A THERMAL COMFORT AND ECONOMIC COMPARISON OF TWO PASSIVE SOLAR HEATING SYSTEMS: DIRECT GAIN AND A TROMBE WALL

By

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PREFACE

This study is concerned with the thermal comfort and economic comparison of two comparable passive solar heating systems, direct gain and a Trombe wall. The two systems were modeled in a case study residence so that each system required approximately the same amount of auxiliary heat input. The thermal comfort analysis is based on a set of linear equations determined by a combination of various physiological and environmental factors. A first cost economic analysis of the two systems provides for an overall performance assessment of the direct gain and Trombe wall systems.

The author wishes to express his appreciation to his major adviser, Dr. Lester L. Boyer, Professor of Architecture and Architectural Engineering, for his assistance throughout the study. Appreciation is also expressed to Walter T. Grondzik, Assistant Professor of Architecture, for his guidance in developing and organizing the study. A special thanks is given to W. George Chamberlain, Professor of Architecture, for his participation as a committee member.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Definition of Passive Design

Passive solar designs have recently come into the spotlight as a new architectural expression, but the foundations of passive design were developed by the early Greeks. They recognized the potential of allowing sunlight to enter interior spaces and warm surroundings.[1] As Socrates wrote in the 4th century B. C.:

> Now in houses with a south aspect, the sun's rays penetrate into the porticoes in winter, but in summer, the path of the sun is right over our heads and above the roof, so that there is shade. If then, this is the best arrangement, we should build the south loftier to get winter sun, and the north side lower to keep out the cold winds. To put it shortly, the house in which the owner can find a pleasant retreat at all seasons and can store his belongings safely is presumably at once the pleasantest and the most beautiful.[2]

Passive solar applications were utilized in other parts of the world at different periods of time as well. The twelfth century Anasazi Indians of the southwestern United States faced their dwellings south to capture the maximum radiation from the low angle winter sun.[3] They constructed their dwellings of adobe, which absorbs the sun's heat during the day and releases it by conduction through the adobe to the interior living quarters as the evening air temperatures decline. These massive dwellings delayed the heat from entering the space until it was most needed. To prevent overheating in the summer, the Indians built their buildings into cliffs to utilize the natural overhang to block out the high angle summer sun as shown in Figure 1.

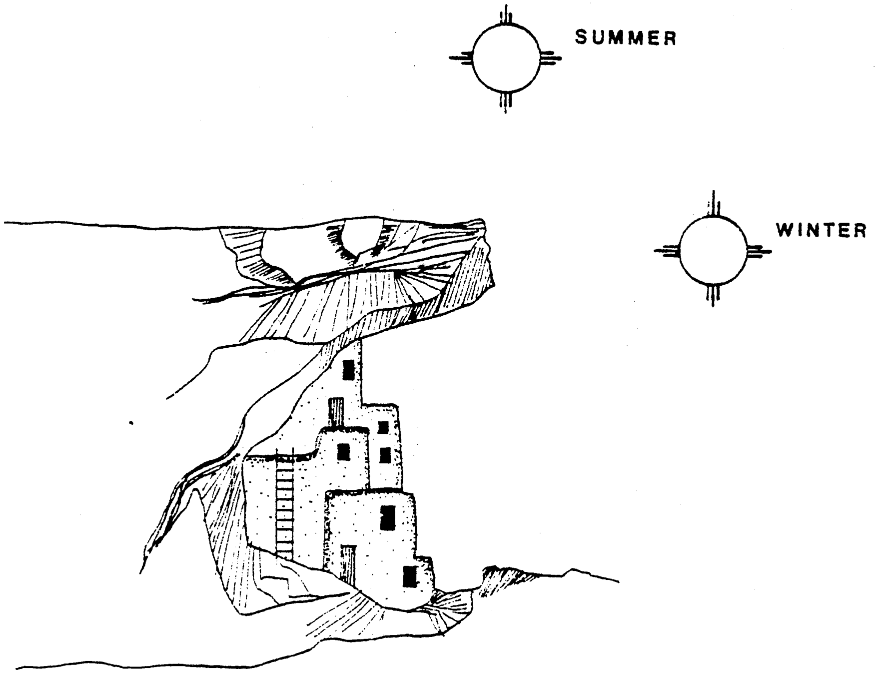


Figure 1. Early Indian Passive Solar Homes of the Southwest

As man increased his technological advancements, he began to neglect nature by designing against the natural forces, rather than with them. This practice has led twentieth century architecture to a dependency upon a seemingly endless supply of non-renewable energy and mechanical means to provide a habitable climate within buildings. Because of this, one can now see essentially the same type of building from coast to coast regardless of specific local climatic features.[4]

The high cost of familiar energy sources and their rapid depletion have forced a reevaluation of recent design practices. The shape of today's homes reflects the words of Socrates by beginning to take advantage of the free energy in the warm winter sun. America's philosophy has changed from a belief in the existence of never ending supplies of oil and gas to a belief in the need for energy conservation. The public now demands homes that use the least energy while providing the most comfort. These demands have prompted architects and engineers to rediscover the significance of working in harmony with the sun and earth in constructing homes, thus prompting the surge of contemporary passive solar designs now appearing throughout the country.

"Passive solar" is a broad term that requires definition. A formal definition of a passive solar system is the following: "Passive solar designs are methods for heating or cooling buildings or for heating domestic water in which thermal energy flows by natural means (i.e. without pumps or fans)".[5] This definition may sound suspicious to those who relate large expanses of collectors, pumps, and energy storage systems with the words "solar energy." This is not true of passive solar systems, which are integrated into the structure and become part of the building itself.

There are many ways to incorporate passive solar features into a residence. All designs have the same two basic components: exposed south facing glass for solar collection, and thermal mass located in the building interior for heat absorption, retention, and reradiation. Passive solar heating systems are best categorized as direct gain, indirect gain, and isolated gain.

Direct gain is the most basic of the passive systems and involves no sophisticated controls. A direct gain system allows the sun to enter the living space and strike the storage mass directly. The space serves as a live-in collector, illustrated in Figure 2.

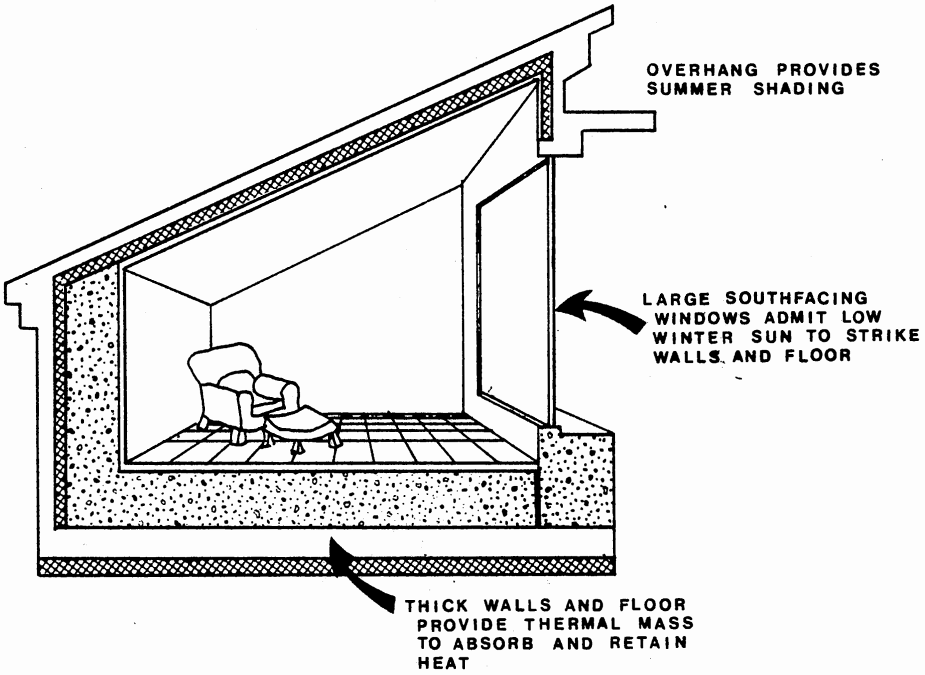


Figure 2. Direct Gain Heating Schematic

Upon striking the storage mass, a large percentage of the incident radiation is absorbed, and the remaining energy not absorbed is reflected from the mass as short wave radiation. The energy absorbed is reradiated from the storage mass with a change to long wave radiation. With this wavelength change, the glazing becomes opaque to the radiation, and the trapped energy heats the air in the space. This physical process of trapping heat is commonly known as "the greenhouse effect." A good example of the greenhouse effect is an automobile. When an auto sits in the sun with windows up, the inside becomes extremely warm due to the greenhouse effect.

Direct gain and a Trombe wall are both examined in this study. The Trombe wall is classified as an indirect gain system. Radiation from the sun does not travel through the living space to reach the storage mass shown in Figure 3. Since the radiation does not enter the space, a Trombe wall system provides better control against direct overheating. The wall, located only a few inches behind the glazing, is usually painted black for absorption, has a range of construction materials such as concrete, adobe, brick, stone, and the recently developed phase change liquids. Heat conducted through the wall is distributed to the space by radiation, and to some degree by convection from the inner face. Many variations can be incorporated into a Trombe wall to enhance the performance of the wall or to better control the heat flow. These two systems, direct and indirect, are the basis of the following analysis.

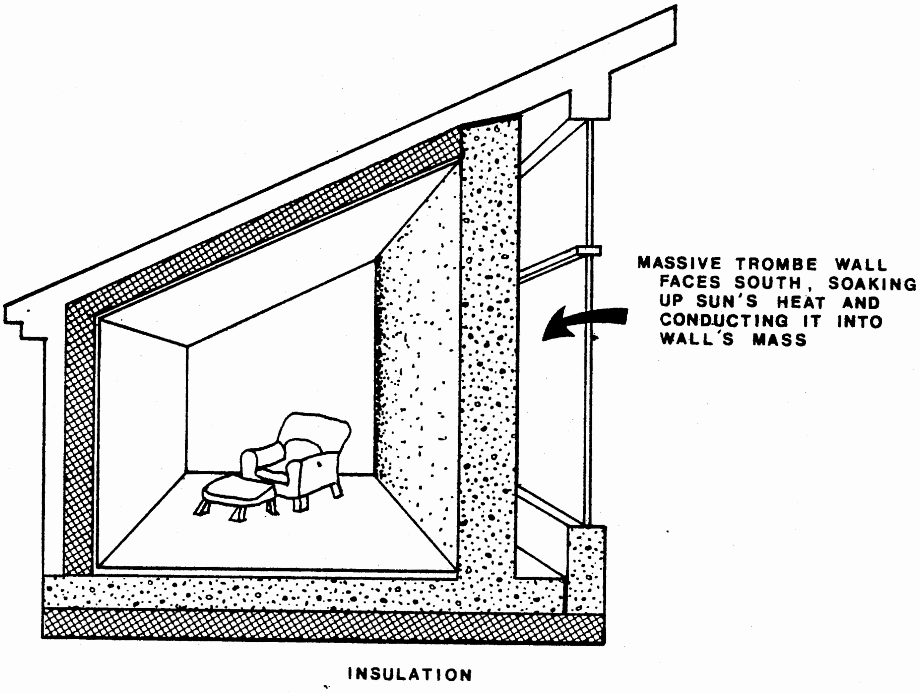


Figure 3. Indirect Gain Heating Schematic With A Trombe Wall

Passive Solar Design: Advantages and Disadvantages

When discussing passive solar heating systems, the question often asked is: why should passive design be incorporated into a building? The reasons can be separated into three categories: economic, architectural, and comfort.

The economic savings come in a variety of forms depending upon whether the system is direct gain or Trombe wall. One advantage of all passive systems is the possibility of providing a significant amount of required heat during the winter with little or no additional cost to the original design and construction of a non-passive home.

Direct gain systems are not only an inexpensive form of solar collector, but they serve other habitation functions as well. For instance, while allowing solar radiation to enter buildings, the system provides natural daylight and visual access to the outside. But even with these incentives to use the direct gain system, there are several problems that can arise if not addressed. The major considerations are as follows:

1. The large glazing area inherent with direct gain can result in visual glare, and lack of privacy.
2. Solar radiation can adversely affect exposed fabrics and paint.
3. To prevent diurnal temperature swings of 15° to 20° F., a large amount of thermal mass is necessary.
4. The large glazing area has high heat loss, and the means to reduce the loss can be expensive.[6]

Additional problems can result with passive systems due to reduction in the level of controls compared to mechanically controlled homes.

Use of a Trombe wall can help overcome some of these complications. When a Trombe wall is employed, a reduction in temperature drifts occurs, glare and fabric fading do not take place, and there is a time delay between the absorption and reradiation which provides heat when needed most. Trombe walls also offer more control than direct gain of the sun's radiation since the rays do not directly enter the living space. As with direct gain, however, there are still several negative points to consider. Most important, with any large amount of glazing, there is a need to control heat loss, and the construction of two walls can increase costs significantly in residential homes. Also, daylighting and visual aspects are essentially eliminated, perhaps requiring additional compensating measures.

Careful design planning can provide solutions to the architectural and comfort problems, while life cycle cost analysis can justify increases in the initial cost of a building. Thus, in order to fully benefit from a passive design, the system integrated into the structure should provide a balanced solution to the potentially dichotomous situation provided by both economics and comfort requirements.

FOOTNOTES

[1] A. L. Harney, "Those Proliferating Atria", AIA Journal, Vol.68, (July, 1979), p. 51.

[2] Solar Energy Research Institute, Passive Design: It's a Natural (Washington: U.S. Government Printing Office, 1980.)

[3] Pacific Gas and Electric Company, The Passive Solar Story (San Francisco, California, 1980.)

[4] E. Mazria, The Passive Solar Energy Book (Emmaus, Pennsylvania, 1979), p. 23.

[5] J. D. Balcomb, Passive Solar Design Handbook: Passive Solar Design Analysis, Vol. 2, Los Alamos Scientific Laboratory (Washington, D. C., 1980), p. A-1.

[6] Ibid, p. A-24.

CHAPTER II

PROBLEM STATEMENT

Objectives

The objectives of this study are to analyze two passive solar heating systems and various associated parameters influencing resulting thermal comfort levels and energy performance. The specific goals of the study are:

1. Develop a qualitative and quantitative comfort analysis of two thermally comparable direct gain and Trombe wall passive solar heating systems.
2. Examine the impact on comfort and energy performance of various parametric changes.
3. Establish design recommendations for the passive solar heating systems analyzed.
4. Provide an economic comparison of the two thermally comparable passive solar heating systems.

Purpose

With energy costs rising, passive solar heated homes have become abundant, creating a need for a comprehensive study of the two most common systems; direct gain and a Trombe wall. This analysis will examine the expected thermal comfort levels of two different passive solar heating systems which provide approximately the same thermal energy input to a space. The comfort ratings will then be compared to economic differences between the two heating systems. After analyzing the results of the comfort study and economic analysis, an evaluation as to which system provides the more habitable environment; both thermally and economically will be conducted.

This study will provide incentives for the public to utilize passive solar heating. Investigation of different building parameters will show the effect of such changes and allow the architect or engineer to decide which configuration is most cost and comfort effective. The parametric studies will also produce some passive solar design guidelines for the northeastern United States climatic region. The guidelines will provide "ballpark" figures to aid the architect or engineer in the initial design phase of a project.

Scope and Limitations

Until recently, only the thermal output of passive solar systems was studied, with little regard given to the assessment of resulting thermal comfort. The surge of public acceptance of passive solar homes has prompted more in-depth analyses of passive solar heating systems.[1] Analysis has led to comfort studies in non-uniform environments. This research effort integrates both thermal comfort and economic comparisons to provide an overall assessment of direct gain and Trombe wall systems located in a northeastern temperate climate.

In order to evaluate the two passive solar heating systems, a typical passive home was designed as a theoretical case study model. The model was designed for a location in the northeastern United States at approximately 40° north latitude. The model was designed to facilitate the analysis of two different heating systems in the same space and does not address architectural design or cooling potential in detail. The study is primarily concerned with comfort and economic comparisons. Several parameters that influence comfort and economics are examined.

The study is limited to the heating mode of the model located in the northeastern United States. Problems of assessing thermal comfort in both uniform and non-uniform environments have been extensively researched by Fanger.[2] From Fanger's research, Wray derived a set of linear equations that enables one to predict thermal comfort levels in passive solar heated homes.[3] Wray's comfort index is a theoretical method of assessing the thermal environment within a structure. A critical point not addressed, but requiring attention when designing passive solar heating systems, is the prevention of overheating during the summer.

The solar energy contribution to a home is commonly expressed in terms of solar savings fraction (SSF) which is a ratio of auxiliary heat input required by a solar building to that auxiliary heat input required by a comparable non-solar building.[4] This is a frequently used and well documented method of presenting the expected performance of individual solar heating systems. Several parameters involving thermal storage material and nighttime insulation are investigated. The most common building materials found in the construction field are analyzed.

Approach

This study deals with a multi-faceted analysis of two passive solar heating systems, direct gain and indirect gain with a Trombe wall. The first part of the analysis pertains to the balancing of the direct gain and Trombe wall to require equivalent amount of auxiliary heat input to maintain an ambient air temperature of 65° F. The Princeton Energy Group's PEGFIX program is utilized to simulate the thermal performance of a passive system for a typical January day and determine the auxiliary heat input.[5] PEGFIX calculates the solar input and auxiliary heat required through mathematical modeling techniques. Both passive solar heating systems are modeled with and without nighttime insulation to determine the impact of insulation on comfort performance. The PEGFIX program also provides valuable data, in the form of hourly storage and air temperatures, that are employed in the comfort analysis.

The second part of the study involves a quantitative comfort analysis of the two thermally comparable heating systems. This analysis utilizes the linear equations developed by Wray at the Los Alamos Scientific Laboratory.[6] The equations are based on a weighted combination of the mean radiant temperature (mrt) and the ambient air temperature.

The use of mrt necessiated the development of an equation that would calculate the mrt anywhere within the study space. With the help of the Oklahoma State University Math Department, an equation was derived utilizing solid angle geometry.

A four foot by five foot grid was marked off in the study space to determine analysis points for the comfort assessment. After the equivalent uniform temperature (Teu) for each point in the space was determined on a three hour cycle, a plot of equal temperature contours was plotted using "SYMAP."[7] The contours illustrate regions of varying comfort sensations based on Fanger's Predicted Mean Vote (PMV). From this analysis, an assessment as to which system provides the most acceptable comfort conditions during the 24-hour simulation period was conducted.

A study model home in which both passive solar heating systems where investigated was selected and modified. The prototype home requiring relatively the same auxiliary energy was compared against both performance and economics of each passive solar heating system. The economic analysis was based on first cost, since the operation of either system would cost the owner the same.

FOOTNOTES

[1] W. O. Wray, " A Semi-Emperical Method for Estimating the Performance of Direct Gain Passive Solar Heated Buildings", Proceedings of the Third Annual Passive Solar Conference (San Jose, California, January 11-13, 1979).

[2] P. O. Fanger, Thermal Comfort - Analysis and Applications in Environmental Engineering (New York, 1970).

[3] W. O. Wray, "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings", Solar Energy, Vol. 25 (1980), p. 327.

[4] J. D. Balcomb, Passive Solar Design Handbook: Passive Solar Design Analysis, Vol. 2, Los Alamos Scientific Laboratory (Washington, D. C., 1980), p. 10.

[5] W. L. Glennie, PEGFIX/PEGFLOAT Handbook, Princeton Energy Group (Princeton, New Jersey, 1978).

[6] W. O. Wray, "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings", Solar Energy, Vol. 25 (1980), pp. 327-335.

[7] J. Dougenik, et al. "SYMAP", Harvard University Laboratory for Computer Graphics and Spatial Analysis (Cambridge, MA, 1975).

CHAPTER III

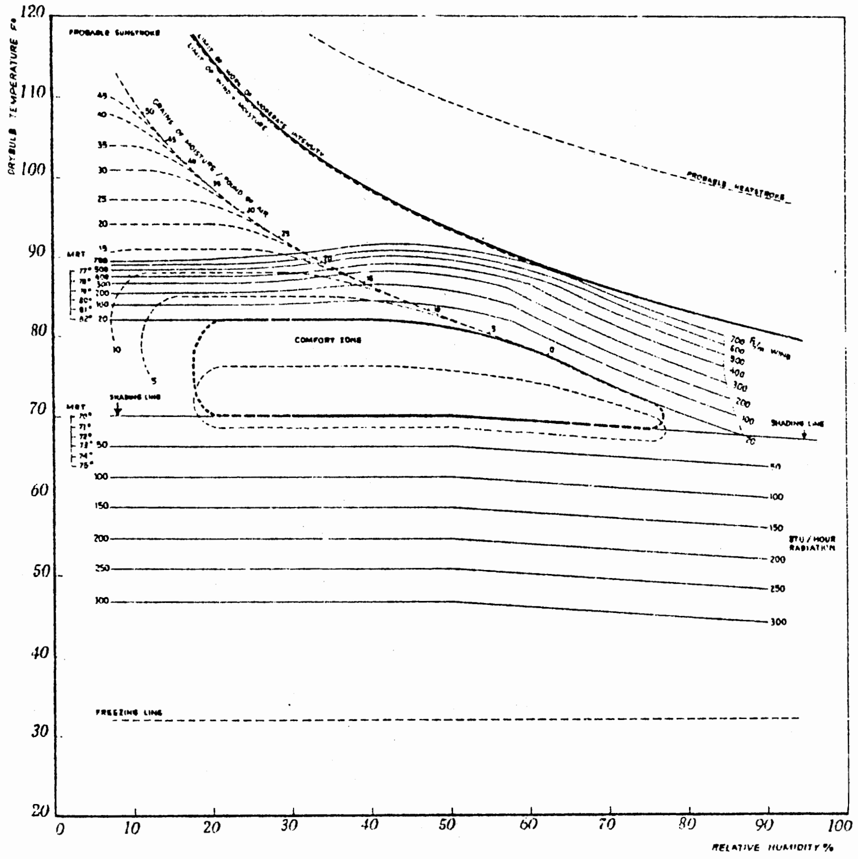
COMFORT AND ENERGY ASSESSMENTS

Comfort Parameters

In the ever changing building environment, a complex relationship exists between the environment and human comfort. The human body strives to achieve a point where minimum expenditure of energy is required to adjust itself to the environment. The condition thus achieved can be defined as the "comfort zone."[1] The building enclosure is the main facility for meeting the needs of comfort within a building. The major elements of the climatic environment which affect occupant comfort can be categorized as: air temperature, mean radiant temperature, air motion, and humidity. The architect/engineer must design an environment, utilizing the above elements, that does not put a strain on the human body in order for one to be comfortable. Studies have shown that the effects of the climatic elements can be grouped onto a single chart. Olgyay combined climatic elements and formed what is known as the bioclimatic chart.[2] The chart is illustrated in Figure 4.

The relationship of the various climatic elements in an environment is shown on the chart. The chart is useful to the architect who is designing passively controlled buildings. Expected conditions in a passive home can be plotted on the chart and the architect/ engineer can determine what corrective measures are required to maintain comfort conditions. With passive designs, it is the task of the architect/

engineer to make utmost use of natural means available to produce a comfortable environment, and to achieve energy conservation by minimizing the use of mechanical aids for comfort control. In this study, two passive solar heating systems are investigated; direct gain and a Trombe wall, to determine comfort conditions produced by the systems.



Source: V. Olgyay, Design With Climate,
Princeton, NJ, 1963, p. 26.

Figure 4. Bioclimatic Chart

Comfort Indices

Most analyses of building thermal performance rely exclusively on computed energy savings as the figure of merit. This is acceptable when one is comparing similar indoor environments. Passive solar conditioned environments differ significantly from those environments found in mechanically conditioned buildings. Passively conditioned spaces result in differing surface temperatures which create a non-uniform environment. Several indices have been developed to assess thermal comfort in a non-uniform building environment.

Two rationally derived indices for characterizing non-uniform thermal environments are presented in the ASHRAE Fundamentals Handbook.[3] The first index is the "operative temperature", defined as "the uniform temperature of an imaginary enclosure in which a human will exchange the same dry heat by radiation and convection as in the actual environment". The second index is called "humid operative temperature" defined as "the uniform temperature of an environment at 100 percent relative humidity, with which a human will exchange the same heat from his skin surface by radiation, convection through his clothing, and evaporation as in the actual environment". These two indices were not used in this study because the indices lack generality and neither is explicitly related to assessing thermal comfort.[4]

Another index recently developed by Carroll of the University of California at San Diego Energy Center is described as a discomfort index for passive solar homes.[5] The discomfort index is a single number which ranks residential designs and operating strategies based on overall comfort implications. The index can also be utilized to identify worst-case episodes. This is particularly useful in studying passive homes with or without a mechanical back-up system. A computer program has been developed to incorporate the index into a building thermal performance simulation program. The index is valuable if one has access to a mainframe computer and thermal building analysis program. The index is an expanded version of Wray's "Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings" which is utilized in this study.[6] The index provides the information needed for one to make a quick assessment of the thermal comfort level in passive solar buildings where the mean radiant temperature differs significantly from the air temperature. A more in-depth description of the index procedure is presented in Chapter VII.

Energy Equivalence

One of the major objectives of this study is a comfort investigation of two thermally equal passive solar heating systems. In order to achieve this thermal equilibrium between the two systems, a computer program simulating passive performance was utilized to determine how much auxiliary heat was required for a typical January day. A trial and error procedure was used to balance the two systems, so that each required approximately the same amount of Btu's to maintain an air temperature of 65° F in a case study residence. This approach provided a foundation for the comfort analysis of two equal systems. That is, from an energy standpoint, it did not matter which system was installed since both would cost an owner the same amount to operate. This study focuses on the analysis of comfort conditions provided by the two comparable systems.

FOOTNOTES

[1] E. Mazria, The Passive Solar Energy Book (Emmaus, Pennsylvania, 1979), p. 389.

[2] V. Olgyay, Design With Climate (Princeton, New Jersey, 1973), p. 15.

[3] Ibid, p. 22.

[4] ASHRAE Handbook -- 1977 Fundamentals (New York, 1977) p. 817.

[5] W. O. Wray, "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings", Solar Energy, Vol. 25 (1980), p. 327.

[6] J. A. Carroll, "An Index to Quantify Thermal Comfort in Residential Buildings", ASHRAE 1981 Transactions, Vol. 87 (1981), p. 121.

[7] W. O. Wray, "A Simple Procedure for Assessing Thermal Comfort in Passive Solar Heated Buildings", Solar Energy, Vol. 25 (1980), p. 327-333.

CHAPTER IV

PASSIVE SOLAR EXAMPLE HOME

Passive Design Concepts

Passive solar design involves a knowledge of weather and solar trends, impacts of external thermal forces on the building envelope, development of optimum building shape, and building orientation. Before detailed investigation of passive solar heating systems can be initiated, an understanding of the aforementioned factors is essential.

Passive solar heating relies on the sun to provide energy input to a system. Solar radiation is difficult to compute. ASHRAE tabulated solar heat gain factors are provided for calculating the design cooling load; the values are a maximum and not typical daily amounts of solar radiation impacting a vertical surface. There are also difficulties in extrapolation of incident radiation upon vertical surfaces from horizontal solar radiation data. The surface reflection for each specific site will impact the amount of solar radiation. The solar data for this study was obtained from Mazria's The Passive Solar Energy Book.[1] The solar radiation total for the month of January in New York was proportioned throughout the daylight hours. The proportioning was based on solar heat gain factors published by ASHRAE.

Exact solar data is not mandatory during design development, as relative insolation data can provide sufficient information. Table I indicates the radiation impacts on the prime orientations of a building in each of the 4 climatic regions.[2] July 21 and December 21 were chosen as indices for summer and winter conditions. The table shows that in the New York City region, the south side of a building receives 77% more radiation in the winter than in the summer. This increased radiation, when compared to the summer may be very beneficial to offset winter heating requirements of a home.

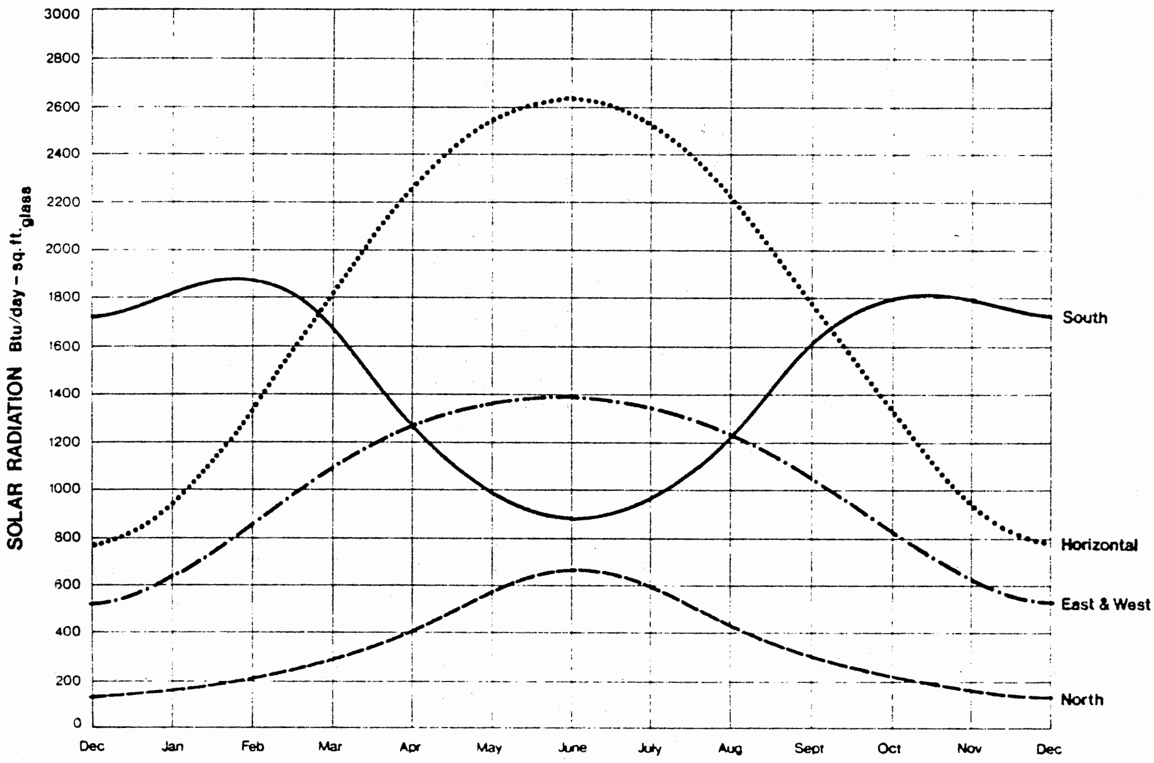
TABLE I

SOLAR RADIATION IMPACTS ON BUILDING ORIENTATIONS

		Btu/Ft^2/Day	
		Winter	Summer
Minneapolis	E	416	1314
	S	1374	979
	W	416	1314
	N	83	432
New York	E	517	1277
	S	1489	839
	W	517	1277
	N	119	430
Phoenix	E	620	1207
	S	1606	563
	W	620	1207
	N	140	452
Miami	E	734	1193
	S	1620	344
	W	734	1193
	N	152	616

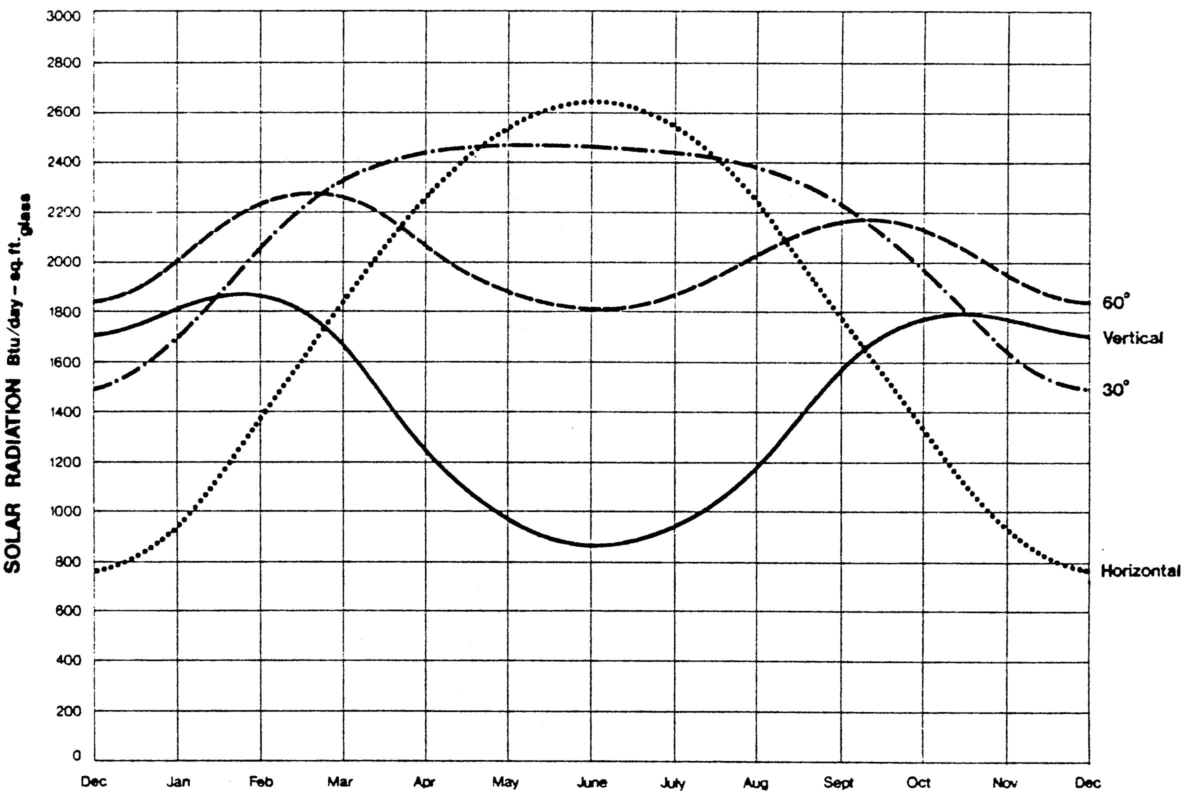
Most passive solar heating systems use vertical south facing glass.

More radiation strikes the glazing during the heating season than during the summer. Figure 5 illustrates the effect of changing the glazing orientation on solar radiation input to a space. The solar radiation values are for the northeast (40°NL) region of the United States. Passive solar designs usually use glazing in a vertical format, rather than a tilted position, because of difficulties in construction, shading and increases in cost. More important is the reduction in the overall performance inherent with glazing other than vertical. Figure 5 shows the performance of various tilted positions.



Source: E. Mazria, <u>The Passive Solar Energy Book</u>, Emmaus, Pa., 1979, p. 103.

Figure 5. Comparison of Window Orientations with Respect to Solar Radiation



Source: E. Mazria, The Passive Solar Energy Book, Emmaus, Pa., 1979, p. 129.

Figure 6. Comparison of South-facing Tilted Surfaces with Respect to Solar Radiation

Optimum Building Shape

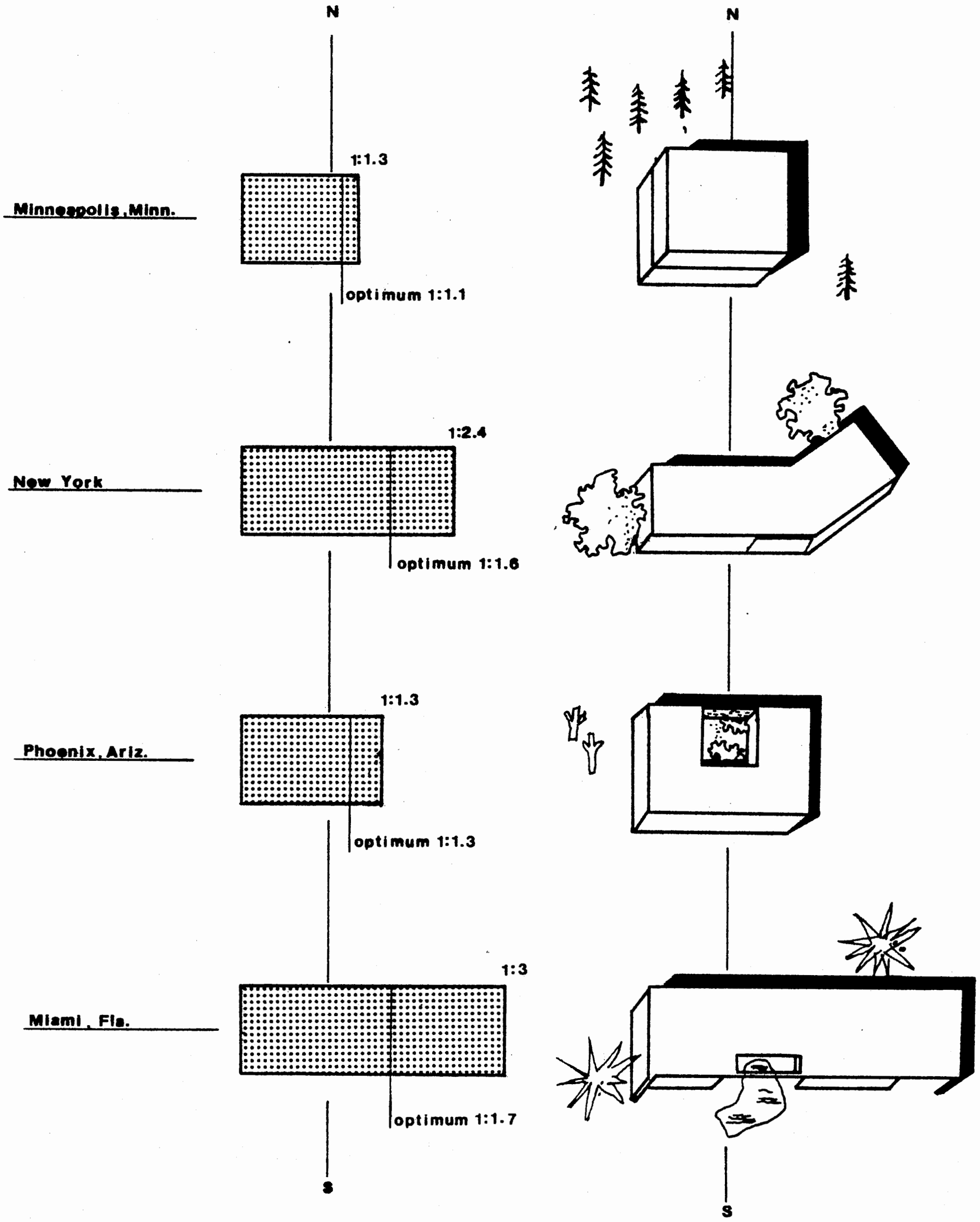
The overall shape of a home has a major influence on how efficiently the structure utilizes solar energy. The old belief that a square building is the most efficient, that is, uses the least amount of energy is no longer, and may never have been, valid. Victor Olgyay in Design With Climate investigated what he considered the optimum shape of a building for each of four major climatic regions. From his observations, he ascertained the following for conventional above ground housing:

1. The square house is not the optimum form in any location.
2. All houses elongated on a north-south axis work with less efficiency in both summer and winter than a square house.
3. The optimum shape lies in every case in a form elongated somewhere along the east-west direction.[3]

It can be noted that a building extended along an east-west axis provides a southern exposure ideal for the collection of solar radiation. Figure 7 shows Olgyay's optimum building shapes for four climatic regions.

The interior of a building should be arranged to fully utilize the solar radiation input from south facing glass. The room depth for a Trombe wall heating system should be limited to 15 to 20 feet. This is considered to be the maximum effective distance from a radiant wall.[3] A Trombe wall limits the amount of natural daylight entering a space. Additional daylight can be brought into a space through clerestories and skylights.

With a direct gain system, the maximum space depth should not exceed $2\text{-}^{1}/_{2}$ times the window height.[4] For an average window height of 7 feet, the space depth maximum is 18 feet. This depth assures that sunlight will penetrate the entire space.

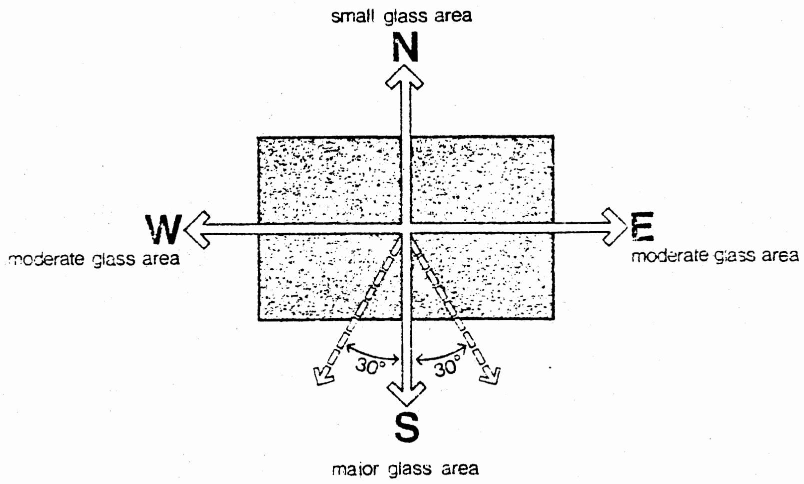


Source: V. Olgyay, Design With Climate, Princeton, NJ, 1963, p. 90.

Figure 7. Optimum Building Shapes

Glazing Orientation

One of the most significant factors influencing the performance of passive solar heating systems is the orientation of the glazing. The optimum orientation for maximum net energy input is due south. Variations east or west of south, up to 30°, will have marginal impact, while larger variations will reduce window performance substantially.[5] Figure 8 illustrates guidelines for glass location. The location of moderate amounts of glass is a result of east-west facing single or double pane windows either breaking even or losing energy during the winter. Since the low angle winter sun casts a shadow over the north side of a home, any windows oriented north would be a continuous source of heat loss. These are some of the factors that affect window placement; others are visual relief, daylighting, and privacy.



Source: E. Mazria, The Passive Solar Energy Book, Emmaus, Pa., 1979, p. 102.

Figure 8. Location of Glazing Area.

Technical Description of Study Model

In order to facilitate the thermal comfort analysis of direct gain and Trombe wall passive solar heating systems, a model home was designed in order to to simulate the systems. A basic floor plan was selected from The First Passive Solar Home Awards developed by the U.S. Department of Housing and Urban Development.[6] The building was altered to better suit the needs of passive solar heating. Large massive interior bearing walls were added to increase the thermal mass of a primarily wood frame structure. The roof configuration was also changed to increase the passive solar heating potential by enlarging the glazing area. The home utilizes a clerestory to provide natural illumination and added solar radiation to the spaces located in the rear of the home. The garage and mechanical space serve as a buffer against the north winds. The glazing is oriented due south to maximize the collection of solar radiation. Floor plan, elevations, sections, and details are illustrated in Figures 9-14.

The exterior walls and roof contain fiberglass batt insulation with R-values of 22 and 40 respectively. The floor storage mass has a tile finish to permit retention of solar radiation. North, east, and west windows are triple pane in order to minimize winter heat loss. The floor slab is insulated along the perimeter with 2" extruded polystyrene insulation. A concise list of construction materials is in Table II.

TABLE II

CONSTRUCTION MATERIALS IN CASE STUDY

Element	Insulation	R-value (total)
Roof	12" fiberglass	40.4
Walls	6" fiberglass	22.6
Windows	Double pane	2.3
	Triple pane	3.4
Floor Slab	2" polystyrene	10.0

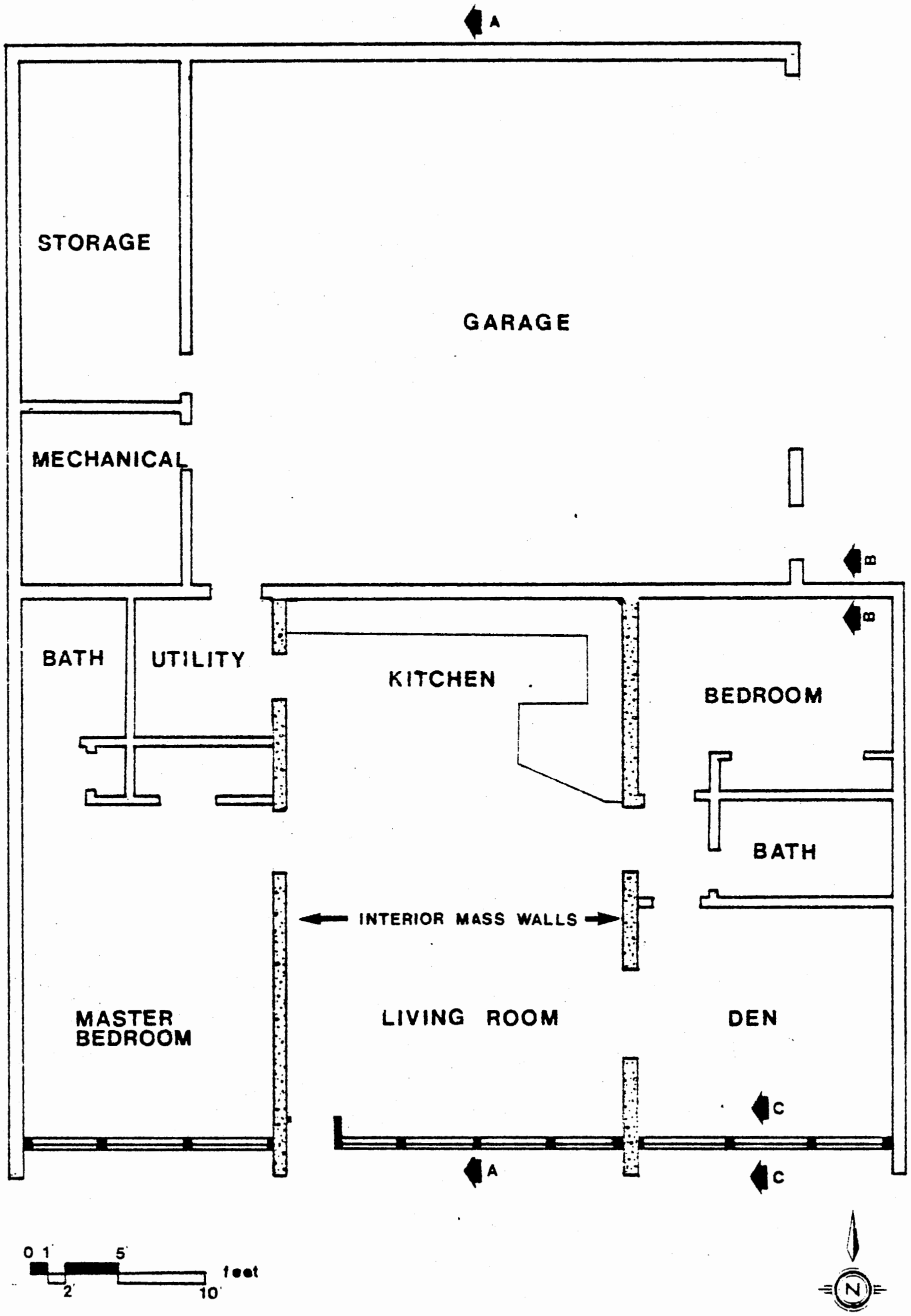


Figure 9. Case Study Model Floor Plan

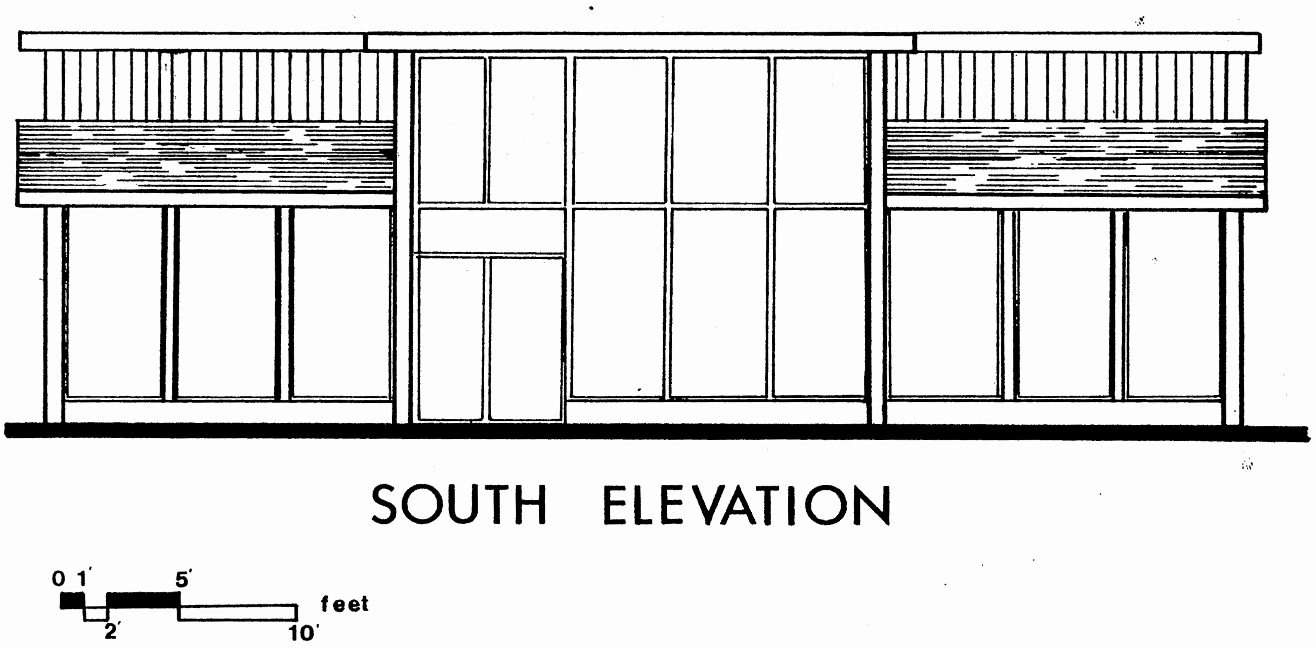


Figure 10. South Elevation

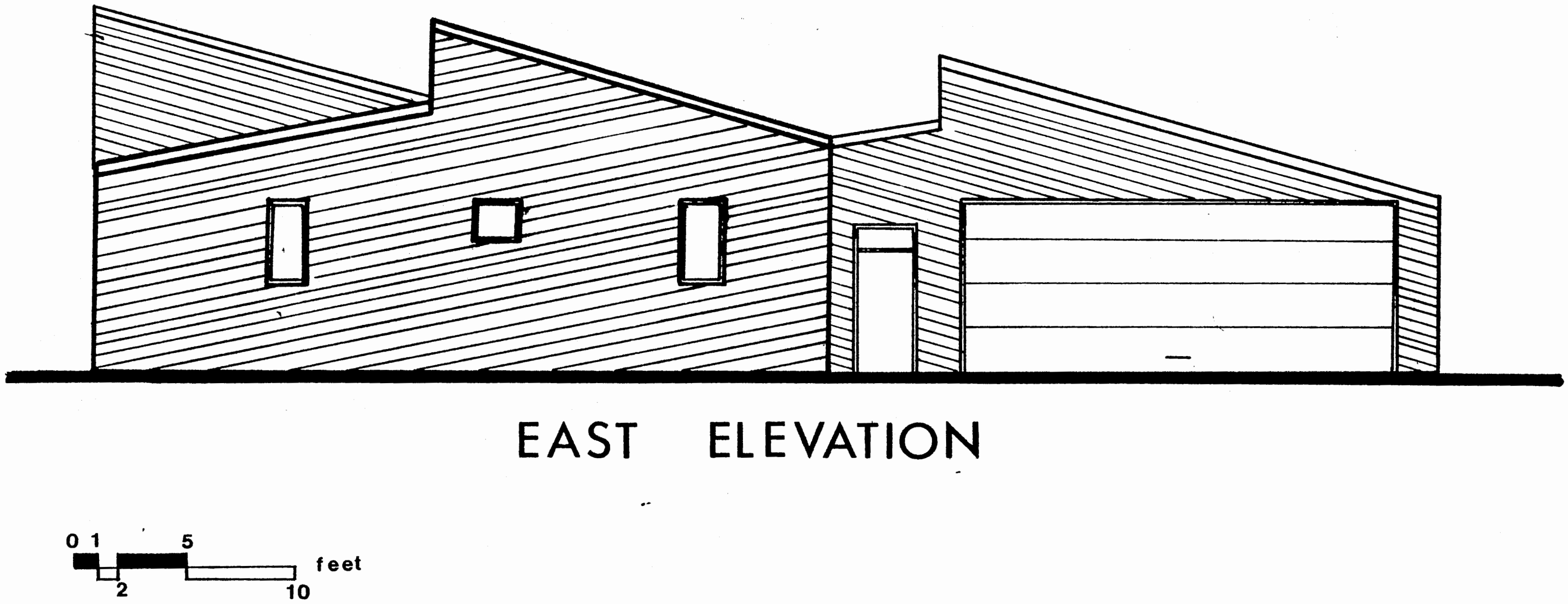


Figure 11. East Elevation

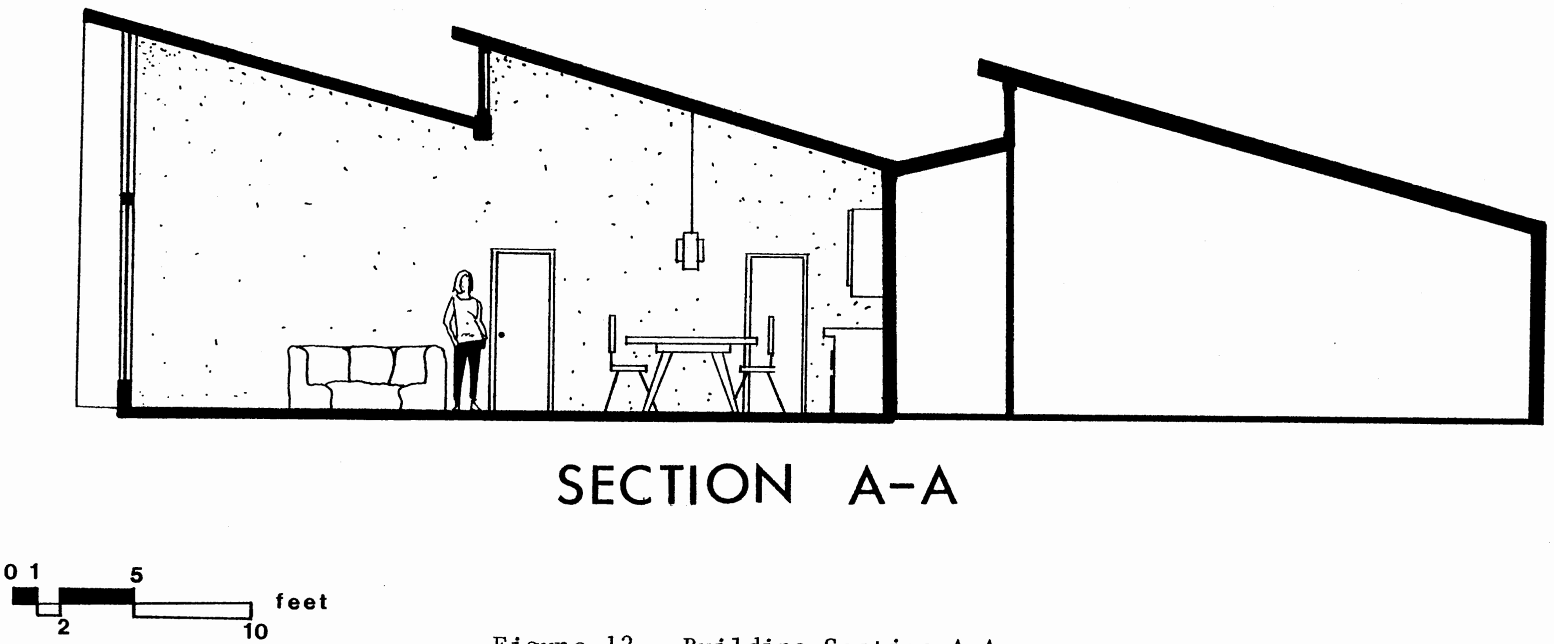


Figure 12. Building Section A-A

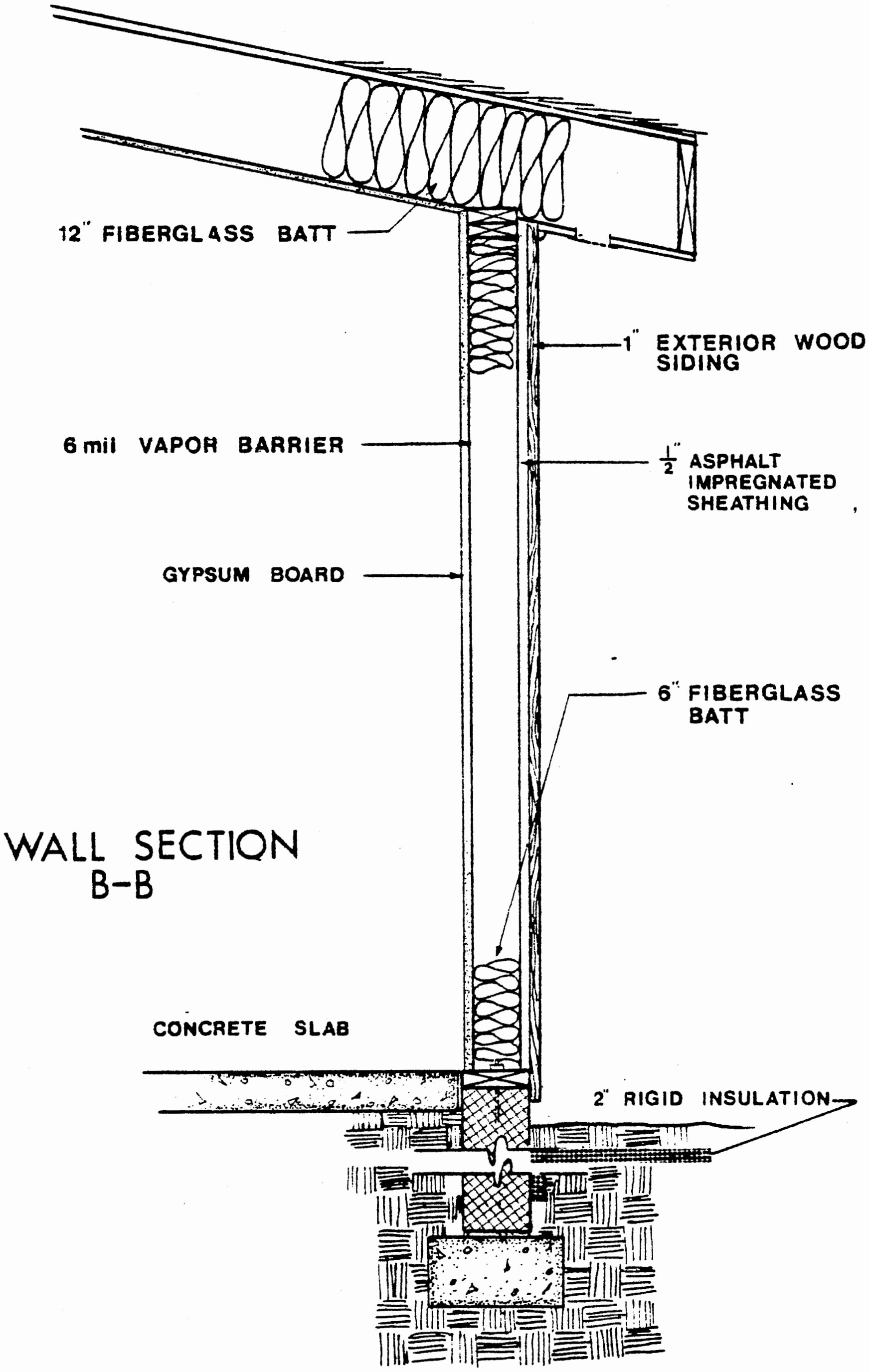


Figure 13. Exterior Wall Section B-B

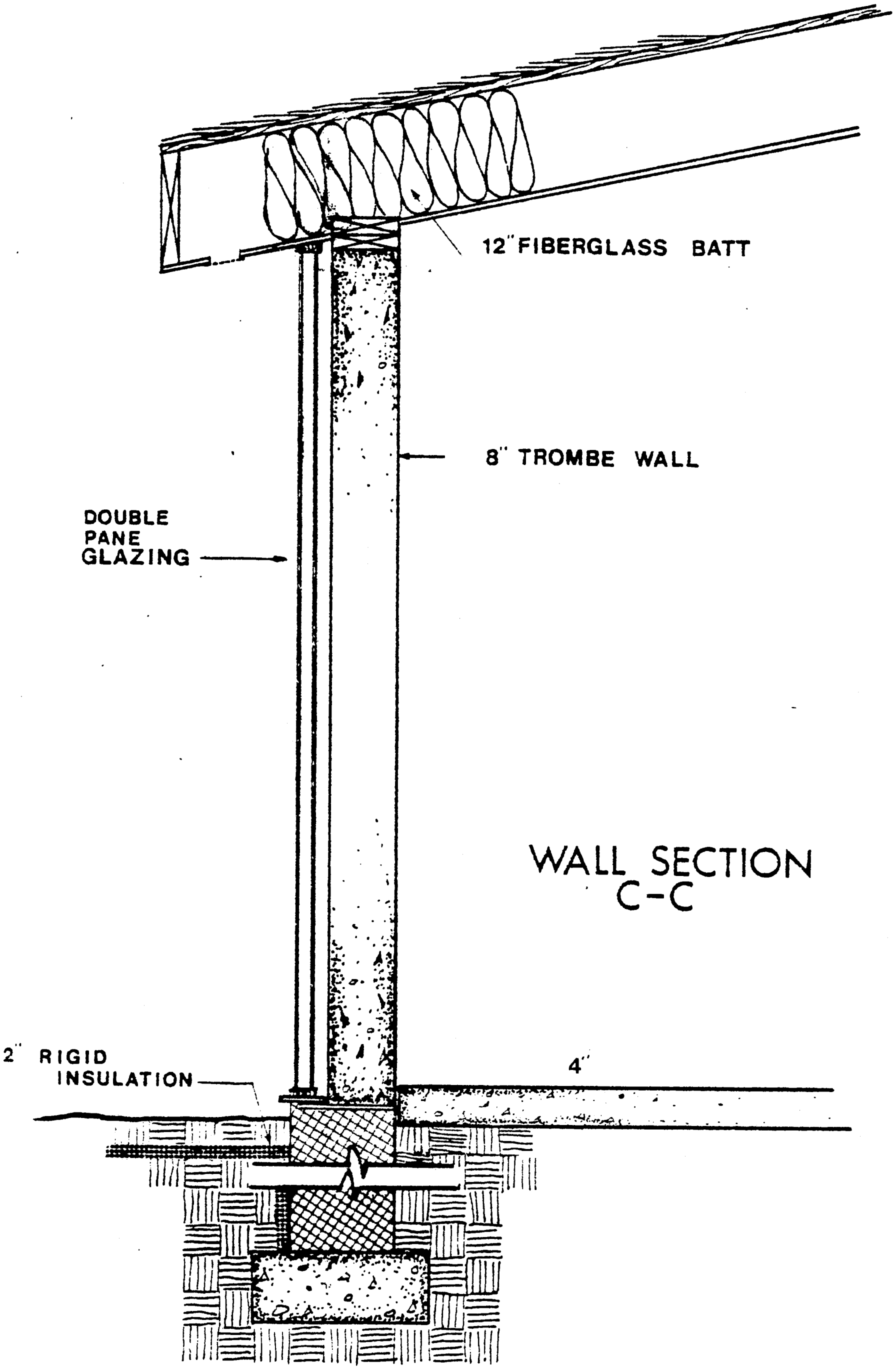


Figure 14. Trombe Wall Section C-C

FOOTNOTES

[1] V. Olgyay, Design With Climate (Princeton, New Jersey, 1973), p. 86.

[2] Ibid, p. 90.

[3] E. Mazria, The Passive Solar Energy Book (Emmaus, Pennsylvania, 1979), p. 84.

[4] Ibid, p. 104.

[5] U.S. Department of Housing and Urban Development, The First Passive Solar Home Awards (Washington, D. C., 1979), p. 135.

CHAPTER V

BUILDING HEAT LOSS

The heating requirements of a building are determined by the total heat loss through the structure's envelope. Heat losses occur primarily in the following manner: 1) Transmission losses, heat transfered through the confining walls, glass, floor, ceiling, or other surfaces. 2) Infiltration losses, energy required to heat outdoor air which leaks into the space through cracks and crevices around windows and doors or through open windows and doors. Heat loss is a physical phenomenon in which energy flows from a high energy sink to a lower source due to a difference in temperature. Winter warm interior air is continuously dissipated to the cooler exterior surroundings creating the need to replenish the lost heat energy. Energy efficient homes cut back the loss of energy thus reducing energy consumption. A reduction in the rate of heat loss can be achieved through the use of insulating materials having low conduction rates, the interposition of air spaces, reduction of air exchange, and the reduction of radiant transfer through the use of reflective linings within the air spaces.

This study requires an hour-by-hour heat loss calculation to corollate with hourly solar radiation gains. Calculation of the hourly heat losses requires hourly outdoor air temperatures for a typical January day. A typical single day analysis is useful for checking typical performance during a month. The outside air temperature data for New York, NY was obtained from "weatherun", a data file containing average hourly temperatures for January based on a 20 year period.[1] The outdoor air temperature profile is shown in Figure 15. These temperatures are used to calculate the hourly heat loss for each hour in a typical January day. The month of January was chosen to represent design winter conditions.

Procedure

Heat loss calculations for the study home utilize methods from the 1977 ASHRAE Fundamentals.[2] Total hourly heat loss is the sum of the convective and conductive losses of each separate building component. The method to calculate the losses is as follows:

Step 1: Determine the heat transfer coefficients (U) for the exterior walls, windows, roof, and doors. The U-value for each construction type is then multiplied by the respective area. The U-values and areas (A) are substituted into equation 5.1, where Ti is the interior ambient air temperature and To is the hourly outdoor air temperature.

$$Q = UA\,(Ti - To) \qquad (5.1)$$

Step 2: Heat loss due to infiltration is determined by equation 5.2. For the passive model home, the infiltration rate is assumed to be one-half air change per hour, which is the minimum for health.[3]

$$Q = 1.1\,(CFM)\,(Ti - To) \qquad (5.2)$$

Step 3: The floor is slab-on-grade which contributes to the home's overall heat loss. The length of exposed edge is totaled and multiplied by the loss per foot value obtained from ASHRAE.[2]

Summing steps one through three provides the total building heat loss for a given hour. Completing the calculations for the 24 hour period determines the daily heat loss. Table III indicates the breakdown of the daily heat loss.

TABLE III

DAILY HEAT LOSS FOR CASE STUDY

Component	Daily Heat Loss (Btu)
Envelope (No Glazing)	59879
Infiltration	85484
Edge loss	151680
Internal Gains	-48,000
24 hour total	249,043

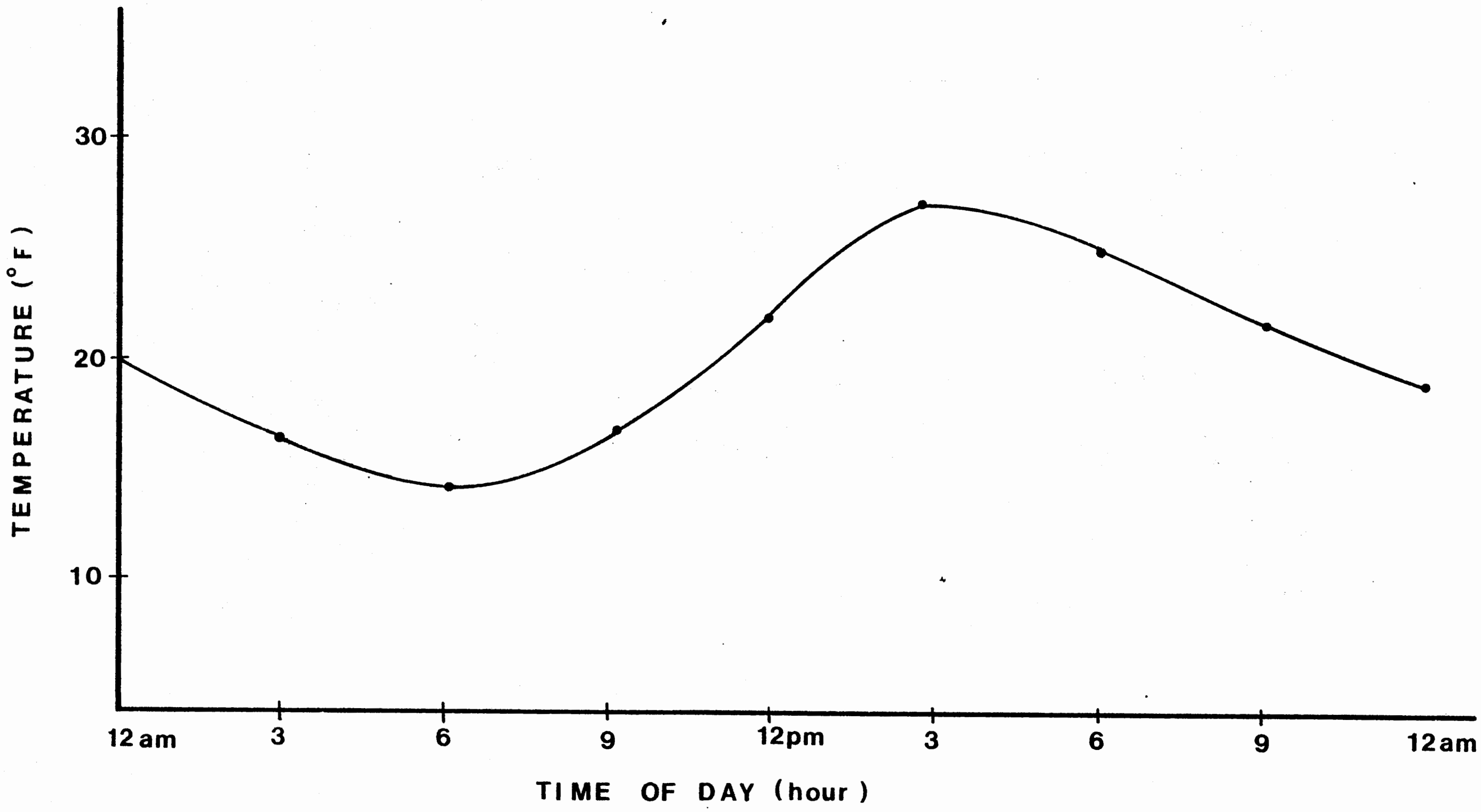


Figure 15. Typical Temperatures for a January day in New York City.

FOOTNOTES

[1] O. Donovan, "Weathr," Pennsylvania State University Computer-Aided Design Laboratory (University Park, PA, 1977).

[2] ASHRAE Handbook -- 1977 Fundamentals, Chapter 24 (New York, 1977).

[3] J. D. Balcomb, Passive Solar Design Handbook: Passive Solar Design Analysis, Volume 2, Los Alamos Scientific Laboratory (Washington, D.C., 1980), p. 37.

CHAPTER VI

PASSIVE SOLAR CONTRIBUTION

System Performance Evaluation

This study is concerned with a comfort evaluation of two comparable systems. In order to analyze the direct gain and Trombe wall passive solar heating system for occupant thermal comfort, the systems need to be balanced so that each would require the same amount of auxiliary heat input to maintain an ambient indoor air temperature of 65° F. Balancing the auxiliary instead of the SSF will result in each system costing the owner the same amount to operate.

PEGFIX computer analysis was utilized to determine the quantity of auxiliary heat input, thus balancing direct gain and Trombe wall heating systems.[1] The balancing procedure involved a trial and error process in which maximum aperture and storage for both systems was simulated. Investigations of R-9 nighttime insulation were conducted for the insulation's impact on occupant comfort.

Princeton Energy Group Programs Methodology

The Princeton Energy Group developed two programs to calculate the performance of passive solar heating systems. The programs, PEGFIX and PEGFLOAT, were designed to facilitate the modeling of solar heating systems with minimal knowledge of computer programming.[1] A basic understanding of heat flow, type of building construction, and passive systems is necessary to provide the required input data. The programs utilize mathematical modeling to determine auxiliary heat requirements, storage surface temperatures, air temperature, and heat loss for a 24 hour simulation period. The differences between the programs are that PEGFIX allows the user to program an interior air temperature range in which any excess air temperatures are vented and auxiliary heat is utilized to make up deficiencies; PEGFLOAT allows only solar gains to control interior air temperatures thus the air temperature will float. PEGFIX is utilized in this study to model a typical passive home with a back-up system.

Procedure for PEGFIX

Utilization of PEGFIX to balance the two passive solar heating systems is as follows:

Step 1: Determine effectiveness of storage mass, based on thickness of the concrete storage, utilizing a subroutine "B" of PEGFIX program. The storage capacity (MC sto) is the sum of both primary and secondary storage. The difference between primary and secondary storage is that the primary area receives direct sunlight a majority of the day and secondary receives little or no direct sunlight.

Step 2: Compute the overall building heat loss coefficient, both night and day, (UA day and UA night). This allows the use of nighttime insulation common practice in northeastern designs.

Step 3: Calculate the heat transfer coefficient (UA sto) which regulates the rate at which the heat leaves storage by radiation and natural convection.

Step 4: Determine the solar split (f sto, f air), which is the proportion of: 1) fraction that is absorbed by storage (f sto); 2) the fraction heating the air.

Step 5: Set the upper (T max) and lower (T min) limits of air temperature. When the temperature is below T min, auxiliary heat is supplied to bring temperature to T min, and when the upper limit is exceeded, the excess heat will be vented to the outside.

Step 6: Store daily average temperature (T avg) and daily temperature swing.

Step 7: Store area of unshaded glazing (Ag). In order to input individual hourly solar radiation data, the area should be zero.

Step 8: Input hourly solar radiation (I hour). I hour is the area of the glazing multiplied by the transmittance of the glass and solar radiation on a vertical surface.

Step 9: Estimate initial storage mass temperature (Tsto). The change of the storage temperature should be within one degree of initial temperature at the end of simulation period (24 hours) for accurate results.

Step 10: Execute PEGFIX to calculate auxiliary heat input, storage temperature, and air temperature for a 24 hour period. The SSF can be calculated by subtracting auxiliary heat total from heating load and dividing by the heating load. Table IV shows the final results of balancing the two systems.

The direct gain system consisted of 410 ft^2 of double pane glazing and 1200 ft^2 of 6" concrete floor storage. The Trombe wall system consisted of 310 ft^2 of double pane glazing and 310 ft^2 of 8" concrete storage wall. These two systems require approximately the same amount of auxiliary heat input and therefore are thermally comparable. This thermal comfort investigation examines the comfort conditions of the two thermally similar systems.

TABLE IV

PEGFIX PERFORMANCE PREDICTIONS

Heating System	Auxiliary Heat	SSF
Direct Gain*	107,000 Btu's	.76
Trombe Wall*	108,000 Btu's	.73

*contains R-9 nighttime insulation

Due to the harsh climate, the direct gain structure lost too much thermal energy through the glazing aperture to remain competitive with a Trombe wall in the absence of nighttime insulation.[2]

Simulations of the passive solar heating systems provide data for the development of Figures 16, 17, 18, and 19. The figures illustrate several inherent phenomena with each particular system. Figures 17 and 18 indicate the relatively rapid response of the direct gain system to the solar input when compared to the Trombe wall system. Realization of a system's time lapse will aid the designer in the planning of a home. Functions of the space can be combined with passive solar heating to correlate performance peaks of the system with space occupancy. The heat loss profiles are directly related to the temperature profile in Figures 18 and 19. Trombe wall heat input does not affect the ambient air temperature until early evening, whereas a direct gain system impacts air temperature at noon. This is due to the fact that with a Trombe wall, the solar radiation does not come in contact with the air since the radiation is intercepted by the storage mass. These subtle differences between the two systems may not be apparent when examining only thermal energy input. Knowledge of the characteristics of the two systems can contribute to an efficient, well organized design.

The main thrust of the computer simulation was to balance the thermal input required to operate the study home over a 24 hour day and to obtain ambient and storage temperatures necessary for a comfort analysis. Discussion of the inherent properties of each system was important to the development of a study of the two systems. Data obtained from the PEGFIX simulation forms the foundation of the study on human comfort in passive solar homes.

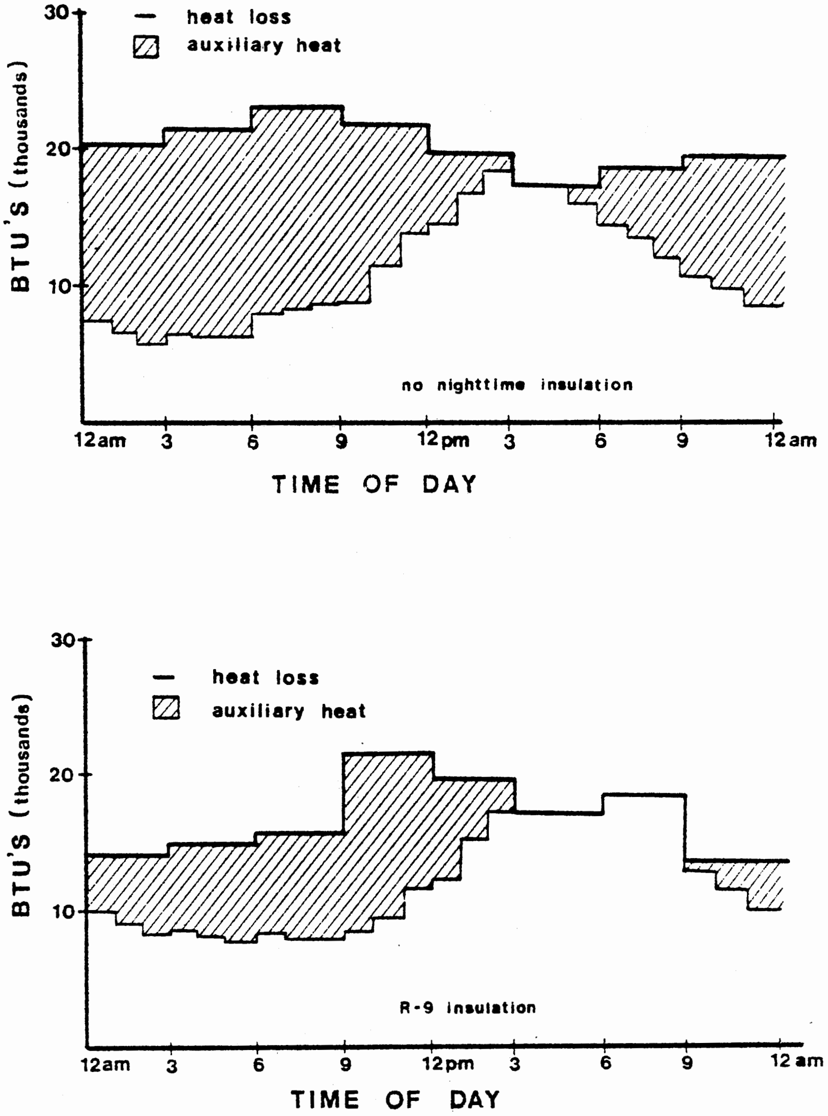


Figure 16. Trombe Wall Home Heat Loss Profiles

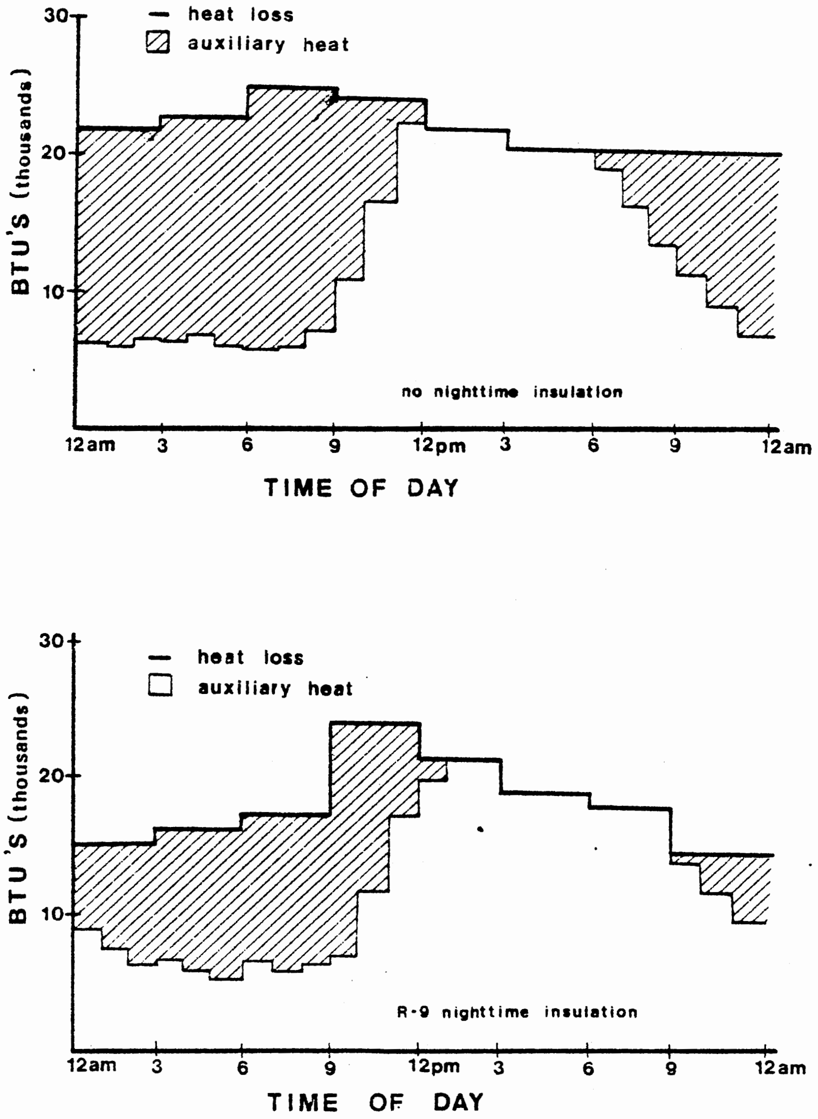


Figure 17. Direct Gain Home Heat Loss Profiles

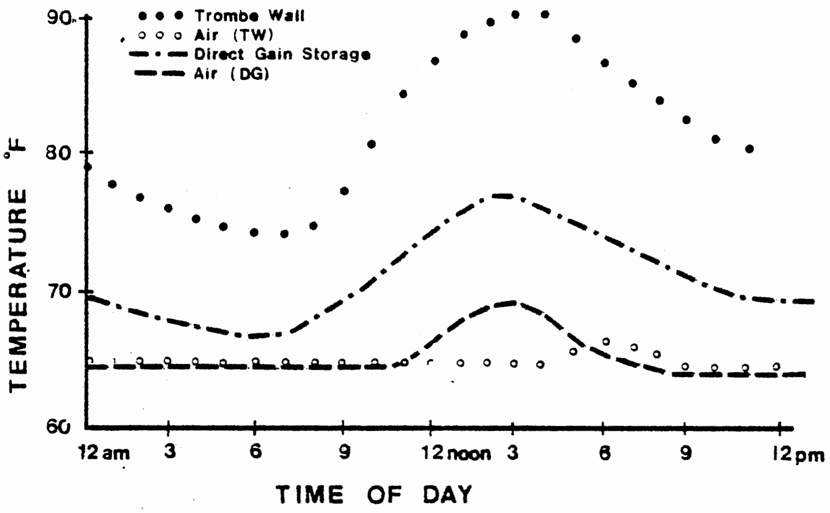


Figure 18. Temperature Profile of Passive Solar Heating Systems Without R-9 Nighttime Insulation

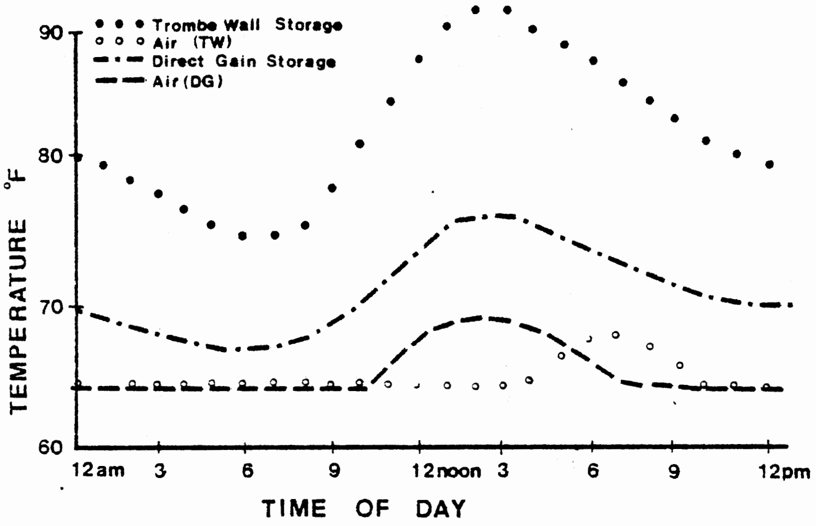


Figure 19. Temperature Profile of Passive Solar Heating Systems With R-9 Nighttime Insulation

FOOTNOTES

[1] W. L. Glennie, PEGFIX/PEGFLOAT Handbook (Princeton, New Jersey, 1978).

[2] J. D. Balcomb, Passive Solar Design Handbook: Passive Solar Design Analysis, Vol. 2, Los Alamos Scientific Laboratory (Washington, D.C., 1980), p. 142.

CHAPTER VII

THERMAL COMFORT INDEX PREDICTIONS

Methodology

The major emphasis of this study is the evaluation of thermal comfort provided by two comparable passive solar heating systms. Until recently, most analysis of a building's thermal performance relied exclusively on computed energy savings as the determining factor of the success of a passive heating system. Research efforts lately have been focused on considering the impact of system performance on overall occupant comfort.[1,2,3] With passive solar heated spaces, the thermal environment is inherently more diverse than in mechanically controlled spaces. Designers of passive solar environments need to understand the impact of variant radiant fields, common with passive systems, on human comfort.

In most conventional thermally conditioned buildings, the construction is lightweight with a nominal amount of glazing. The thermal environment associated with this type of construction is fairly uniform. The term "uniform" refers to an environment in which the air and mean radiant temperature (mrt) are nearly equal. This is not true of passive solar heating systems, where there are large glazed areas and thermal mass, both of which contribute to a non-uniform environment. A glazed area and storage element in the occupied space will have temperatures either cooler or warmer than the ambient air temperature.

The storage mass temperature will be at least equal to air temperature and usually warmer due to retention of solar energy. The glazed areas, directly in contact with the living space such as is the case with direct gain systems, induce significant fluctuations in mean radiant temperatures. At night, the cold glazing surface temperature reduces the mrt of the space. Nighttime insulation can minimize the swing of the interior glazing surface temperature.

Non-uniformity of temperatures in a living space compounds the problem of assessing the thermal comfort of such an environment. Fanger has done extensive research work on the assessment of occupant comfort in a uniform environment.[4] From Fanger's effort, Wray of Los Alamos Scientific Laboratories, derived an expression for "equivalent uniform temperature.", Teu, which is defined as "the uniform temperature of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment."[5] The ambient air temperature and mean radiant temperature are integrated into the Teu by the following functional form:

$Teu = X(Ta) = 1 - X(Tmr)$ where Ta = air temperature

and $X = f(M,C,H,V)$ Tmr = mean radiant temperature (mrt)

where M is the metabolic rate, C is a clothing insulation value, H is the space relative humidity, and V is relative interior air velocity. The importance of mrt and air temperature is dependent upon the aforementioned physiological and environmental parameters.

Utilization of the equivalent uniform temperature concept is useful as one assesses thermal comfort levels in a non-uniform environment. The Teu is explicitly related to human comfort and includes the effects of latent heat loss which is more realistic than ASHRAE's "operative temperature."[6]

Comfort Analysis

The comfort investigation of the living space in the case study home focused on an array of analysis points in the space. The living space was chosen since there are likely to be occupants in the space from morning till evening. Figure 20 shows the grid system utilized to determine mrt and plot Teu contour lines throughout the space. The dense concentration of points near the south wall was a result of initial investigations indicating this area as a critical zone in which the temperature of the wall has a significant impact on the overall comfort level.

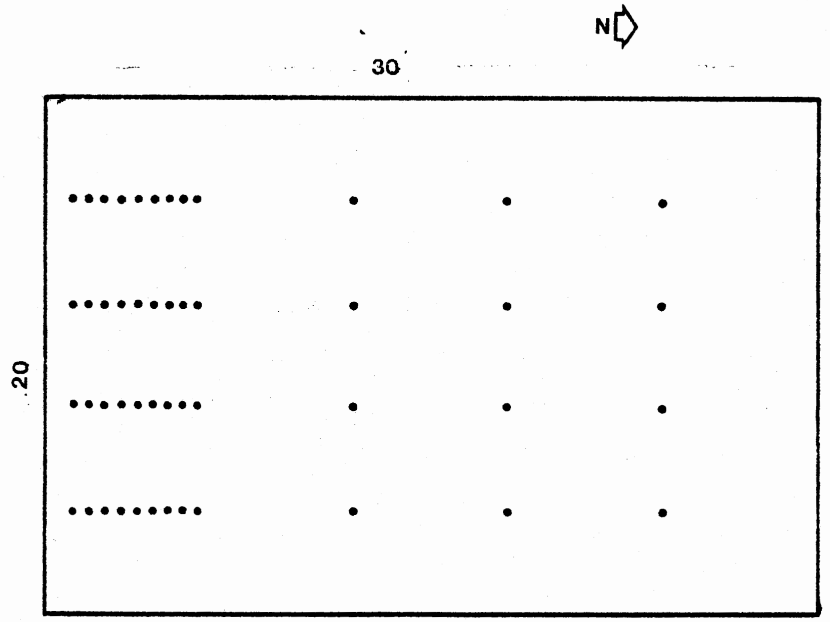


Figure 20. Analysis Points in Living Space.

At each point, the mrt was calculated utilizing solid angle fractions for each of the six bounding surfaces and their respective surface temperatures. A solid angle fraction is defined as the portion of the projected area, of the surface being examined, onto a sphere with a radius of 1. Calculating the solid angle fraction (ψ) required derivation of an equation and then programming the equation on a HP-9845B in order to minimize the calculation time. With the assistance of Professor Maxwell, of the Oklahoma State University Math Department, the following equation was developed:

$$\psi = \frac{1}{4\pi}\left[\arcsin\left(\frac{Z_1}{\sqrt{X_o^2+Z_1^2}} \bullet \frac{Y_1}{\sqrt{X_o^2+Y_1^2}}\right) - \arcsin\left(\frac{Z_o}{\sqrt{X_o^2+Z_o^2}} \bullet \frac{Y_1}{\sqrt{X_o^2+Y_1^2}}\right) + \arcsin\left(\frac{Z_o}{\sqrt{X_o^2+Z_o^2}} \bullet \frac{Y_o}{\sqrt{X_o^2+Y_o^2}}\right) - \arcsin\left(\frac{Z_1}{\sqrt{X_o^2+Z_1^2}} \bullet \frac{Y}{\sqrt{X_o^2+Y_o^2}}\right)\right] \qquad (7.1)$$

where X_o = distance along positive x-axis to surface being examined,

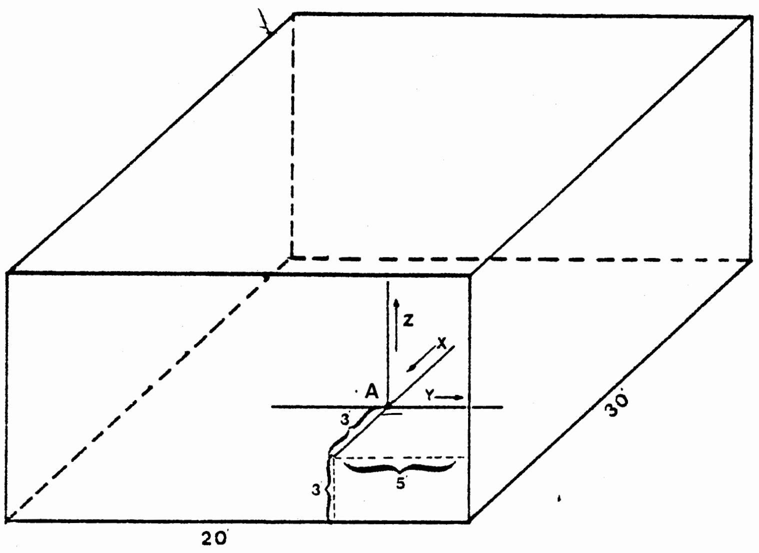
Y_o = negative distance along the negative y-axis to edge of surface,

Y_1 = distance along the positive y-axis to edge of surface,

Z_o = negative distance along the negative z-axis to bottom of surface,

Z_1 = distance along the positive z-axis to top of surface.

Example:



Determine the solid angle fraction (ω) for the front wall for point A.

$X_o = 3$ $Z_o = -3$

$Y_o = -15$ $Z = 13$

$Y_z = 5$

Inserting these values into equation 7.1 yields = 0.284. What 0.284 signifies is that the wall surface temperature is multiplied by ω to determine the contribution of the wall surface temperature to the overall mrt at point A. The same procedure was carried out for the remaining five surfaces to determine the overall mrt at point A. This procedure was completed for all of the grid points in the living space, for each parameter, on an hour-by-hour basis. There are several assumptions necessary for one to compute the mrt.

With the direct gain system the following criteria were established:

1. the surface temperature of the ceiling, north wall, and two side walls is 1° F less than air temperature due to the interior air film.
2. Tmr = ωfloor * Tfloor = ωsouth wall * Tsouth wall + 1 - (ωfl = ωsw) (Tair - 1).

   T = temperature of surface

   ω = solid angle fraction

For the Trombe wall system, the criteria was:

3. the surface temperature of the ceiling, north wall, two side walls, and floor is 1° F less than air temperature due to interior air film
4. Tmr = ωwall * Twall + 1 - ωwall * (Tair - 1)

After computing the mrt for all positions during each study hour, the comfort evaluation of each passive heating system can begin.

Determining Teu Contours

The assessment of occupant thermal comfort is accomplished by first determining the Teu at each point and then plotting contours of equal Teu in the study space. The equivalent uniform temperature is determined by solving equation 7.2.

$$\mathrm{Teu} = \left(\frac{1}{1 - S}\right) \mathrm{Tmr} + \left(\frac{S}{S-1}\right) \mathrm{Tair} \qquad (7.2)$$

where S is the slope of the comfort line. The value of S was obtained from Figure 21.[7] The slope of the comfort line is indicative of the relative importance of the mean radiant temperature and the air temperature. For example, a slope of minus 2 implies that a 1° F increase in air temperature must be compensated by a 2° F decrease in mean radiant temperature in order to maintain an optimum comfort level. In this case, air temperature is the more sensitive of the two temperatures. For this analysis, the following representative conditions were chosen: a clo value of 0.75 which represents medium weight clothing, a metabolic rate of $60\mathrm{W/m^2}$ representing sedentary work, relative humidity equal to 0.5 (50%) and air speed equal to 20 fpm typical of free convective conditions in a passive home.[7] From Figure 20, S was determined to be -1.18. Inserting S = -1.18 into equation 7.2, the solution for the Teu equation is:

$$\mathrm{Teu} = 0.46\ (\mathrm{Tmr}) + 0.54\ (\mathrm{Tair}).$$

At this point, knowing the air temperature and mrt for each grid point during the study hours, contour lines of equal Teu were generated. Figures 22 - 25 contain the contour plots for the direct gain and Trombe wall heating systems with and without nighttime insulation.

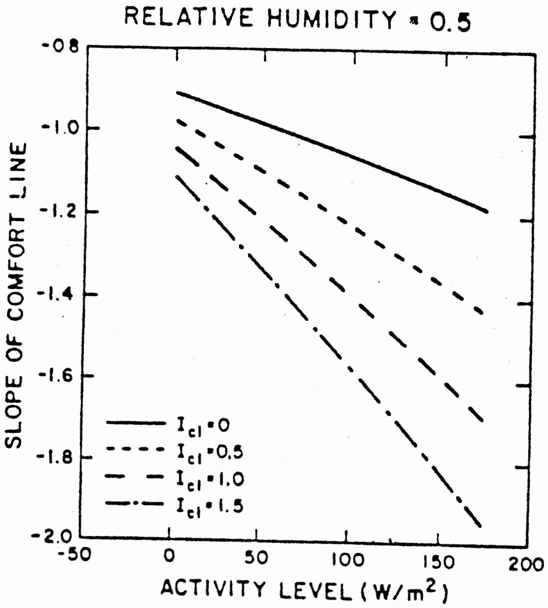
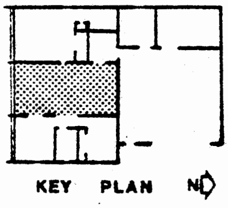
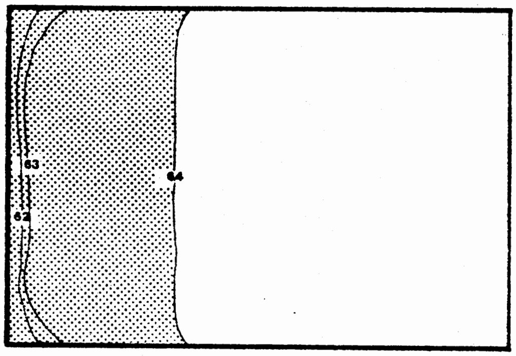


Figure 21. Comfort Line Slope at RH = 50%

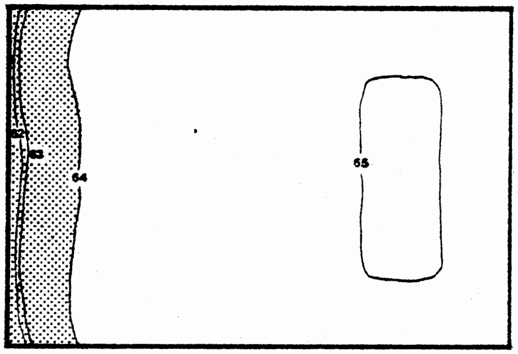
Assessment of Teu Contours

The construction of the equivalent uniform temperature contours in Figures 22-25, provided a foundation for evaluation of occupant thermal comfort in the case study space. Contour comparison of the two passive solar heating systems indicated the Trombe wall provides a more desirable comfort condition during the 24 hour simulation period. The Trombe wall consistently produced higher Teu temperatures in the living space throughout the 24 hour period and at no time did the Trombe wall produce temperatures less than air temperature. With the space heated by direct gain, there are significant areas where the Teu drops below air temperature. During early morning and late evening hours, the Teu temperature drops as low as 62° F. (Figure 22-A,B,E). The cooler temperatures associated with direct gain heating occur in a "zone" between the front glazing and approximately seven feet back. This zone contains the greatest temperature variation whether it is decreasing temperature and comfort inherent with direct gain or increasing temperature and comfort apparent with a Trombe wall. Figure 26 illustrates the zone effects of the two systems by comparing the best and worst conditions without nighttime insulation.

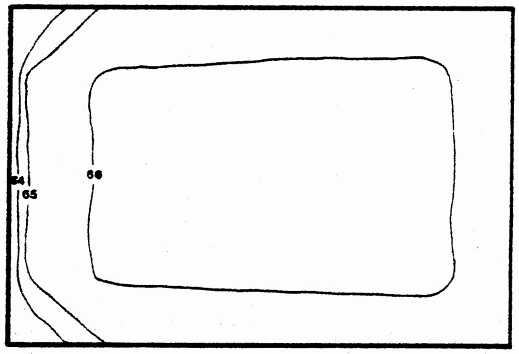




A 6 am Tair 65°F

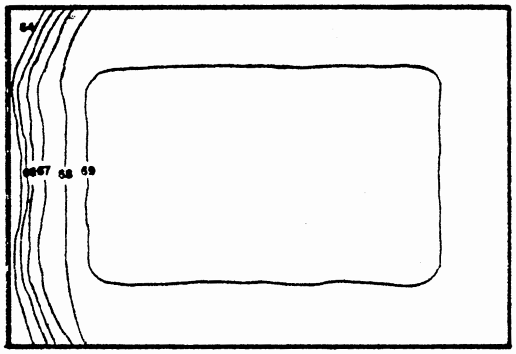


B 9 am Tair 65°F

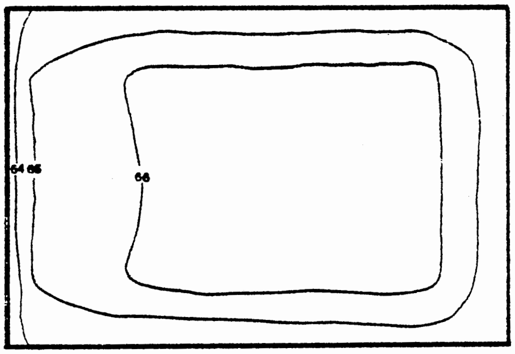


C 12 noon Tair 66.4°F

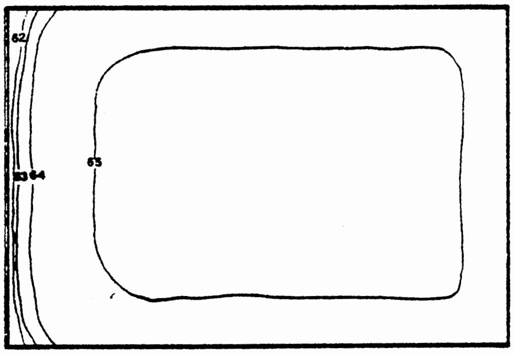
Figure 22. Equivalent Uniform Temperature (Teu) Contours for Direct Gain Heating System No Nighttime Insulation



D 3pm Tair 69°F

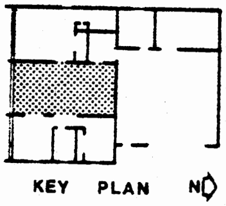


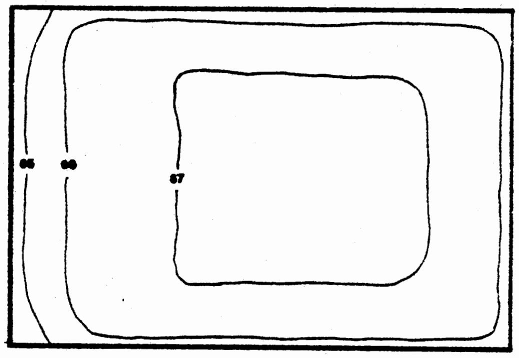
E 6 pm Tair 65.6°F



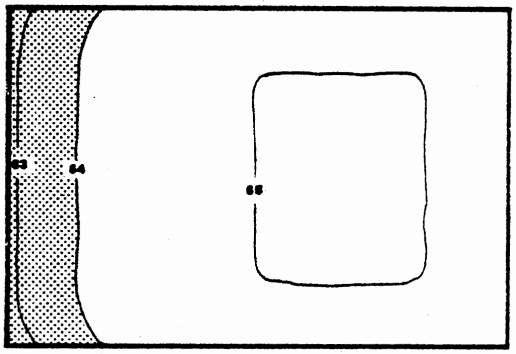
F 9pm Tair 65°F

Figure 22 (Continued)

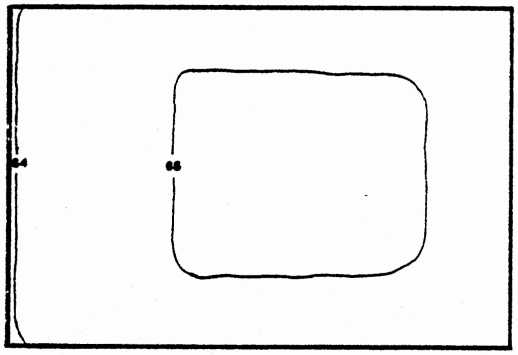




A 6 am Tair 65°F

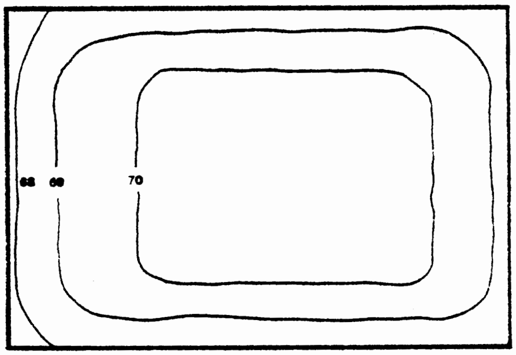


B 9 am Tair 65°F

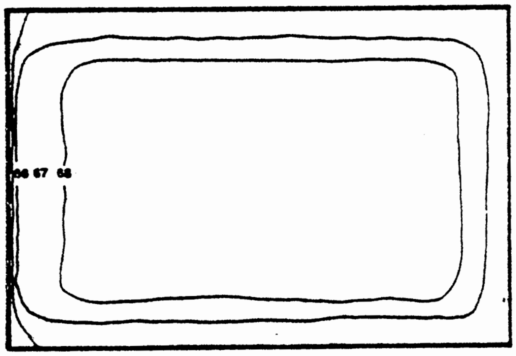


C 12 noon Tair 66.6°F

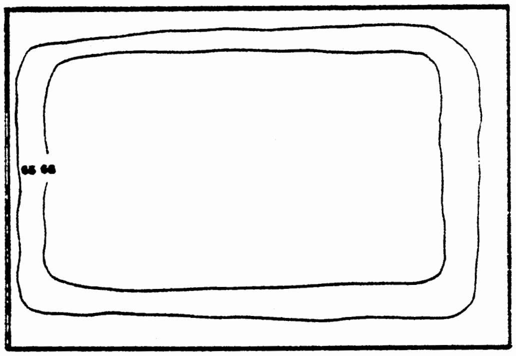
Figure 23. Equivalent Uniform Temperature (Teu) Contours for Direct Gain Heating System With R-9 Insulation.



22.D 3 pm Tair 69.5°F

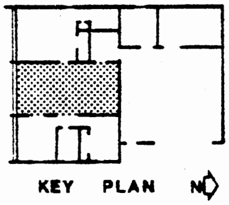


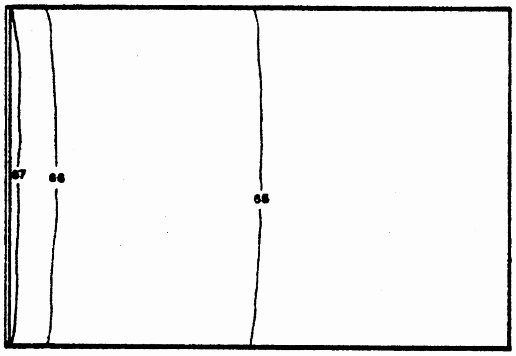
22.E 6 pm Tair 67.5°F



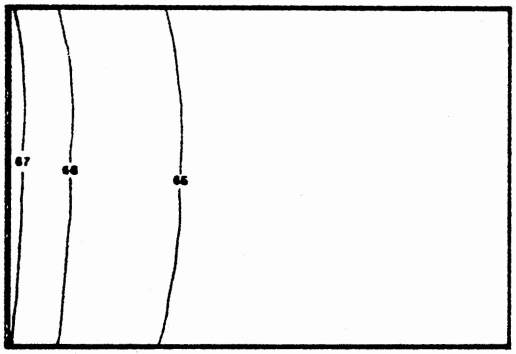
22.F 9pm Tair 65°F

Figure 23 (Continued)

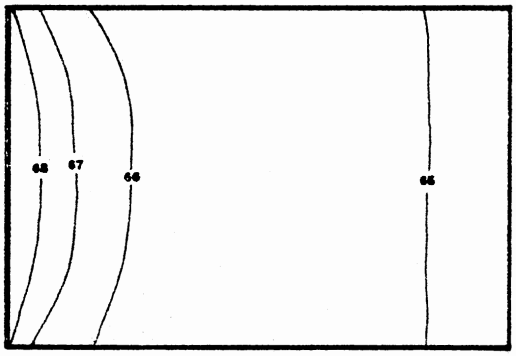




A 6 am Tair 65°F

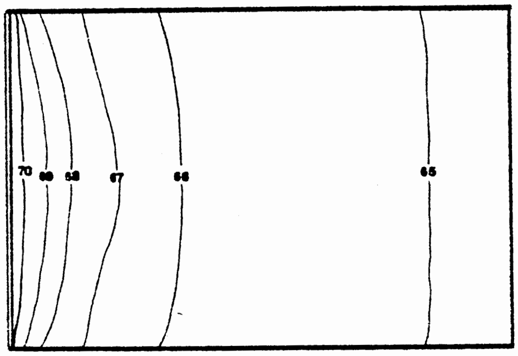


B 9 am Tair 65°F

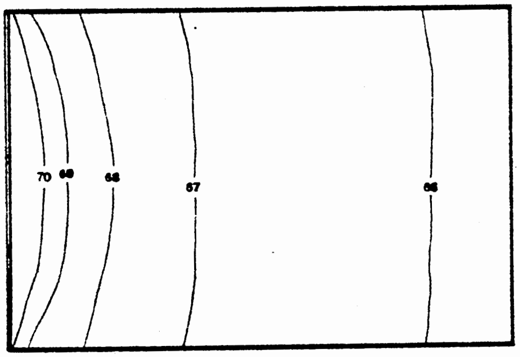


C 12 noon Tair 65°F

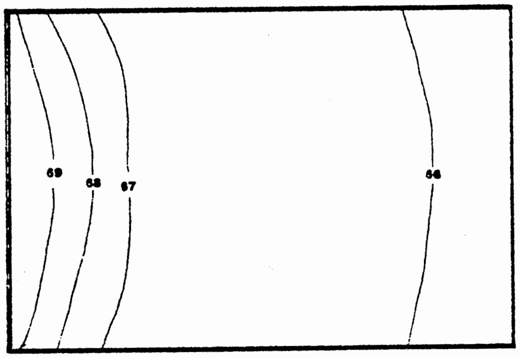
Figure 24. Equivalent Uniform Temperature (Teu) Contours For Trombe Wall Heating System - No Nighttime Insulation



D 3pm Tair 65°F

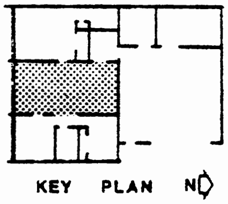


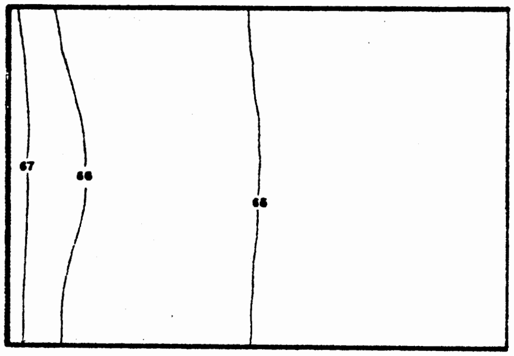
E 6 pm Tair 66°F



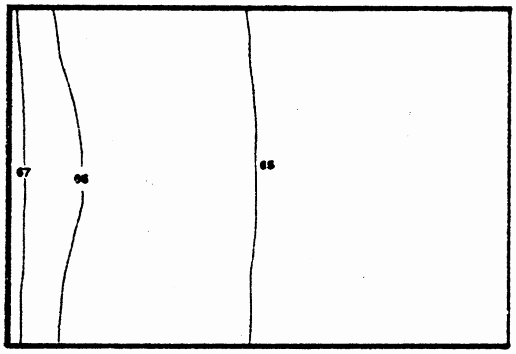
F 9 pm Tair 66°F

Figure 24 (Continued)

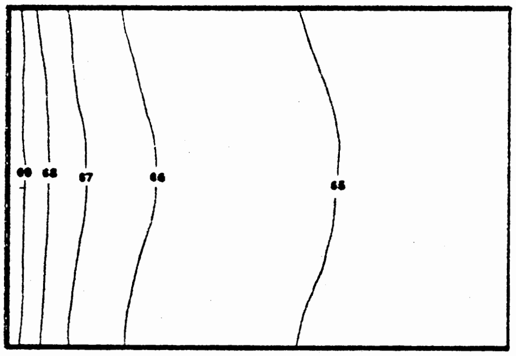




A 6 am Tair 65°F

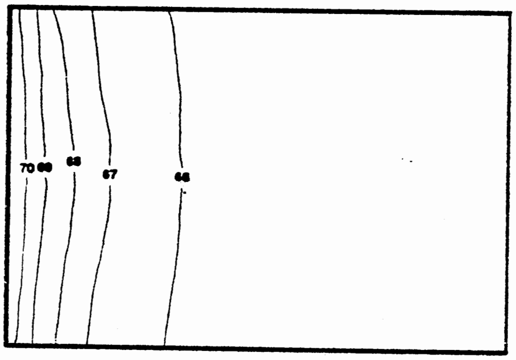


B 9 am Tair 65°F

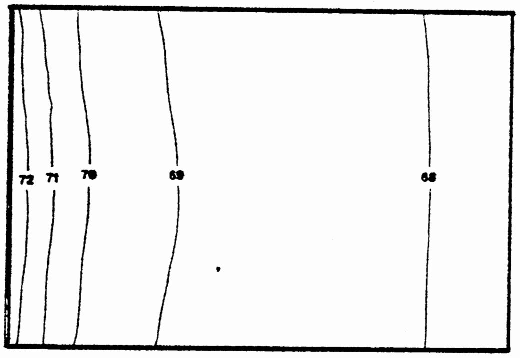


C 12 noon Tair 65°F

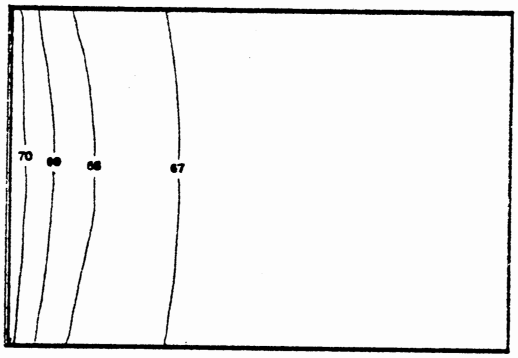
Figure 25. Equivalent Uniform Temperature (Teu) Contours for Trombe Wall Heating System With R-9 Insulation



D 3pm Tair 65°F



E 6 pm Tair 68°F



F 9 pm Tair 67°F

Figure 25 (Continued)

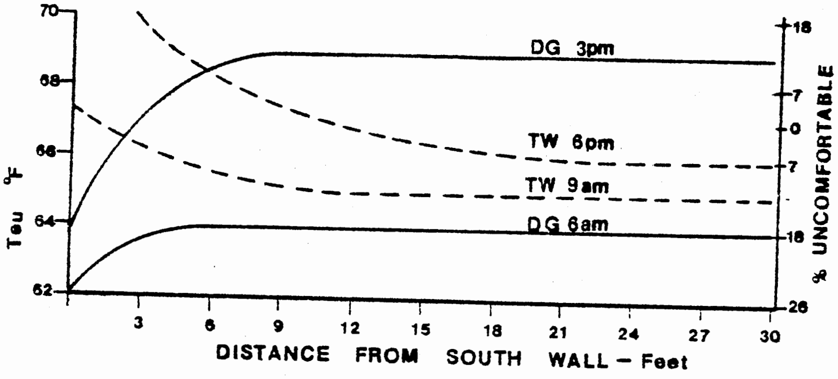


Figure 26. System Comfort Performance as a Function of Distance from South Wall Without Nightime Insulation

The critical zone is a direct result of the mean radiant temperature of the south surface being the dominant thermal contributor to the Teu temperature due to the large solid angle fraction of the south facing surface. Outside of this zone, Teu becomes relatively stable in both systems because of a lesser contribution from the south facing surface.

Parametric studies involving the addition of R-9 nighttime insulation were conducted to determine the impact of the insulation on thermal comfort. Addition of nighttime insulation to the Trombe wall system had a negligible effect on improving comfort within the study space. Nighttime insulation, located between the external environment and the Trombe wall, does not directly affect the mrt and thus any impact is not apparent when predicting thermal comfort performance.

Although nighttime insulation does not significantly affect thermal comfort of a Trombe wall, insulation does enhance the energy performance. An analysis of cost effectiveness would determine whether or not nighttime insulation is appropriate.

With a direct gain heating system, addition of nighttime insulation significantly improves the comfort conditions. Comparing contours of Figure 22 E with 23 E, the improved condition can be observed. Insulation not only improves comfort, but drastically improves the energy performance. In the northeastern region, the impact of nighttime insulation so markedly improves both the energy and comfort performance that the addition of nighttime insulation is strongly recommended for all direct gain systems. By adding insulation to the direct gain system, the comfort performance of the space begins to approach that of a Trombe wall. Figure 27 illustrates the best and worst conditions of the two heating systems with R-9 insulation. One of the factors inherent with a direct gain system is consideration of direct sun striking the occupants. Solar radiation on the occupant could improve comfort condition during daylight times when the space is below air temperature but cannot improve evening or early morning hour periods of discomfort when it is needed most. Other factors that can alter comfort predictions are: the age of occupants, the amount of clothing, raising the relative humidity, and mechanically increasing the air temperature.

Differences in age can affect the thermal comfort sensation of the occupant. It has been found that men and women over the age of 40 prefer a temperature 1° F. higher than those under the age of 40.[8] Although the difference is minimal, a designer should be aware of the occupant's needs.

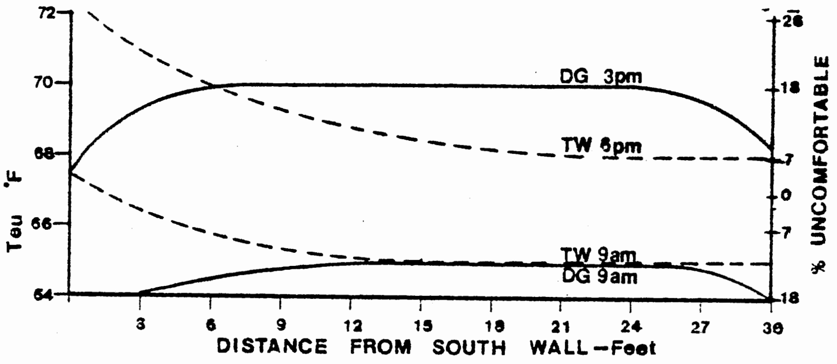
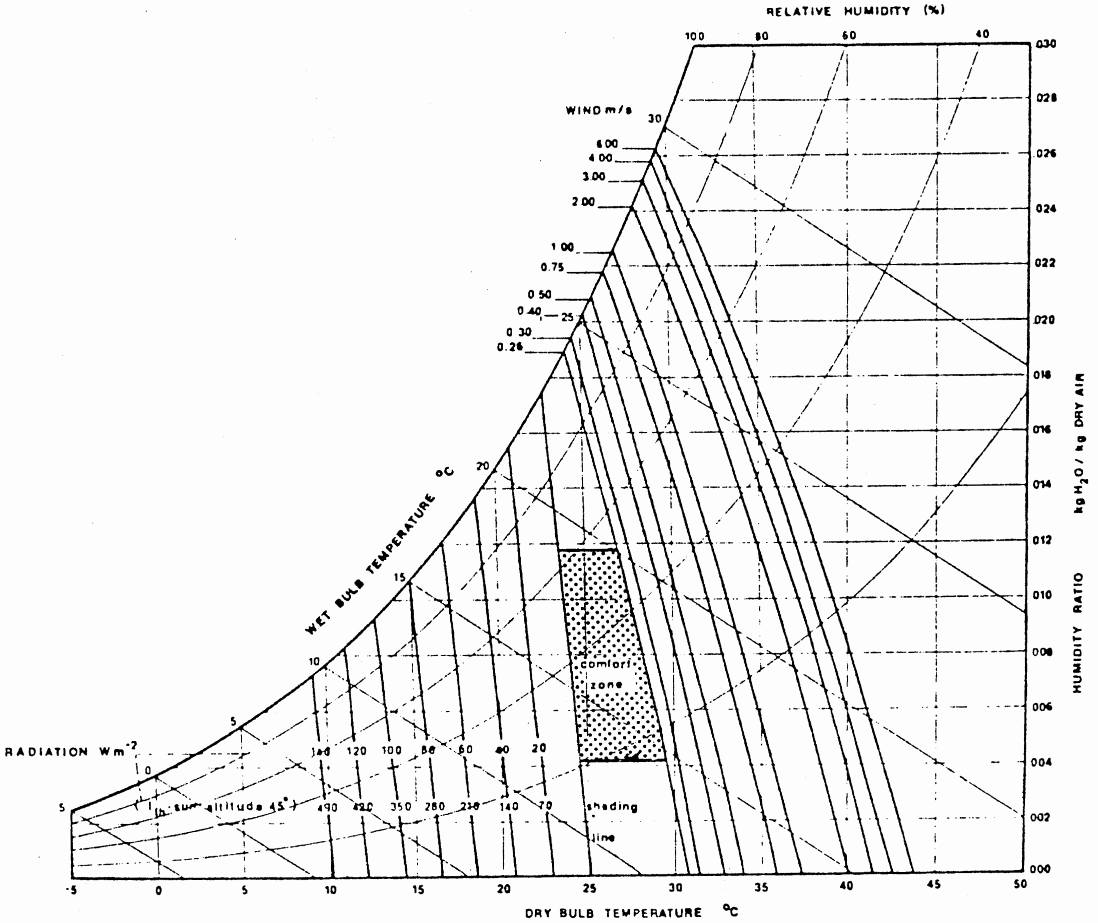


Figure 27. System Comfort Performance With Nighttime Insulation as a Function of Distance from South Wall

Adding or removing pieces of clothing allows occupants to adjust to a fluctuating environment. During periods of low temperatures, adding a sweater will increase the comfort tolerance to an otherwise unacceptable condition. Periods of discomfort due to warm temperatures can be countered by shedding long sleeve garments and donning lighter weight attire. This is a simple and often overlooked method of comfort control compatible with passive designs.

Another means of adjusting the habitability of a space without altering the mrt or ambient air temperature is by increasing the relative humidity. Figure 28 illustrates how a condition (point A), out of the comfort zone can be changed to a condition within the comfort range by adding moisture to the air. The bioclimatic chart was developed to provide architects and engineers with a basis for designing buildings which take advantage of natural forces to maintain a comfortable environment.[9] The bioclimatic chart presented on the following page is an updated version of V. Olgyay's chart developed during the humidity can produce adverse effects due to condensation on the cool glazing surface. Careful planning and using nighttime insulation can alleviate the condensation problem.



Source: E. Arens, "A New Bioclimatic Chart for Passive Solar Design" (Berkeley California, 1980).

Figure 28. Bioclimatic Chart For Passive Solar Design

The obvious, and first to come to mind, is the option of increasing the thermal comfort in a space is to increase the thermostat setting from 65° F. to a higher setting. Discussion of this alternative was reserved for a good reason. This should be the last source of comfort improvement in a passive solar building. The motive behind passive design is to decrease the dependency on mechanical control of a space. Raising the thermostat induces a greater consumption of energy and defeats the purpose of passive solar heating. In order to conserve energy and provide a habitable environment, a successful passive design should require a minimal thermostat setting to prevent extreme drops in air temperature and should allow passive solar heating systems to contribute the bulk of a building's thermal requirements. This is the whole concept behind any passive design.

FOOTNOTES

[1] J. A. Carroll, "An Index to Quantify Thermal Comfort in Residential Buildings," ASHRAE 1981 Transactions, Vol. 87 Part 1 (New York, 1981).

[2] W. Place, et. al., "Human Comfort and Auxiliary Control Considerations in Passive Solar Structures", Proceedings of the 1981 Annual AS/ISES Meeting (Phoenix, Arizona, 1980).

[3] A. Emery, "A Parametric Study of a Passive Solar-heated House with Special Attention on Evaluating Occupant Thermal Comfort", Proceedings of the 6th Passive Solar Conference (Portland, Oregon, 1981).

[4] P. O. Fanger, Thermal Comfort-Analysis and Applications in Environmental Engineering (New York, 1970).

[5] W. O. Wray " A Simple Procedure for Assessing Thermal comfort in Passive Solar Heated Buildings", Solar Energy, Vol. 25 (1980), p. 328.

[6] Ibid, p. 330.

[7] Ibid, p. 331.

[8] P. O. Fanger, Thermal Comfort-Analysis and Applications in Environmental Engineering (New York, 1970), p. 85.

[9] E. Arens, "A New Bioclimatic Chart for Passive Solar Design", AS/ISES Proceedings of the 5th National Passive Solar Conference (Amhurst, Massachusetts, 1980).

CHAPTER VIII

ECONOMIC COMPARISON

Cost Analysis

Interest in passive solar design has grown dramatically over the past several years. With this growing interest comes the need for a continued evaluation of passive solar economic performance along with thermal comfort and thermal energy performance. A secondary facet of this study is a cost analysis of the direct gain and the Trombe wall passive solar heating systems. The cost analysis is based on first cost since each of the two heating systems were balanced to require approximately the same amount of auxiliary heat input, thus having equal operating costs.

The direct gain system consists of 410 ft^2 of glazing and 1200 ft^2 of 6" concrete floor storage. The Trombe wall system consists of 310 ft^2 of 8" concrete Trombe wall and 310 ft^2 of glazing. The cost breakdown of direct gain and Trombe wall heating systems is presented in Tables V and VI.

Totalling the cost of each system provided data for an overall assessment of the two heating system. Through the economic and comfort analysis, it was determined that the direct gain system provided less desirable results in both the comfort and economic performance in the harsh northeastern climate when compared to a Trombe wall system. The substantial winter heat loss through the glazing inherent with the direct gain system and the large glazing required to provide comparable energy performance to that of a Trombe wall, resulted in the Trombe wall out-performing direct gain in all aspects of this study.

TABLE V

DIRECT GAIN COSTS

ITEM	$/FT^2
double glazing	3.25
framing	3.50*
floor slab @ 2"	0.76
R-9 insulation	4.50

* Per linear foot

TABLE VI

TROMBE WALL COSTS

ITEM	$/FT^2
double glazing	3.25
framing	3.50*
wallforms @ 8"	3.04
concrete @ 8"	3.04
R-9 insulation	4.50

* Per linear foot

Source: S. A. Noll, "Trombe Walls and Direct Gain: Patterns of Nationwide Applicability," Proceedings of the 3rd National Passive Solar Conference, San Jose, California, Jan. 1979.

TABLE VII

SYSTEM COSTS

System	No Nighttime Insulation	Nighttime Insulation
DG	$3,891.50	$5,736.50
TW	$3,452.50	$4,847.53

CHAPTER IX

SUMMARY AND CONCLUSIONS

Summary of Procedure

Two passive solar heating systems; direct gain and a Trombe wall were balanced so that the systems require the same amount of auxiliary heat input for a typical January day. The two systems were modeled in a case study passive home. A comfort analysis of the two comparable systems, during the 24-hour simulation period, was completed to determine which system provides the most habitable conditions. Detailed calculation and input values were documented to enable a better understanding of the procedure of comfort analysis. To provide an overall assessment of the two passive solar heating systems, an economic analysis based on first cost was conducted.

Parametric studies concerning the impact of nighttime insulation on occupant comfort were also examined. The study dealt totally with the heating mode of a passive solar case study residence in the northeast.

Summary of Findings

In both investigations, economic and comfort, the Trombe wall provided superior performance. The Trombe wall cost less to install due to the fact that the Trombe wall was more efficient in converting solar energy into space energy and thus required less glazing and wall storage material. Comfort performance of the Trombe wall contributed to better habitability within the case study residence than the direct gain system.

Parametric studies involving the use of nighttime insulation showed that the use can have a significant impact on improving the comfort conditions of the direct gain system but had a negligible effect on improving the comfort provided with the Trombe wall system. Due to the harsh climate and improved energy performance, nighttime insulation should be utilized anytime there is any expanse of glazing.

Conclusions

With rising energy costs, passive solar heating becomes a viable means of reducing the nonrenewable energy consumption of residences. Until recently, only energy performance was analyzed, but now comfort performance has arisen as criterion for system selection. This study examined two comparable passive solar heating systems, direct gain and Trombe wall, for comfort performance and economic costs.

It was found that the Trombe wall provided a larger comfort range at a lower initial cost. It is felt that in the northern latitudes, the Trombe wall system achieves better overall performance than the direct gain. An optimum solution may involve a combination of direct gain with a Trombe wall. The knowledge of comfort requirements and factors affecting occupant comfort is essential in the design field.

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APPENDIX A

HEAT LOSS CALCULATIONS

A- 1 CONSTRUCTION U - VALUES

EXPOSED SURFACES

Wall -

	R - Value
external air film	0.17
3/4" sheathing	0.93
1/2" celotex	1.32
6" fiberglass batt	19.00
1/2" gypsum	0.45
internal air film	0.68
	R = 22.55

$$U - \text{Value} = \frac{1}{R} = 0.044$$

Roof -

external air film	0.17
asphalt shingle	0.21
3/4" plywood	0.93
12" fiberglass batt	38.00
1/2" gypsum	0.45
internal air film	0.61
	R = 40.37

$$U - \text{Value} = \frac{1}{R} \quad 0.025$$

Glass -

triple pane with modification for wood frame
U = (0.31) (0.95) = 0.29

double pane with modifier
U = (0.49) (0.90) = 0.44

Door -

wood with storm door
U = 0.34

Source: ASHRAE, 1977 Handbook of Fundamentals, Chapter 22, Design Heat Transfer Coefficients American Society Heating, Refrigerating, and Air-Conditioning Engineers, (New York, 1977)

A-2 HEAT LOSS CALCULATIONS

PARAMETER 1 DIRECT GAIN - NO NIGHTTIME INSULATION

1. Heat loss through exposed surfaces
   Door = (0.34) (21 Ft^2) = 7.14 Btuh/^{o}F
   Roof = (0.025) (1540) = 38.5 Btuh/^{o}F
   Wall = (0.044) (1204.5) = 53 Btuh/^{o}F
   E & W Glazing = (0.29) (36) = 10.44 Btuh/^{o}F

   Total without south glazing = 109.1 Btuh/^{o}F
   Glazing = (410) (0.44) = 180.4 Btuh/^{o}F
   Clerestory = (54) (0.44) = 23.76 Btuh/^{o}F

2. Infiltration Losses
   1/2 air change/hour
   Volume = 19110 Ft^3
   1.1 (19,110)/60 x 2 = 172 Btuh/^{o}F

3. Slab edge loss
   edge loss factor = 40 Btuh/Ft
   exposed length = 160 Ft
   Total loss = 160 (40) = 6400 Btuh

4. Heat Loss Summary
   edge loss = 6400 Btuh
   exposed surfaces and infiltration losses = 485.26 Btuh/^{o}F
   internal heat gain = 2000 Btuh

HOURLY LOSSES

				Daytime				
Time	12am	3am	6am	9am	12noon	3pm	6pm	9pm
Loss (Btuh)	22,000	23,460	24,924	23,950	22,285	21,260	21,260	21,360

PARAMETER 2 DIRECT GAIN - R-9 NIGHTTIME INSULATION

1. Heat losses through exposed surfaces
   same as parameter 1
   Total losses without glazing = 132.9 Btuh/^{o}F

   Glazing losses with R-9 insulation = 37.3 Btuh/^{o}F
   Glazing losses without insulation = 180.4 Btuh/^{o}F

2. Infiltration Losses = 172 Btuh/^{o}F

3. Slab edge loss = 6400 Btuh

4. Heat loss summary
edge loss = 6400 Btuh
exposed surfaces No Nighttime insulation = 485.3 Btuh/^{o}F
R-9 Nighttime insulation = 342.2 Btuh/^{o}F
internal heat gain = 2000 Btuh

HOURLY LOSSES

				Daytime				
Time	12am	3am	6am	9am	12noon	3pm	6pm	9pm
Loss (Btuh)	15,386	16,411	17,437	23,950	22,285	21,260	14,872	14,941

PARAMETER 3 TROMBE WALL - NO NIGHTTIME INSULATION

1. Heat losses through exposed surfaces
Total losses excluding glazing = 132.9 Btuh/^{o}F

Glazing Losses @ 330 ft^{2}

(330) (0.4) = 132.0 Btuh/^{o}F

2. Infiltration losses = 172 Btuh/^{o}F

3. Slab Edge Loss = 6400 Btuh

4. Heat Loss Summary
edge loss = 6400 Btuh
exposed surfaces = 437.0 Btuh/^{o}F
internal heat gains = 2000 Btuh

				Daytime				
Time	12am	3am	6am	9am	12noon	3pm	6pm	9pm
Loss (Btuh)	20,052	21,390	22,726	21,834	19,606	17,380	18,270	19,161

PARAMETER 4 TROMBE WALL WITH R-9 NIGHTTIME INSULATION

1. Heat loss through exposed surfaces
Total losses excluding glazing = 132.9 Btuh/^{o}F

Glazing losses without nighttime insulation = 132.0 Btuh/^{o}F
Glazing losses with R-9 nighttime insulation = 30 Btuh/^{o}F

2. Infiltration losses = 172 Btuh/^{o}F

3. Slab edge loss = 6400 Btuh

4. Heat Loss Summary
   edge loss = 6400 Btuh
   exposed surfaces - no insulation = 485.3 Btuh/^{o}F
   R-9 insulation = 334.9 Btuh/^{o}F

				Daytime				
Time	12am	3am	6am	9am	12noon	3pm	6pm	9pm
Loss (Btuh)	14,026	14,962	15,900	21,834	19,606	17,380	13,500	14,060

APPENDIX B

INPUT AND OUTPUT PEGFIX DATA

B-1 DATA INPUT DESCRIPTIONS

UA day, UA night (BTU/hr ^{o}F) - the total hourly heat loss from the study home for one degree difference between inside and outside air temperatures, during daytime and nighttime hours respectively.

MC sto, (BTU/^{o}F) - the total effective heat capacity of all thermal storage mass capable of collecting and storing thermal energy; storage material is broken down into two categories:

Mc pri - primary storage (receives direct sunlight)

Mc sec - secondary storage (receives little or no direct sunlight

f sto, f air - Proportion of incoming solar radiation.

f sto = (sto) (x) (P-sto)

f air = (air) (x) (P-air)

where x is absorptivity coefficient and P is amount of solar radiation transmitted through glazing which strikes storage

T min, T max - minimum (65^{o}F) and maximum (80^{o}F) interior air temperature limits

T sto (^{o}F) - initial storage temperature for an accurate simulation, the final T sto should be within one degree of initial T sto

T vent (^{o}F) - venting temperature when T vent =0 then venting is assumed to be to the outside air

T avg (^{o}F) - average ambient outside air temperature = 20^{o} F

T swing (^{o}F) - outside air temperature range = 12^{o} F

Ag (ft^{2}) - area of unshaded glazing. Set to zero if inputing I hour

S day (Btu/ft^{2}) - amount of ratiation received through one square foot of collector area. Set to zero if inputing I hour.

L day - number of daylight hours per day. Number of hours used is 9.

I hour (Btuh) - total hourly radiation input through glazing. Based on daily total from E. Mazria, The Passive Solar Energy Book, p.391

B-2 INPUT CALCULATIONS

Trial 1 Direct Gain Maximum Aperture = 410 ft^2

1) Mc sto:

Mc sto = (Volume) (Capacitance) (Effective-Factor)
The effectiveness factor is determined by executing routine "B" of the PEGFIX program.

Available storage
  Interior bearing wall - 8" concrete
  Floor slab - 6" concrete

Primary storage
  Floor slab 805 Ft^2/403 Ft^3
  Bearing Walls 278 Ft^2/186 Ft^3

Secondary storage
  floor slab 200 Ft^2/100Ft^3
  Bearing Walls 565 Ft^2/380Ft^3

Mc pri = (403) (30) (0.79) = 186 (30) (0.63)
Mc pri = 13066
Mc sec = 1/3 * (380) (30) (0.63) + (100) (30) (0.79)
       = 3184
Mcsto = 16250

2) UA sto

UA sto = (1.5) (area of prim. sto) + (0.3) (area of sec sto)
       = (1.5) (1083) + (.3) (765)
       = 1854

3) UA day/UA night - Σ of losses + gains

average day 8 am - 4 pm - 9 hours
average night 5 pm - 7 am - 15 hours

UA day = 488.7 BTU/^{o}F
UA night = 341.9 BTU/^{o}F

4) I hour = glazing area x radiation/Ft^2

8 am -	14,303	4 pm -	14,303
9 am -	33,064	3 pm -	33,064
10 am -	45,923	2 pm -	45,923
11 am -	57,090	1 pm -	57,090
12 am -	59,400		

radiation/ft^2 - for New York City

8 am -	53	4 pm -	53
9 am -	113	3 pm -	113
10 am -	151	2 pm -	151
11 am -	173	1 pm -	173
12 am -	180		
		TOTAL	1160

Source: E. Mazria, <u>The Passive Solar Energy Book</u>, Emmaus, PA p. 391.

Trial 2 Trombe Wall Systems -Maximum Aperture - 410 ft^2

1) Mc sto
   Available storage
     Trombe wall - 8"
     Interior Bearing Wall - 8"
   Primary storage
     Trombe wall $398ft^2/265ft^3$
   Secondary storage
     internal wall $843ft^2/265ft^3$

   Mc pri = (265) (30) (0.79)
   = 6,281
   MC sec = (565) (30) (0.79) (33)
   = 4,463
   Mc sto = 6281 + 4463
   =10,744

2) UA sto = (1.5) (398) + .2(843)
   = 766

3) UA day/UA night same as trial 1
   UA day = 488.7 BTU/°F
   UA night = 341.9 BTU/°F * R-9 night insulation

4) I hour - same as trial 1
   8 am - 14,303   4 pm - 14,303
   9 am - 33,064   3 pm - 33,064
   10 am - 45,923   2 pm - 45,923
   11 am - 57,090   1 pm - 57,090
   12 am - 59,400

Trial 3 Direct Gain -97% of maximum aperture = 398 ft^2

1) Mc sto = 15,763

2) UA sto = 1854 x .97
   = 1,798

3) UA day/UA night - same as trial 1
   UA day =474.6 BTU/°F
   UA night = 336.2

4) I hour
   8 am - 13,874   4 pm - 13,874
   9 am - 32,072   3 pm - 32,072
   10 am - 44,545   2 pm - 44,545
   11 am - 55,377   1 pm - 55,377
   12 am - 57,618

Trial 4 Trombe wall - 90% of maximum aperture = 310 ft^2

1) Mc sto
= 6281 x 9 + 4463
=10,116

2) UA sto
=(1.5) (360) + .2 (843)
= 708

3) UA day/UA night
UA day = 470.8 BTU/°F
UA night = 329.1 BTU/°F * R-9 insulation

4) I hour - 360 Ft^2 glazing
8 am - 12,873 - 4 pm
9 am - 29,758 - 3 pm
10 am - 41,331 - 2 pm
11 am - 51,381 - 1 pm
12 am - 53,460

Trial 5 Trombe wall 80% of maximum aperture = 320 ft^2

1) Mc sto
= 6,281 (.8) + 4463
= 9,488

2) UA sto
= (1.5) (320) + .2(843)
= 649

3) UA day/UA night
UA day = 445.6 BTU/°F
UA night = 311.7 BTU/°F * R-9 insulation

4) I hour - (320 Ft^2 glazing)
8 am - 11,442 - 4 pm
9 am - 26,451 - 3 pm
10 am - 36,738 - 2 pm
11 am - 45,672 - 1 pm
12 am - 47,520

Trial 6 Direct Gain 400 Ft^2 aperture

1) Mc sto -same as trial 1
=16,250

2) UA sto -same as trial 1
= 1,854

3) UA day/UA night
(heat loss factor constant during night and day)
UA day = 488.7 BTU/°F
UA night = 488.5 BTU/°F

4) I hour - same as trial 1
8 am - 14,383 - 4 pm
9 am - 33,864 - 3 pm
10 am - 45,923 - 2 pm
11 am - 47,890 - 1 pm
12 am - 59,400

Trial 7 Trombe wall (320 Ft^2) - no insulation

1) Mc sto - same as trial 5
=9,488

2) UA sto - same as trial 1
= 649

3) UA day/UA night - (heat loss factor constant)
UA day = 445.6 BTU/^{o}F
UA night = 445.6 BTU/^{o}F

4) I hour - same as trial 5
8 am - 11,442 - 4 pm
9 am - 26,451 - 3 pm
10 am - 36,738 - 2 pm
11 am - 45,672 - 1 pm
12 am - 47,520

PAGE ___ OF ___ PAGES **PEGFIX PEGFLOAT User Worksheet**

INPUT VALUES				I_{hour} (hourly radiation rate)			
				hour	value	hour	value
UA_{day}	488.7	A_g	0	8	14303	1	57090
UA_{night}	341.9	S_{day}	0	9	33064	2	45923
MC_{sto}	16250	L_{day}	9	10	45923	3	33064
UA_{sto}	1854	T_{avg}	20	11	57090	4	14303
f_{sto}	0.70	T_{swing}	12	12	59400		
f_{air}	0.21	T_{min}	65				
T_{sto}	71	T_{max}	80				
		T_{vent}	0	Total Daily S_{day}			

HOURLY RESULTS									
Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	70.4	6,090		13	68.3	75.0		
2	65	69.8	7,440		14	69.3	76.5		
3	65	69.3	8540		15	69.5	77.3		
4	65	68.8	9,390		16	68.8	77.4		
5	65	68.4	10,000		17	68.2	76.6		
6	65	68	10,500		18	67.5	75.7.		
7	65	67.7	10700		19	67.1	74.8		
8	65	67.7	16200		20	66.7	74.0		
9	65	68.4	12000		21	65.7	73.1		
10	65	69.6	6660		22	65	72.2	620	
11	65	71.2	1140		23	65	71.4	2730	
12	66.6	73.1			24	65	70.7	4620	

DAILY TOTALS	
T_{air}	
T_{sto}	
Q_{loss}	440000
Q_{ex}	
Q_{aux}	-107 000
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	-16200

NOTES:

DIRECT GAIN
R-9 NIGHT INSULATION
MAX GLAZING (410 FT^2)

PROJECT: ______________________ TRIAL #: 1 By:
LOCATION: ______________________ DATE:

PAGE __OF__PAGES

PEGFIX PEGFLOAT User Worksheet

INPUT VALUES				I_{hour} (hourly radiation rate)			
UA_{day}	488.7	A_g	0	hour	value	hour	value
UA_{night}	341.9	S_{day}	0	8	14303	1	57090
MC_{sto}		L_{day}	9	9	33064	2	45923
UA_{sto}	766	T_{avg}	20	10	45923	3	33064
f_{sto}	0.95	T_{swing}	12	11	57090	4	14303
f_{air}	0.0	T_{min}	65	12	59400		
T_{sto}	85	T_{max}	80				
		T_{vent}	0	Total Daily S_{day}			

HOURLY RESULTS									
Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	83.6	1890		13	65	91	2170	
2	65	82.3	3100		14	65.6	93.6		
3	65	81.1	4110		15	67.3	95.2		
4	65	80.0	4920		16	68.3	95.4		
5	65	79.0	5550		17	68.2	94.1		
6	65	78.0	6020		18	72.7	92.6		
7	65	77.1	6340		19	71.4	91.2		
8	65	76.9	13400		20	70.0	89.7		
9	65	78.1	12800		21	68.5	88.3		
10	65	80.6	11200		22	67.0	86.8		
11	65	83.9	8590		23	65.6	85.3	941	
12	65	87.6	5450		24	65	84		

DAILY TOTALS	
T_{air}	
T_{sto}	
Q_{loss}	440 000
Q_{ex}	
Q_{aux}	− 86400
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	13400

NOTES:

TROMBE WALL
R-9 INSULATION
MAX. AMOUNT OF GLAZING

PROJECT: __________ TRIAL #: II By:

LOCATION: __________ DATE:

PAGE ___OF___PAGES

PEGFIX PEGFLOAT User Worksheet

INPUT VALUES				I_{hour} (hourly radiation rate)			
UA_{day}	474.6	A_g	0	hour	value	hour	value
UA_{night}	336.2	S_{day}	0	8	13874	1	55377
MC_{sto}	15763	L_{day}	9	9	32072	2	44545
UA_{sto}	1798	T_{avg}	20	10	44545	~~4~~3	32072
f_{sto}	.70	T_{swing}	12	11	55377	4	13874
f_{air}	.21	T_{min}	65	12	57618		
T_{sto}	70	T_{max}	80				
		T_{vent}	0	Total Daily S_{day}			

HOURLY RESULTS

Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	69.2	9540		13	67.7	74.3		
2	65	68.8	10400		14	68.7	75.8		
3	65	68.4	11100		15	68.8	76.6		
4	65	68.0	11500		16	68.7	76.6		
5	65	67.7	11800		17	68.6	75.8		
6	65	67.4	11900		18	67.9	75		
7	65	67.1	17300		19	67	74.1		
8	65	67.2	13100		20	66	73.2		
9	65	67.9	7810		21	65.1	72.3		
10	65	69.1	2360		22	65	71.6	1950	
11	65	70.7			23	65	70.8	3920	
12	66.1	72.5			24	65	70.2	5680	

DAILY TOTALS

T_{air}	
T_{sto}	
Q_{loss}	437000
Q_{ex}	
Q_{aux}	-127000
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	-17,300

NOTES:

DIRECT GAIN
97% GLAZING
R-9 NIGHT INSULATION

PROJECT: ______________________ TRIAL #: 3 By:

LOCATION: ______________________ DATE:

PAGE ___OF___PAGES

PEGFIX PEGFLOAT User Worksheet

INPUT VALUES				I_{hour} (hourly radiation rate)			
				hour	value	hour	value
UA_{day}	470.3	A_g	0	8	12873	1	51381
UA_{night}	329.1	S_{day}	0	9	29758	2	41331
MC_{sto}	10,116	L_{day}	9	10	41331	3	29758
UA_{sto}	708	T_{avg}	20	11	51381	4	12873
f_{sto}	0.95	T_{swing}	12	12	53460		
f_{air}	0.00	T_{min}	65				
T_{sto}	84.0	T_{max}	80				
		T_{vent}		Total Daily S_{day}			

HOURLY RESULTS

Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	82.7	3110		13	65	90		
2	65	81.5	4170		14	65	92.5		
3	65	80.4	5050		15	66	93.9		
4	65	79.4	5740		16	66.8	94.0		
5	65	78.4	6270		17	69.3	92.8		
6	65	77.5	6640		18	71.2	91.3		
7	65	76.6	6880		19	69.9	89.9		
8	65	76.4	13600		20	68.5	88.4		
9	65	77.6	11500		21	67.0	87.0		
10	65	80.0	9160		22	65.5	85.5		
11	65	83.2	6320		23	65	84.1	937	
12	65	86.7	3370		24	65	83.0	2360	

DAILY TOTALS	
T_{air}	
T_{sto}	
Q_{loss}	419000
Q_{ex}	
Q_{aux}	-98,800
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	13600

NOTES:

TROMBE WALL
R-9 INSULATION
90% GLAZING (360)FT²

PROJECT: __________ TRIAL #: 4 By:
LOCATION: __________ DATE:

PAGE ___ OF ___ PAGES

PEGFIX PEGFLOAT User Worksheet

INPUT VALUES				I_{hour} (hourly radiation rate)			
UA_{day}	445.6	A_g	0	hour	value	hour	value
UA_{night}	311.7	S_{day}	0	8	11442	1	45672
MC_{sto}	9,488	L_{day}	9	9	26451	2	36738
UA_{sto}	649.0	T_{avg}	20	10	36738	3	26451
f_{sto}	0.95	T_{swing}	12	11	47520	4	11442
f_{air}	0.0	T_{min}	65	12	47520		
T_{sto}	83	T_{max}	80				
		T_{vent}	0	Total Daily S_{day}			

HOURLY RESULTS

Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	81.8	4010		13	65	88.9	4290	
2	65	80.7	4920		14	65	91.3	1960	
3	65	79.7	5670		15	65	92.6	271	
4	65	78.7	6250		16	65	92.6		
5	65	77.8	6680		17	65.5	91.4		
6	65	76.9	6970		18	67.3	90.0		
7	65	76.1	7140		19	69.8	88.5		
8	65	76.0	13400		20	68.5	87.1		
9	65	77.1	12900		21	67.1	85.7		
10	65	79.3	11500		22	65.7	84.3	753	
11	65	82.4	9410		23	65.0	83.1	2100	
12	65	85.7	6900		24	65.0	82.0	3340	

DAILY TOTALS	
T_{air}	
T_{sto}	
Q_{loss}	393000
Q_{ex}	
Q_{aux}	-108000
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	13400

NOTES:

TROMBE WALL
R-9 INSULATION
80% GLAZING (320FT^2)

PROJECT: ____________________ TRIAL #: 5 By:

LOCATION: ____________________ DATE:

PAGE ___OF___PAGES

PEGFIX PEGFLOAT User Worksheet

INPUT VALUES				I_{hour} (hourly radiation rate)			
UA_{day}	488.7	A_g	0	hour	value	hour	value
UA_{night}	488.7	S_{day}	0	8	14303	1	57090
MC_{sto}	16250	L_{day}	9	9	33064	2	45923
UA_{sto}	1854	T_{avg}	20	10	45923	3	33064
f_{sto}	.70	T_{swing}	12	11	57090	4	14303
f_{air}	.21	T_{min}	65	12	59000		
T_{sto}	70	T_{max}	80				
		T_{vent}		Total Daily S_{day}			

HOURLY RESULTS

Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	69.5	15300		13	68.1	74.7		
2	65	69.0	16500		14	69.1	76.2		
3	65	68.5	17500		15	69.3	77.1		
4	65	68.2	18100		16	68.6	77.1		
5	65	67.8	18500		17	67	76.3		
6	65	67.5	18700		18	65.6	75.2		
7	65	67.2	18700		19	65	74.1	1330	
8	65	67.3	17000		20	65	73.1	4000	
9	65	68	12700		21	65	72.2	6520	
10	65	69.3	7320		22	65	71.4	8870	
11	65	70.9	1730		23	65	70.7	11000	
12	66.4	72.8			24	65	70.1	13000	

DAILY TOTALS	
T_{air}	533000
T_{sto}	
Q_{loss}	
Q_{ex}	
Q_{aux}	207000
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	18700

NOTES:

DIRECT GAIN
NO INSULATION
410 FT² GLAZING

PROJECT: __________ TRIAL #: 6 By:
LOCATION: __________ DATE:

PAGE ___OF___PAGES **PEGFIX PEGFLOAT User Worksheet**

INPUT VALUES				I_{hour} (hourly radiation rate)			
UA_{day}	445.6	A_g	0	hour	value	hour	value
UA_{night}	445.6	S_{day}	0	8	11442	1	45672
MC_{sto}	9,488	L_{day}	9	9	26451	2	36738
UA_{sto}	649	T_{avg}	20	10	36738	3	26451
f_{sto}	0.95	T_{swing}	12	11	45672	4	11442
f_{air}	0.0	T_{min}	65	12	47520		
T_{sto}	80	T_{max}	80				
		T_{vent}		Total Daily S_{day}			

HOURLY RESULTS

Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}	Hour	T_{air}	T_{sto}	Q_{aux}	Q_{ex}
1	65	79	12700		13	65	87.6	5150	
2	65	78.1	13500		14	65	90.1	2760	
3	65	77.2	14200		15	65	91.5	148	←1020
4	65	76.4	14600		16	65	91.6	296	
5	65	75.7	14800		17	65	90.4	1430	
6	65	74.9	14900		18	65	88.7	3000	
7	65	74.3	14800		19	65	87.2	4600	
8	65	74.2	14600		20	65	85.7	6190	
9	65	75.5	14000		21	65	84.3	7750	
10	65	77.8	12600		22	65	83	9230	
11	65	81.0	10400		23	65	81.9	10600	
12	65	84.4	7820		24	65	80.7		

DAILY TOTALS	
T_{air}	
T_{sto}	
Q_{loss}	478000
Q_{ex}	
Q_{aux}	-211000
$Q_{loss\ max}$	
CFM max	
$Q_{aux\ max}$	-14900

NOTES:

TROMBE WALL
No INSULATION
320FT² GLAZING

PROJECT: ________________ TRIAL #: 7 By:

LOCATION: ________________ DATE:

APPENDIX C

COMPUTER PROGRAMS AND OUTPUT

C-1 SOLID ANGLE COMPUTATION PROGRAM

```
1      REM ---CALCULATION OF MEAN RADIANT TEMPERATURE PERCENTAGES
2      REM --- PROGRAM BY JOHN W. ZANG
3      REM --- MASTERS THESIS   FALL 1981
20     PRINT PAGE
30     FOR I=1 TO 3
40     FOR J=1 TO 2
50     ON I GOSUB X,Y,Z
60     NEXT J
70     NEXT I
80     GOTO Calculate
90 X:    IF J=2 THEN 150
100 DISP "ENTER X"&VAL$(J-1);
110    INPUT X(J-1)
120    RETURN
130 Y:   DISP "ENTER Y"&VAL$(J-1);
140    INPUT Y(J-1)
150    RETURN
160 Z:   DISP "ENTER Z"&VAL$(J-1);
170    INPUT Z(J-1)
180    RETURN
190 Calculate:  !
200    Den1=SQR(X(0)^2+Z(1)^2)
210    Den2=SQR(X(0)^2+Y(1)^2)
220    Den3=SQR(X(0)^2+Z(0)^2)
230    Den4=SQR(X(0)^2+Y(0)^2)
240    P=1/(4*PI)*(ASN(Z(1)/Den1*Y(1)/Den2)-ASN(Z(0)/Den3*Y(1)/Den2)+ASN(Z(0)/Den
3*Y(0)/Den4)-ASN(Z(1)/Den1*Y(0)/Den4))
250    PRINT P*100;"%"
260    PRINT "REMAINING WALLS CONTRIBUTE";(1-P)*100;"%"
261    GOTO 30
520    END
```

C-2 TOTAL EQUIVALENT UNIFORM TEMPERATURE PROGRAM

```
1      REM --- CALCULATION OF Teu
2      REM --- PROGRAM BY JOHN W. ZANG
3      REM --- MASTERS THESIS   FALL, 1981
10     GOTO Equation
20 Equation:        !
30     Z=0
40     SHORT Teu(40)
41     PRINTER IS 0
50     DISP "INPUT THE TIME TO BE CHECKED, use solar time, i.e. 12:30,
60     INPUT Hour$
70     PRINT "          THE TIME CHECKED IS ";Hour$
80     DISP "INPUT VALUE OF - X";
90     INPUT X
100    DISP "INPUT VALUE OF - Y";
110    INPUT Y
120    DISP "INPUT VALUE OF Tair";
130    INPUT Tair
140    DISP "INPUT NUMBER OF POSITIONS FOR MRT ";
150    INPUT N
160    PRINT "VALUE OF X ";X,"VALUE OF Y ";Y,"AIR TEMPERATURE ",Tair
170    FOR I=1 TO N
180    Z=Z+1
190    DISP "INPUT";Z;"Mrt";
200    INPUT Mrt
210    Teu=X*Mrt+Y*Tair
220    PRINT Z;Teu
230    NEXT I
231    PRINT LIN(2)
240 !  FOR I=1 TO N
250    !  PRINT Teu
260 !  NEXT I
270  ! DISP "DO YOU WISH HARD COPY (Y=YES, N=NO) ";
280 !  INPUT K
290 !  IF K<>Y THEN 480
300  ! PRINTER IS 0
310 !  MAT PRINT Teu
320    DISP "DO YOU WISH TO RUN ANOTHER HOUR (Y=YES, N=NO) ";
330    INPUT H
340    IF H<>Y THEN 360
350    GOTO Equation
360    PRINTER IS 16
370    END
```

C-3 TEU OUTPUT

```
          THE TIME CHECKED IS 12PM DG NNI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1   65.23
 2   65.322
 3   65.322                                  1  64.402
 4   65.23                                   2  64.448
 5   65.184                                  3  64.31
 6   65.322                                  4  64.356
 7   65.322                                  5  64.218
 8   65.184                                  6  64.264
 9   65.184                                  7  64.08
 10   65.23                                  8  64.126
 11   65.23                                  9  63.942
 12   65.184                                 10  63.988
 13   65                                     11  63.758
 14   65                                     12  63.85
 15   65                                     13  63.62
 16   65                                     14  63.666
 17   64.54                                  15  63.436
 18   64.54                                  16  63.436
 19   64.54
 20   64.54


          THE TIME CHECKED IS 3AM DG NNI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1   65.046
 2   65.092
 3   65.092                                  1  64.172
 4   65.046                                  2  64.218
 5   64.954                                  3  64.08
 6   65.092                                  4  64.126
 7   65.092                                  5  63.988
 8   64.954                                  6  64.034
 9   64.954                                  7  63.85
 10   65                                     8  63.942
 11   65                                     9  63.712
 12   48.624                                 10  63.712
 13   64.77                                  11  63.528
 14   64.77                                  12  63.62
 15   64.77                                  13  63.39
 16   64.77                                  14  63.436
 17   64.31                                  15  63.206
 18   64.264                                 16  63.206
 19   64.264
 2   64.31
```

C-3 TEU OUTPUT

```
          TI   TIME CHECKED IS 6AM DG NNI
VALUE OF X  .45      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  64 26
 2  64.305
 3  64.26                                  1  63.942
 4  64.17                                  2  64.034
 5  64.26                                  3  63.85
 6  64.26                                  4  63.988
 7  64.17                                  5  63.758
 8  64.305                                 6  63.804
 9  64.305                                 7  63.62
 10  64.35                                 8  63.712
 11  64.35                                 9  63.482
 12  64.305                                10  63.528
 13  63.945                                11  63.252
 14  63.945                                12  63.39
 15  63.945                                13  63.16
 16  63.945                                14  63.206
 17  63.45                                 15  62.976
 18  63.405                                16  62.976
 19  63.405
 20  63.45


          THE TIME CHECKED IS 9AM DG NNI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  65
 2  65.046
 3  65.046                                 1  64.08
 4  65                                     2  64.172
 5  64.908                                 3  63.988
 6  65                                     4  64.126
 7  65                                     5  [illegible]
 8  330.328                                6  [illegible]
 9  64.862                                 7  [illegible]
 10  64.908                                8  [illegible]
 11  64.908                                9  63.62
 12  64.862                                10  63.62
 13  64.678                                11  63.39
 14  64.678                                12  63.528
 15  64.678                                13  63.298
 16  64.678                                14  63.344
 17  64.218                                15  63.068
 18  64.172                                16  63.068
 19  64.172
 20  64.218
```

C-3 TEU OUTPUT

```
         THE TIME CHECKED IS 12N DG NNI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       66.4
 1   66.768
 2   66.906                                 1   66.078
 3   66.906                                 2   66.124
 4   66.768                                 3   65.986
 5   66.768                                 4   66.032
 6   66.906                                 5   65.894
 7   66.906                                 6   65.894
 8   66.768                                 7   65.756
 9   66.722                                 8   65.756
 10   66.814                                9   65.618
 11   66.814                                10   65.618
 12   66.722                                11   65.388
 13   66.538                                12   65.388
 14   66.538                                13   65.25
 15   66.538                                14   65.25
 16   66.538                                15   65.02
 17   66.078                                16   65.02
 18   66.124
 19   66.124
 20   66.078


         THE TIME CHECKED IS 3PM DG NNI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       69.3
 1   69.622
 2   69.76                                  1   69.3
 3   69.76                                  2   69.3
 4   69.622                                 3   69.162
 5   69.622                                 4   69.162
 6   69.852                                 5   69.024
 7   69.852                                 6   69.024
 8   69.622                                 7   68.886
 9   69.622                                 8   68.886
 10   69.76                                 9   68.748
 11   69.76                                 10   68.748
 12   69.622                                11   68.518
 13   69.484                                12   68.518
 14   69.576                                13   68.334
 15   69.576                                14   68.334
 16   69.484                                15   66.77
 17   69.024                                16   66.678
 18   69.116                                      5
 19   69.116
 20   69.024
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 6PM DG NNI
  E OF X  .46       VALUE OF Y  .54       AIR TEMPERATURE       65.6
 1  66.382
 2  66.52
 3  66.52                                 1  65.876
 4  66.382                                2  65.876
 5  66.382                                3  65.738
 6  66.612                                4  65.738
 7  66.612                                5  65.692
 8  66.382                                6  65.554
 9  66.382                                7  65.554
10   66.52                                8  65.508
11   66.2716                              9  65.37
12   66.2578                             10   65.324
13   66.244                              11   65.14
14   66.336                              12   65.14
15   66.336                              13   65.002
16   66.244                              14   64.956
17   65.784                              15   64.772
18   65.83                                16   64.68
19   65.784
20   65.83


        THE TIME CHECKED IS 9PM DG NNI
VALUE OF X  .46       VALUE OF Y  .54       AIR TEMPERATURE       65
 1  65.598
 2  65.69
 3  65.69
 4  65.598                               1  64.862
 5  65.552                               2  64.862
 6  65.736                               3  64.77
 7  65.736                               4  64.77
 8  65.552                               5  64.678
 9  65.552                               6  64.678
10   65.644                              7  64.54
11   65.644                              8  64.54
12   65.552                              9  64.402
13   65.368                             10   64.402
14   65.46                              11   64.172
15   65.46                              12   64.08
16   65.368                             13   64.034
17   64.908                             14   64.034
18   64.[illegible]                     15   63.804
19   64.[illegible]                     16   63.804
20   64.908
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 12M TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  66.242
 2  66.058
 3  66.38
 4  66.196
 5  66.518
 6  66.334
 7  66.656
 8  66.472
 9  66.84
 10  66.656
 11  66.932
 12  66.886
 13  67.254
 14  66.932
 15  67.484
 16  67.438


        THE TIME CHECKED IS 3AM TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  66.058
 2  65.874
 3  66.15
 4  65.966
 5  66.288
 6  66.104
 7  66.426
 8  66.242
 9  66.564
 10  66.426
 11  66.242
 12  66.518
 13  66.426
 14  66.656
 15  66.61
 16  66.61
```

C-3 TEU OUTPUT

```
              THE  TIME CHECKED IS 9AM DG NI
   VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE      65
    1  65.092
    2  49.728
    3  65.138                                 1  64.126
    4  65.092                                 2  64.218
    5  65.092                                 3  64.034
    6  65.138                                 4  64.08
    7  65.138                                 5  63.942
    8  65.092                                 6  63.988
    9  65                                     7  63.804
    10  65.046                                8  63.85
    11  49.176                                9  63.666
    12  65                                    10  63.712
    13  64.862                                11  63.436
    14  64.908                                12  63.574
    15  6[illegible]08                        13  63.344
    16  64.[illegible]62                      14  63.344
    17  64.494                                15  63.16
    18  64.494                                16  63.16
    19  64.494
    20  64.494
```

C-3 TEU OUTPUT

```
         THE TIME CHECKED IS 12N DG NI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       66.6
 1  66.968
 2  67.06
 3  67.06
 4  66.968                                  1  66.278
 5  67.06                                   2  66.324
 6  67.152                                  3  66.186
 7  67.152                                  4  66.186
 8  67.06                                   5  66.048
 9  66.968                                  6  66.094
 10  67.06                                  7  65.956
 11  66.968                                 8  65.772
 12  346.188                                9  65.818
 13  66.922                                 10  65.542
 14  66.922                                 11  65.634
 15  66.922                                 12  65.45
 16  66.876                                 13  65.404
 17  66.462                                 14  65.22
 18  66.508                                 15  65.174
 19  66.508                                 16  65.174
 20  66.462


         THE TIME CHECKED IS 3P     NI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE
 1  70.144
 2  70.282
 3  70.282                                 1  69.454
 4  70.144                                 2  69.454
 5  70.236                                 3  69.362
 6  70.374                                 4  69.362
 7  70.374                                 5  69.224
 8  70.236                                 6  69.224
 9  70.19                                  7  69.086
 10  70.282                                8  69.086
 11  70.282                                9  68.948
 12  70.19                                 10  68.948
 13  70.19                                 11  68.718
 14  70.144                                12  68.718
 15  70.144                                13  68.534
 16  70.19                                 14  68.534
 17  69.684                                15  68.304
 18  69.73                                 16  68.304
 19  69.73
 20  69.684
```

69.5

✓

C-3 TEU OUTPUT

```
          THE TIME CHECKED IS 6PM DG NI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE      67.5
 1  68.604
 2  68.696
 3  68.696                               1  68.374
 4  68.604                               2  68.282
 5  68.696                               3  68.328
 6  68.7                                 4  357.576
 7  68.742                               5  357.576
 8  68.696                               6  68.19
 9  68.65                                7  68.19
 10  68.742                              8  68.144
 11  68.742                              9  68.144
 12  68.65                               10  68.052
 13  68.65                               11  68.052
 14  68.742                              12  67.96
 15  68.742                              13  67.96
 16  68.65                               14  67.868
 17  68.466                              15  67.868
 18  68.558                              16  67.73
 19  68.558
 20  68.466


          THE TIME CHECKED IS 9PM DG NI
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE      65.7
 1  66.344
 2  66.436
 3  66.436
 4  66.344                               1  66.252
 5  66.482                               2  66.252
 6  66.574                               3  66.298
 7  66.574                               4  66.206
 8  328.682                              5  66.252
 9  66.574                               6  66.16
 10  66.574                              7  66.16
 11  66.574                              8  66.114
 12  66.574                              9  66.114
 13  66.436                              10  66.022
 14  66.528                              11  66.022
 15  66.528                              12  65.93
 16  345.656                             13  65.93
 17  66.206                              14  65.838
 18  6[illegible]8                       15  65.792
 19  [illegible]                         16  65.746
 20  6[illegible]
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 6AM TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE      65
 1  65.782
 2  65.644
 3  65.874
 4  65.759
 5  65.966
 6  65.828
 7  66.104
 8  65.966
 9  66.196
 10  66.104
 11  66.426
 12  66.242
 13  66.61
 14  66.518
 15  66.702
 16  66.702
```

```
        THE TIME CHECKED IS 9AM TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE      65
 1  65.828
 2  65.69
 3  65.92
 4  65.782
 5  66.196
 6  66.058
 7  66.288
 8  66.196
 9  66.472
 10  66.334
 11  66.61
 12  66.518
 13  66.702
 14  66.702
 15  66.702
 16  66.794
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 12N TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  66.84
 2  66.61
 3  67.024
 4  66.794
 5  67.208
 6  66.978
 7  67.438
 8  67.208
 9  67.668
 10  67.438
 11  68.082
 12  67.714
 13  68.22
 14  68.082
 15  68.542
 16  68.45
```

```
        THE TIME CHECKED IS 3PM TW NNI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  67.622
 2  67.346
 3  67.898
 4  67.53
 5  68.128
 6  67.806
 7  68.45
 8  68.128
 9  68.726
 10  68.45
 11  69.278
 12  68.864
 13  69.508
 14  69.278
 15  69.922
 16  69.83
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 6PM TW NNI M=60
VALUE OF X  .46     VALUE OF Y  .564    AIR TEMPERATURE       67.3
 1  70.2032
 2  69.8812
 3  70.3872
 4  70.1112
 5  70.6172
 6  70.3412
 7  70.8932
 8  70.6172
 9  71.1692
 10  70.8932
 11  71.6752
 12  71.2612
 13  71.8592
 14  71.6752
 15  72.2272
 16  72.1[illegible]2


        THE TIME CHECKED IS 9PM TW NNI M=60
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE       67.1
 1  67.974
 2  67.744
 3  68.158
 4  67.928
 5  68.342
 6  68.112
 7  68.572
 8  68.342
 9  68.802
 10  68.572
 11  69.216
 12  68.848
 13  69.354
 14  69.216
 15  69.676
 16  69.584
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 12M TW NI M=60
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE       65
 1  66.334
 2  66.15
 3  66.472
 4  66.242
 5  66.61
 6  66.426
 7  66.748
 8  66.564
 9  66.932
 10  66.794
 11  67.254
 12  66.978
 13  67.392
 14  67.254
 15  67.622
 16  67.53


        THE TIME CHECKED IS 6AM TW NI M=60
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE       65
 1  66.012
 2  65.828
 3  66.104
 4  65.966
 5  66.242
 6  66.058
 7  66.38
 8  66.196
 9  66.518
 10  66.38
 11  66.748
 12  66.564
 13  66.886
 14  66.748
 15  67.07
 16  67.024
```

C-3 TEU OUTPUT

```
       THE TIME CHECKED IS 9AM SAME AS ABOVE
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE      65
 1  67.024
 2  67.024
 3  67.024
 4  67.024
 5  67.024
 6  67.024
 7  67.024
 8  67.024
 9  67.024
 10  67.024
 11  67.024
 12  67.024
 13  67.024
 14  67.024
 15  67.024
 16  67.024
```

```
       THE TIME CHECKED IS 12N TW NI M=60
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE      65
 1  67.024
 2  66.748
 3  67.208
 4  66.932
 5  67.392
 6  67.116
 7  67.622
 8  67.346
 9  67.852
 10  67.622
 11  68.266
 12  67.944
 13  68.45
 14  68.266
 15  68.772
 16  68.68
```

C-3 TEU OUTPUT

```
        THE TIME CHECKED IS 3PM TW NI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       65
 1  67.76
 2  67.438
 3  68.036
 4  67.668
 5  68.312
 6  67.944
 7  68.588
 8  68.266
 9  68.91
 10  68.588
 11  69.462
 12  69.002
 13  69.692
 14  69.462
 15  70.152
 16  70.014
```

```
        THE TIME CHECKED IS 6PM TW NI M=60
VALUE OF X  .46      VALUE OF Y  .54      AIR TEMPERATURE       67.3
 1  70.198
 2  69.922
 3  70.382
 4  70.106
 5  70.566
 6  70.29
 7  70.796
 8  70.52
 9  71.072
 10  70.796
 11  71.486
 12  71.118
 13  71.624
 14  71.486
 15  71.992
 16  71.9
```

C-3 TEU OUTPUT

```
         THE TIME CHECKED IS 9PM TW NI M=60
VALUE OF X  .46     VALUE OF Y  .54     AIR TEMPERATURE      67.1
 1  68.296
 2  68.02
 3  68.434
 4  68.204
 5  68.664
 6  68.388
 7  68.894
 8  68.618
 9  69.124
 10  68.894
 11  69.538
 12  69.17
 13  69.676
 14  69.538
 15  70.044
 16  69.952
```

APPENDIX D

SYSTEM COST CALCULATIONS

D-1 System Cost Calculations

Direct Gain Costs

Glazing 410 ft^2 @ 3.25 = \$1,332.50
Floor Slab (6"-4") (0.76) (1200 ft^2) = \$1,824.00
Framing (210 ft^2)(3.50) = \$ 735.00

Total without insulation = \$3,891.50

R-9 nighttime insulation 410 ft^2 (4.50) = \$1,845.00

Total with R-9 nighttime insulation = \$5,736.50

Trombe Wall Costs

Glazing 310 ft^2 @ 3.25/ft^2 = \$1,007.50
Wall forms 310 ft^2 @ \$3.04/ft^2 = \$ 942.40
8" Concrete 310 ft^2 @ 3.04/ft^2 = \$ 942.40
Framing @ 160 ft @ 3.50) = \$ 560.00

Total without insulation = \$3,452.30

R-9 nighttime insulation 310 ft^2 @ 4.50 = \$1,395.00

Total with R-9 nighttime insulation = \$4,847.30

VITA 2

John William Zang III

Candidate for the Degree of

Master of Architectural Engineering

Thesis: A THERMAL COMFORT AND ECONOMIC COMPARISON OF TWO PASSIVE SOLAR HEATING SYSTEMS: DIRECT GAIN AND A TROMBE WALL

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