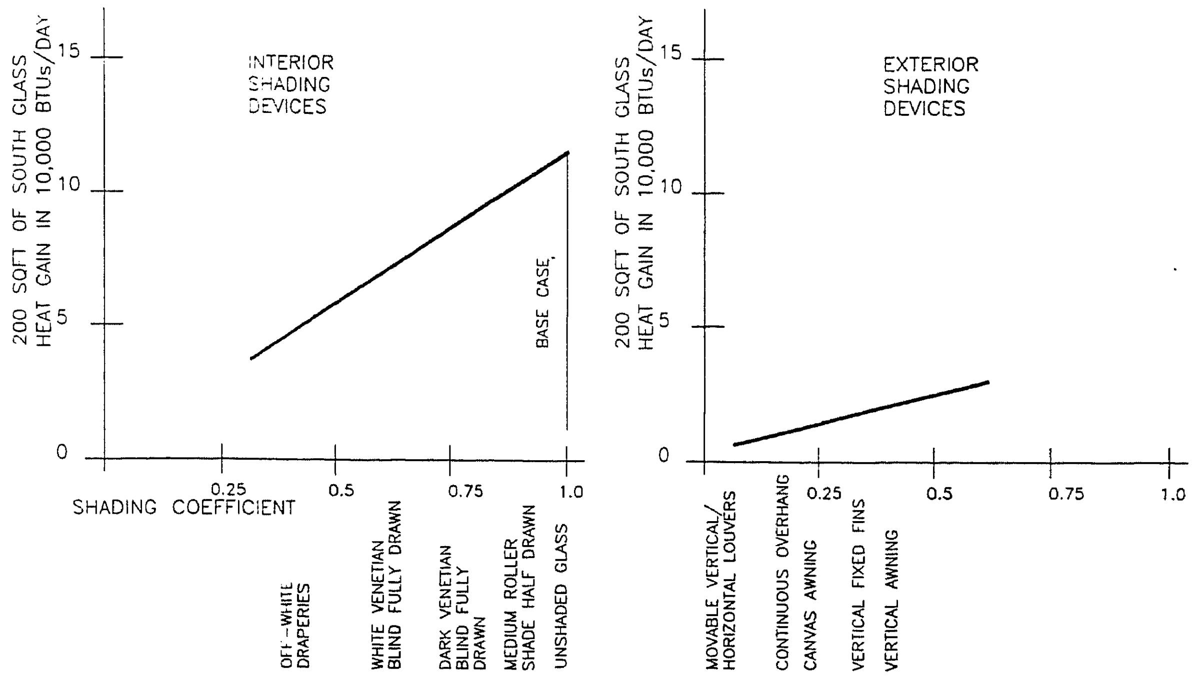


Figure 13 Sensitivity of Shading Devices (Based on Olgyay and ASHRAE)

Shading is a means of controlling radiation that may enter a building. Solar radiation through glazing areas are welcome during the winter but not desired during the summer. In the temperate region shading reduces the heat impact on the glazing to *one-eighth* in the east and west faces and to *one-fourth* in the south, resulting in appreciable economies. Both latitude and orientation contribute to the formulation of an effective shading device. Heat radiation is most effectively halted before it reaches the building envelope. Hence exterior shading devices are more effective. Glazings with reflective aluminum screens or white draperies transmit 48,080 BTU/day compared to 120,200 BTU/day transmitted through unshaded glass. Continuous horizontal overhangs reduce transmission to 13,000 BTU/day, and are adequate in the south. For east and west orientations a combination of vertical and horizontal overhangs are necessary as the sun subtends low altitude angles.

4.13 Landscape

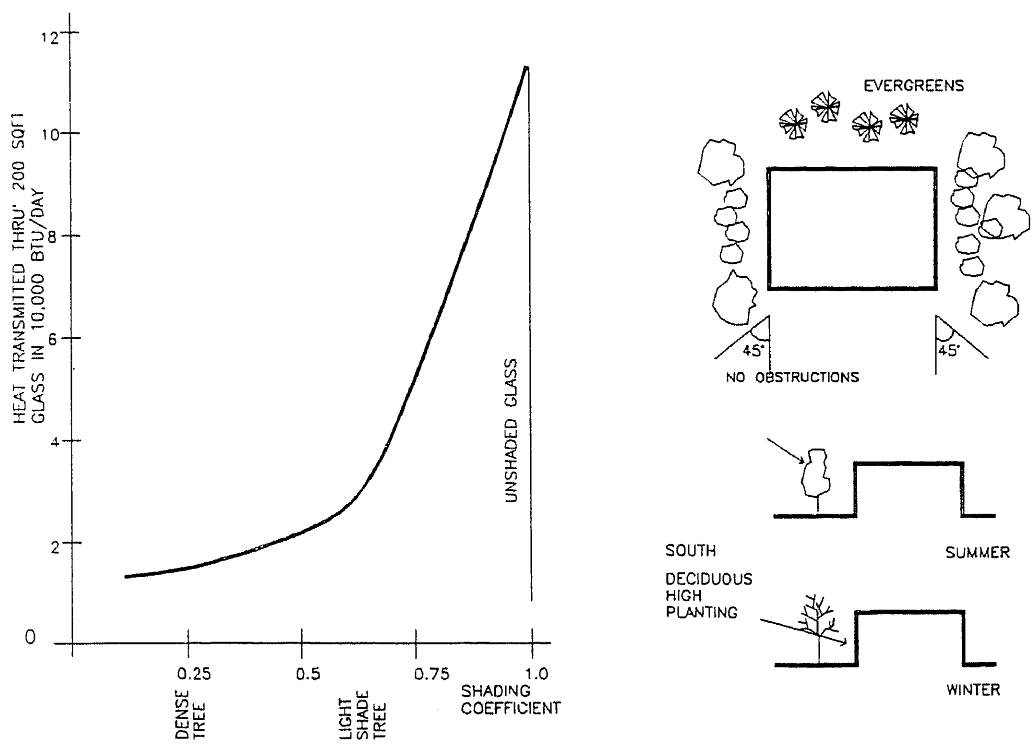


Figure 14 Landscape Elements (Based on Olgyay)

Trees contribute to the physical environment and enhance the thermal performance of the building and its site. They are useful for providing shade. For a single tree, the shading coefficient is 0.25 for a dense tree and 0.6 for a light shade tree. Assuming that the shade is cast by a dense tree on 200 sqft. of glass, heat transmitted by radiation is only 15,000 BTU/day compared to 120,000 BTU/day for unshaded glass. The shape and character of a tree both in winter and summer has to be considered and also the shape of its shadow. Evergreen windbreaks can reduce the heat loss from buildings in winter on the north side. Deciduous trees and shrubs can are useful for shading east and west sides. Towards the south deciduous trees may be placed *very close* (<= 5') to the building so that they do not interfere with the winter sunshine. In summer, vegetation absorbs radiation and cools the air by evaporation processes (Passive Solar Industries Council). Quantification of the effects of landscape need further research.

4.14 Interior Mass

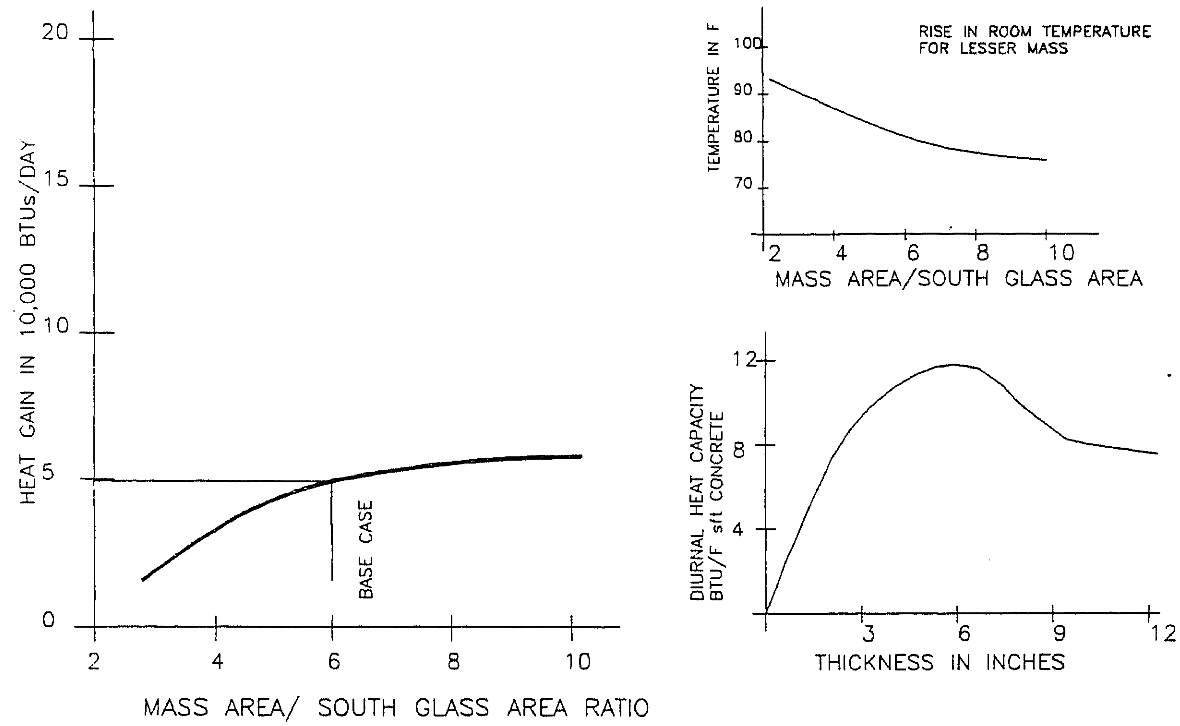


Figure 15 Sensitivity of Interior Mass (Based on Balcomb, Jones, McFarland, and Wary)

Thermal storage mass is an essential component of all passive solar houses. Some amount of mass is present in all houses, in the framing, gypsum wall, and ceiling board. Construction materials like brick, cast concrete, concrete masonry, slabs or tile may be used as mass. Water and phase change materials have excellent heat storage capacities. Amount of mass required is correlated to the amount of south glass used. In the base case, mass area is assumed as 6 times south glass area as temperature swing is reasonable for this number. Increasing solar glazing without adding mass causes large temperature swings and uncomfortable interiors. For lesser mass area to glazing area ratios (2:1) indoor temperatures may rise to 90°F. Detailed information on the thermal behavior of interior mass requires higher levels of calculation and further research.

Mass Distribution: Thermal mass should be distributed over as large an area as practical. Mass located in direct sun is more effective than mass out of the sun. Optimum performance is achieved by locating thermal storage mass on vertical surfaces rather than horizontal surfaces. Best results are obtained when mass is located on the north, east, and west walls of a room with south windows.

Mass Thickness: Per pound, mass in thin sections is more effective than mass in thick sections. For concrete masonry, added mass beyond 4" in thickness is less effective than mass closer to the surface. Beyond a certain thickness, the effectiveness actually decreases.

Thickness	1"	2"	3"	4"	5"	6"	7"	8"
Heat Capacity	2	5	8	9.5	10.5	11	10.75	10.4

CHAPTER 5

DECISION MAKING: USING THE CHARTS

Energy responsive design involves all the above parameters, some of which are relatively more important. These parameters cannot produce the best result in isolation, since they are interrelated. The situation dictates their relative importance. The following section illustrates the use of sensitivity analysis for design decisions using important energy-related parameters.

As an illustration, the 20' x 40' x 10' box is used to design for winter conditions. Referring to 4.1, orienting the box 45° W of S results in a loss of 20,000 BTUs/day compared to the base case. This may be compensated for by using suitable color(4.4) and insulation(4.5). This is discussed in the following paragraphs. For consideration of building shape, section 4.2 is referred to. By choosing a shape with aspect 1:3, winter heat loss is 250,000 BTUs more than the base case with aspect 1:2. This loss could also be compensated with color and insulation. But the aspect of the shape is assumed as 1:2 for this illustration.

Penalty for orientation(20,000 BTUs/day) may be dealt through color(4.4) and insulation(4.5). The base case is black which loses minimum heat in the winter. Since a lighter color causes a greater heat loss in the winter, the default color with an absorptance of 1 might be retained. Increasing the R-value of the wall from R-19 to R-30 compensates for the 20,000 BTU heat loss.

To determine the size of openings in the exterior wall, sections 4.3, 4.6, and 4.7 are studied. Since south windows gain 3 times more than east and west in the winter, south glass area of 25% of the floor area is desired. Assuming that the building program imposes restrictions and 15% is allowed, winter heat gain is reduced by 10,000 BTUs/day as compared to 25%. Triple glazing(4.7) may be used instead of double glazing which would reduce loss and compensate for lower gain.

Section 4.8 gives an idea of the time lag characteristics of materials. A west side lag is desirable if not in the sleeping area and the designer may choose a suitable material with appropriate lag from the accompanying chart. For example, if an eight hour lag and R-value of 28 is desired for the west wall, 4" solid concrete may be combined with 8" insulating board. Section 4.9 displays the heat capacities of various materials. For the same volume, materials with high heat capacities causes indoor temperature to drop less than low heat capacity materials in winter. Winter heat loss for the base case was 108,000 BTU as estimated above. With concrete, the interior temperature drops by 3.6 °F, and with plywood the drop is 10.9 °F. Interior mass is estimated by referring to 4.14. By decreasing mass area to 5 times south glass area, heat stored is reduced by 8000 BTUs from the base case. Also, temperature swings to 85 °F is experienced.

Similar analogies are used to design for summer conditions. Solar control measures, like night ventilation (4.10), cross ventilation (4.11), shading (4.12), and landscape (4.12) are incorporated to reduce cooling loads. Exterior devices work better in keeping out the sun in the summer. A continuous overhang on 200 sqft. of south glass reduces heat gain due to radiation by nearly 100,000 BTUs/day. Landscape elements can also be used to channel breezes bringing about much desired night ventilation in the summer.

This analysis may be used for structures with different length, breadth, and height dimensions by simple interpolation. Since the dimensions of the base case are known, these may be directly compared to obtain rough estimates of heat gain and loss.

CHAPTER 6

CONCLUSION

There is ample historical precedent of energy responsive designs particularly among early peoples who had very few alternatives. Today, the key to successful implementation of energy conserving techniques is awarenes and information. The individual designer, builder, and tenant must be made aware of the impacts and limitations of the various energy related parameters. A clear perception of the sensitivity of different variables and their relative significance is essential for energy responsive design.

The sensitivity analysis has been performed with 14 parameters. These parameters are considered to be the most importatnt factors pertaining to the energy performance of a building. But there is scope for inclusion of more such parameters which has a direct or indirect influence on energy efficiency. Air temperature has been considered for calculating heat transmission. But comfort conditions are perhaps more dependant on radiant temperature. Again, comfort condition and temperature perception vary depending on levels of human activity and postures like standing, sitting, and sleeping.

Although this analysis has been performed for temperate climate, there may be regional variations. Degree days will differ depending on geographical location and so will the days and pattern of cloud cover. Micro-climatic variations may also occur due to man-made structures. This analysis gives a context for working but background study has to be done in order to use it.

The analysis shows the diurnal performance in summer and winter. Some of the parameters like building mass and ventilation require the sensitivity for different hours of the day in order to explain day and night performance. This is beyond the scope of this thesis and are subjects for future research.

APPENDIX 1

PASSIVE HEATING AND COOLING

Passive Heating

Passive heating is a complete system of collection, storage and use of solar energy : using more south glass, adding significant thermal mass, and taking steps to control and distribute heat energy throughout the house. It also includes energy conservation by maintaining optimal insulation levels, control of air infiltration and glazing type.

The essential elements in a passive solar house are south-facing glass and thermal mass. In the simplest terms, a passive solar system collects solar energy through south facing glass and stores solar energy in thermal mass — materials with a high capacity of storing heat (e.g., brick, concrete masonry, concrete slab, tile, water). The more south-facing glass is used in the house, the more thermal mass must be provided, or the house will overheat and the solar system will not perform as expected. Thus, the balance between glass and mass is crucial in the performance of the passive soar house.

Some of the other considerations in the passive heating system are conservation performance, orientation, mechanical systems (ducts and equipment), site planning for solar access, and interior space planning. Upgrading levels of insulation, reducing air infiltration, window sizing and location, selection of glazing, and shading of windows are the features of a good design. And above all, taking an integrated approach to the house as a total system.

Passive Cooling

Passive solar cooling sounds like a contradiction in terms. Passive cooling strategies work by shielding a building from the effects of the sun. Only a few strategies actually use the sun to "power" cooling systems. Passive cooling systems include shading, ventilation, and evaporative cooling. The same passive solar features that were used to store heat can also be used to reject it as well.

Conservation features identical to passive heating, like insulation, storm windows, and caulking are also effective for passive cooling. Shading devices, both interior and exterior are effective in keeping out the heat. Particular attention is needed for south-facing windows. Natural ventilation, with the windows in the right places as well as induced ventilation helps to in controlling the heat. Vegetation has an important role in the cooling process — it provides shade, induces ventilation, and cools by adding moisture to the air. Other passive cooling tools include evaporative cooling, desiccant cooling and cooling by earth sheltering.

APPENDIX 2

GUIDELINES FOR ENERGY RESPONSIVE DESIGN

Table 1 The Exterior Environment

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
1. SITE SELECTION				
• **Flat Site**	Open to south Expose to prevail-ing breezes.	Open to south Expose to summer and prevailing breezes.	Open to south /southeast Avoid winter wind. Expose to summer breezes.	Open to southeast Shelter from north & west.
• **Sloped Site**	Southeast-east slopes. Lower position to utilize cool air flow.	Southern and northern slopes. High elevations on windward side.	Southeast slopes. Low position for wind shelter.	South-southeast slopes. Middle or lower middle to avoid wind affects and cool air pools.
2. BUILDING FORM	Compact shapes, elongated on E-W axis.	Slender elongation on E-W axis.	Elongation in E-W axis preferable, wings along N-S axis also permitted.	Compact structures with minim. exterior surface, elongated on E-W axis.
• **Volume Effect**	Volume effect important	Volume effect undesirable.	Volume effect is not too important	Volume effect highly desirable.
• **Optimum Length Breadth Ratio w.r.t. energy considera-tion**	1:1.3†	1:1.7 to 1:3.0†	1:1.6†	1:1.1 to 1:1.3†
3. ORIENTATION	25°E of south secures balanced orientation. Exposures between south and 35°E of S also good.†	5°E of south secures balanced orientation. Deviation upto 10° acceptable.†	17.5°E of south secures balanced heat distribution†	Optimum 12°E of south.†

Table 1 The Exterior Environment(Continued)

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
4. ADJACENT BUILDINGS	Avoid blocking prevailing winds and reflecting solar insolation on building	Channel summer breezes. Avoid reflecting solar insolation on building	Block winter winds and avoid blocking sun.	Use as a windbreak from prevailing winds. Avoid blocking sun. Reflect solar insolation on building.
5. GROUPING OF BUILDINGS	Dense layout desirable. Houses should shade other houses and outdoor living areas.	Loose and scattered layout of houses to utilize air movements. Shade is important.	Open and free layout of buildings, merging with nature.	Buildings to be grouped close together but spaced to utilize the sun. Dense layout preferred.
6. LANDSCAPE	Concentration of plant and grass covered areas in the manner of an "oasis."	Water drainage away from house. Grading for run-off of rainstorms.	Indoor outdoor relationships, outdoor living areas functional for several months.	
7. VEGETATION • **Solar Access**	Solar access to be blocked by deciduous species to the south of building. Vegetation absorbs radiation and cools due to evaporative property.	Broad-leafed deciduous species. Trees in rows to the north of building.	South yards to be kept free from trees.	Short, broad deciduous trees that permit maxm. winter sun penetration to the south of building.
• **Wind**	Breezes to flow beneath tree canopies and over ground cover which cools the environment.	Trees with clean trunk and light branching for breeze penetration Low vegetation should not block air movement.	Evergreens may be used to buffer buildings from NW winter winds. Should not block S-SW summer breezes.	Evergreens to the NE-SW of building as wind-breaks. Low shrubs and hedges may be used to divert winds.
• **Shade**	Outdoor areas to be shaded in the hot season.	Lightly twigged trees to the south of building.	Belt of trees to the E and W sides. Solar access not to be blocked.	Deciduous shade trees near house.

Table 1 The Exterior Environment(Continued)

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
8. WATER BODIES	Desired near building because it cools and humidifies the air.	Water bodies cause some cooling, but may cause discomfort due to excessive humidity.	Preferred location along the path of summer breezes. Avoid water bodies in the path of winter winds.	Preferred to south of building for additional reflection of solar insolation. Avoid water bodies in the path of prevailing winds.
9. ROCK FORMATION				
• **Solar Radiation**	Used for shading. Its thermal properties may be used for day time cooling and as night time heat source. Avoid increased heat build-up due to reflection.	Used for summer shading. Avoid increased heat build-up due to reflection.	Preferred for winter solar reflection and as a thermal storage of heat. Used to shade in summer.	Used for solar reflection. Preferred near building to act as a thermal storage of heat. Avoid blocking the path of the sun.
• **Wind**	Used to channel prevailing breezes to building.	Used to channel prevailing breezes to building. Avoid blocking prevailing winds.	Used as a wind break in winter and to channel winds to building in the summer.	Used as a wind break.
10. PAVED AREAS	Avoid excess build -up of solar insolation and reflection on building. Should not be placed in the path of summer winds.	Avoid additional heat gain due to reflection and heat build-up on paved surfaces. Should not be placed in the path of summer winds	Used to reflect additional solar insolation to the building in winter. Should be shaded in summer to avoid heat build-up.	Solar insolation reflected on building is desired to form warm air pocket. Placed in the direction of prevailing winds to carry any heat build-up to building.
11. BERMS	Used to insulate building from hot temperatures in the summer.	Should not block the path of winds that is essential for cross ventilation. Used to direct prevailing winds to building.	Used to insulate buildings from the cold in winter and to channel breezes to building in summer.	Used to insulate buildings from the cold and as a wind break.

† Source: Olgyay 1973.

Table 2 The Building Interior

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
1. HOUSE TYPES	Compact houses with inner courts and high massive buildings are preferred. Group arrangements which create a volume is desired.	Individual, detached, and somewhat elevated houses are desired. Freely elongated, high buildings are preferred, with a loose density.	Flexible arrangements possible. Close relationship between house and nature desirable. Unilateral buildings can be developed with free formations.	Arrangements under one roof are preferable for compactness. Row houses or adjoining buildings with common walls have lesser heat loss.
2. PLAN	Inward looking layout. Heat producing areas should be seperated from other areas. Non-inhabited spaces should be placed on the west side.	Free plans and shading of structure required. Clear air path through interior is important. Heat and moisture producing areas should ve ventilated and seperated.	Spatial connection between indoor and outdoor areas. Buildings should open to S-SE and be closed on westerly sides. Bedrooms to be located on easterly sides.	Compact structure desired. Heat producing areas may be combined with the rest of the spaces.

Table 3 The Building Elements

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
1. EXTERIOR WALL				
• **Color**	White color on sun exposed surfaces to reflect the sun. Deep-set surfaces can be dark colored for winter radiation absorption.	Reflective light colors in the pastel range best to avoid glare.	Medium colors are advantageous. Dark colors only in recessed places protected from summer sun.	Sun exposed surfaces in medium colors. Recessed surfaces of dark absorbent colors.
• **Heat Capacity**	high	low	moderate	high

Table 3 The Building Elements(Continued)

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
• **Thermal Mass**	Mass on south, north, and west outer walls. Time lag of 10 hours for south and west walls.	Mass not required as it causes night re-radiation and morning condensation.	Mass on west wall with 6 hour time lag balances heat distribution.	Mass in the interior to balance heat variations. Time lag of 6 hours for south and west walls.
• **Properties:**				
Absorption	high	nil	high	high
Reflection	high	high	low	low
Reradiation	low	nil	moderate	high
• **Insulation**	Recommended R-Value: 10-15 East and west walls need more insulation.	Recommended R-Value: 5-10 East and west walls need more insulation.	Recommended R-Value: 20-25 South wall can have less insulation	Recommended R-Value: 25-30 South wall can have less insulation.
• **Vapor Barrier**	Vapor barrier on exterior of outer walls.	Vapor barrier placed on outer surface of exterior construction.	Vapor barrier on warm side prevents condensation.	Vapor seal on warm(interior) side of outer walls is important.
2. ROOF				
• **Slope**	Flat	Flat	Sloping roof to facilitate snow removal.	Sloping roof desirable for snow removal by wind action.
• **Drainage**		Must be water tight and properly drained in case of heavy downpours.	Gutters should be able to carry 1" of rain off total roof area in 15 min. Snow and rain pockets must be avoided.	Simple roof formation to prevent moisture penetration and ice-filled gutters.
• **Thermal Characteristics**	High solar reflectivity required. Water spray or pool on roof is effective.	Should reflect solar radiation and be insulated.	Some amount of absorption desired, but roof surfaces should have light colors.	High solar absorption desired. May be enhanced with darkened color.
• **Overhangs**	Wide overhangs for reduction of solar glare and capture breezes.	Wide overhang for rain protection, reduction of solar glare, and to capture the wind.	Eaves should be ventilated in the summer and closed in winter.	

Table 3 The Building Elements(Continued)

	HOT-ARID	HOT-HUMID	TEMPERATE	COLD
3. OPENINGS/ WINDOWS				
• **Location**	Openings should be located on the south, north, and to a lesser degree, on east sides.	Openings desired on all sides, less on the west wall. Windows should be exposed to prevailing winds.	South facing glass is advantageous. Openings on westerly side should be reduced.	Windows on south and east desired. On all other sides, windows should be small.
• **# Glazings**	Double glazing preferred.	Single glazing sufficient.	Double glazing preferred.	Triple glazing preferred, double glazing essential.
• **Protection**	Windows should be shielded from direct radiation, and set high to protect from ground radiation.	Elements such as screening, louvres, jalousies, and grills are useful to admit air flow and protect from sun.	Protection needed for south and west openings from summer radiation.	Windows should be shade protected during overheated times. Thermal shutters may be used during winter to reduce heat loss.
• **Ventilation**	Openings should be small and tight-closing as protection against high diurnal heat.	Ventilation needed 85% of the year. E-W cross ventilation is essential.	Location of openings should allow cross ventilation in the summer.	Controlled ventilation is a primary requirement. Use of sealed windows or fixed glass.
4. SHADING DEVICES				
• **Direction**		Windows should be shaded on all sides, but more on east and west because of powerful radiation	South window to be shaded from summer sun.	Summer shading towards south desirable, but should not block winter sun.
• **Type**	Eggcrate devices with high shading ratio, and vertical fins separated from the wall are suitable.	Use of solar controls such as louvres, movable fins, and overhangs.	Horizontal overhang on south, and eggcrate type sunshade on east and west walls.	Horizontal shading device. External operating devices not practical due to icing problems.
• **Connection**	Devices should be separate from structure, and exposed to wind convection.	Devices should be separate from structure.		

BIBLIOGRAPHY

Anderson, Bruce. 1990. *Solar Building Architecture*. Cambridge, Massachusetts : The MIT Press.

ASHRAE. 1985. *ASHRAE Handbook 1985 Fundamentals*. Atlanta: ASHRAE.

Balcomb, Douglas J., Robert W. Jones, Robert D. McFarland, and William O.Wary. 1984. *Passive Solar Heating Analysis:A Design Manual*. Atlanta: ASHRAE .

Balcomb, Douglas J., editor. 1992. *Passive Solar Buildings*. Cambridge, Massachusetts : The MIT Press.

Braden, Spruille. 1977. *Graphic Standards of Solar Energy*. Boston: CBI Publishing Company.

Brown, G. Z. 1985. *Sun, Wind, and Light*. New York : John Wiley & Sons.

Carter, Cyril. 1990. "Computational Methods for Passive Solar Simulation." *Solar Energy*. 45: 379-384.

Cook, Jeffrey, editor. 1992. *Passive Cooling*. Cambridge, Massachusetts : The MIT Press.

Egan, M. David. 1975. *Concepts in Thermal Comfort*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Erley, Duncan and Martin Jaffe. 1980. *Site Planning for Solar Access*. Chicago, IL : American Planning Association.

Hayes, John and Rachel Snyder, editors. 1980. *Proceedings of the 5th National Passive Solar Conference*. Newark, Delaware: American Section of the International Solar Energy Society, Univ. of Delaware.

BIBLIOGRAPHY
(Continued)

Hayes, John and C. Byron Winn, editors. 1980. *Proceedings of the 5th National Passive Solar Conference.* New York: American Solar Energy Society.

Kreider, Jan F. and Frank Kreith. 1982. *Solar Heating and Cooling, Active and Passive Design.* USA: Hemisphere Publishing Corporation.

Franklin Research Center, Philadelphia. 1979. *The First Passive Solar Home Awards.*Washington D.C.: US Department of Housing and Urban Development, Office of Policy Development and Research.

Germer, Jerry. 1984. "Passive Cooling; State of the Art." *Solar Age.* 9: 32-35.

Givoni, B. 1991. "Characteristics, Design Implications, and Applicability of Passive Solar Heating Systems for Buildings." *Solar Energy.* 47: 425-435.

Holtz, Michael, Donald Frey, Robert Bishop. 1985. "The Future of Passive Solar Design." *Solar Age.* 10: 49-52.

Los Alamos Scientific Laboratory. 1984. *Passive Solar Design Handbook.* New York: Van Nostrand Reinhold Company.

Mazria, Edward. 1979. *The Passive Solar Energy Book.* Emmaus, Pa: Rodale Press.

McGarity, Arthur E. 1976. *Solar Heating and Cooling : An Economic Assesment.* Washington D.C.: National Science Foundation, Division of Policy Research and Analysis.

Novell, B. J. 1983. "Passive Cooling Strategies." *ASHRAE Journal.* 25: 23-28.

O'Callaghan, P. W. 1978. *Building for Energy Conservation.* Oxford, England : Pergamon Press.

BIBLIOGRAPHY
(Continued)

Olgyay, V. 1963. *Design with Climate*. Princeton, N.J. : Princeton University Press.

Passive Solar Industries Council. 1989 *Passive Solar Design Strategies : Guidelines for Home Builders*. Washington D.C. : PSIC.

Paul, J. K., editor. 1979. *Passive Solar Energy Design & Materials*. N.J., USA: Noyes Data Corp.

Robbins, Roland. 1986. "Sun-tracking the Passive Way." *Solar Age*. 11: 14-16.

Schepp, Brad and Stephen M. Hastie. 1985. *The Complete Passive Solar Home Book*. Blue Ridge Summit, Pa : Tab Books Inc.

Schoenau, Greg and Robert A. Kehrig. 1989. "A Correlation Method for Predicting Monthly and Annual Cooling Loads in Direct Gain Passive Solar Heated Buildings." *Energy Conversion and Management*. 29: 175-187.

Stein, Reynolds, and McGuinness. 1986. *Mechanical and Electrical Equipment for Buildings*. New York : John Wiley & Sons.

Thornton, Ron. 1984. "How to Move Heat in Passive Homes." *Solar Age*.9: 26-29.