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# Passive Solar Heating Basics

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# Passive Solar Heating Basics

*Harlan H. Bengtson, PhD, P.E.*

## COURSE CONTENT

### 1. Introduction

The principles of passive solar heating, such as basic types of systems, their description, and the components making up any passive system are presented in this course. Sources of data for heating requirements and available solar radiation throughout the U.S are identified and discussed along with a method for estimating the rate of heat loss from a home. The use of these three inputs in a method for estimating performance of a passive heating system of specified size at a specified location is presented. The data retrieval and calculations are illustrated with numerous examples.

Passive Solar Exterior

Passive Solar Interior

## 2. Learning Objectives

At the conclusion of this course, the student will

- Be able to name the six components which typically make up a passive solar heating system.

- Be able to name five basic types of passive solar heating systems.

- Be able to describe the differences between daytime and nighttime operation of direct gain passive solar heating systems.

- Be able to describe the differences between daytime and nighttime operation of indirect gain passive solar heating systems.

- Be able to obtain and interpret data for solar radiation rate on vertical and horizontal surfaces of buildings at any of the 239 locations in the NREL database.

- Be able to obtain and interpret data for heating degree days at any of the 239 locations in the NREL database.

- Be able to estimate the rate of heat loss (Btu/$^o$F-day/ft$^2$) from a building if one year's monthly power bills for the building are available.

- Be able to estimate the monthly percentage of a buildings heating requirement provided by a given size passive solar heating system at a given location in the U.S., with specified rate of heat loss from the building (Btu/$^o$F-day/ft$^2$).

- Be able to estimate the quantity of thermal storage needed for a passive solar heating system with specified area of glazing.

## 3. Topics Covered in This Course

I. Passive Solar Heating Definition

II. Components of a Passive Solar Heating System

III. Basic Passive Solar Heating System Types

   A. Direct Gain
   B. Thermal Storage Wall
   C. Attached Sunspace
   D. Thermal Storage Roof
   E. Convective Loop

IV. Inputs Needed to Estimate Size/Performance of a Passive Solar Heating System

   A. Heating requirements (degree days) during the heating season at the site of interest
   B. Information on the rate of heat loss from the house
   C. Available solar radiation at the site of interest

V. Size and Performance Calculations for a Passive Solar System

VI. Choice of the Type(s) of Passive Solar Systems to Use

VII. Sizing Solar Storage

VIII. Controls – Summer Shading of Passive Solar Glazing

IX. Construction Details

X. Related Links and References

## 4. Passive Solar Heating Definition

Passive solar heating of a building means using the sun's radiant energy to provide heat  by converting the radiant energy to thermal energy (heat) when it is absorbed by the building.  Some of the incoming thermal energy may be used to directly heat the building and some may be stored in components of the building. In a completely passive system, energy flow within the building is by natural means (conduction, natural convection and radiation) only.  An active solar heating system, on the other hand, uses devices like blowers, pumps and/or fans to move heated fluid, from the collectors to the heated space, from thermal storage to the heated space, and from the collectors to thermal storage.

## 5. Components of a Passive Solar Heating System

A passive solar system is made up of components that have functions very similar to the components of an active solar heating system, but those components look much different and are arranged much differently.  The typical components of either a passive or active solar heating system are:  **aperture** (opening for solar radiation to go through, **absorber** (to absorb the radiant energy and convert it to thermal energy, **thermal mass** (for storage of excess thermal energy for later use), **distribution system**, **controls**, and a **backup heating system**.

In an passive solar heating system, the aperture and absorber are separated physically, while in an active system they are typically both part of the collectors. The **aperture**(s) in a passive solar heating system will be south-facing window(s). It is important that these windows not be shaded by other buildings or trees from 9:00 a.m. to 3:00 p.m. during the heating season.

In a passive system, the **absorber** and the **thermal mass** for storage are both part of the same unit(s), which are components of the building such as floors and walls in the direct path of sunlight.  The floor and/or wall surfaces are typically dark colored so that they will absorbs solar radiation well and convert it to thermal energy, which is stored in the mass of the floors and/or walls. In an active system, the absorber is typically part of the collector and the heat storage system is a separate unit.

A **distribution system** is used to circulate heat from the collection and storage points to different areas of the house. In a strictly passive system, heat will be circulated solely by one or more of the three natural heat flow methods, conduction, natural convection, and radiation. Fans, and/or blowers are sometimes used to help with the distribution of heat throughout the house in an otherwise passive system.

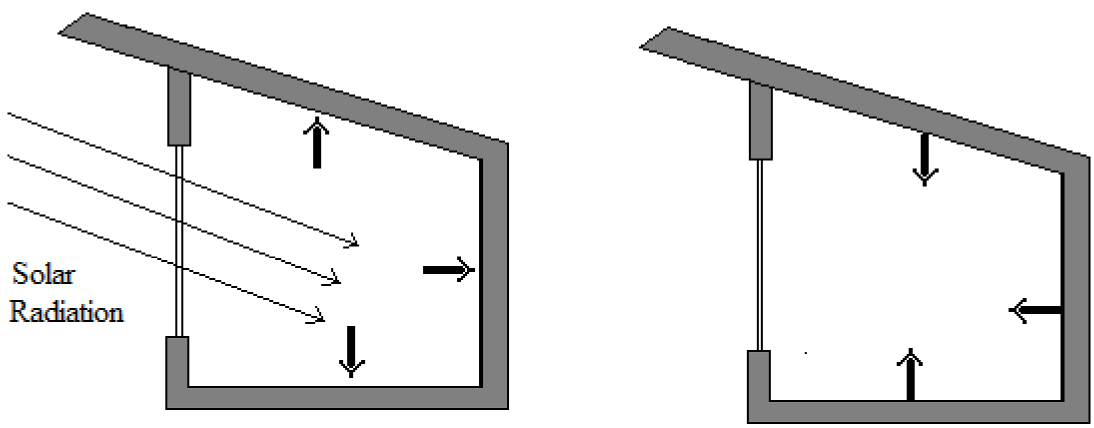
In a passive heating system, **Controls** include items such as operable vents or dampers, moveable window insulation, and/ or roof overhangs or awnings that shade the aperture during summer months. For active systems and nearly passive systems that use fans and/or blowers, controls typically include electronic sensing devices, such as a differential thermostat that signals a fan to turn on or off or a damper to open or close.

The **backup heating system** for either a passive or active system can be any type of non-solar heating system.

## 6. Basic Passive Solar Heating Systems Types

The five basic types of passive solar heating systems are: **direct gain, thermal storage wall, attached sunspace, thermal storage roof,** and **convective loop.** Each of the types contains the components described above. Three of these types, thermal storage wall, attached sunspace and thermal storage roof, are sometimes called indirect gain systems. The convective loop is sometimes called an isolated gain system. A brief description of each of the five types follows.

**Direct Gain** is a simple, straightforward approach to passive solar heating. In this type of system, sunlight enters the living space through south facing windows during the daytime. The incoming solar radiation strikes the walls, floor, and/or ceiling (thermal storage mass) of the living space directly or is reflected to them and is absorbed and converted to thermal energy in that thermal storage mass. The heated wall, floor, and/or ceiling will keep the living space warm. Also, during the daytime, when the storage surface temperature is high enough, heat will be conducted from the hot surface of the walls, floor, and/or ceiling to their interior, where it is stored. When the surface of the thermal storage mass are no longer being heated by the suns rays, the room and the wall, floor and/or surface temperatures will decrease and heat will be conducted from the heated interior of the thermal storage mass to the cooler surface and will heat the living space by convection and radiation. This is illustrated in Figure 1, below.




Daytime - Solar radiation absorbed and stored as heat in walls & floors

Night time - Stored heat is radiated into living space

Figure 1. Direct Gain Passive Solar Heating

A direct gain passive solar heating system needs to have plenty of south facing glass and adequate thermal storage capacity in the living space. A guideline sometimes used for thermal storage capacity is to construct one-half to two-thirds of the total interior surface area of thermal storage materials. Materials typically used for thermal storage are masonry, such as concrete, adobe, brick, etc. Also water walls can be used as well. A water wall consists of water in plastic or metal containers placed in the direct path of the sunlight. Water walls heat more quickly and more evenly than masonry, but they may not be as pleasing aesthetically. The surface temperature of dark colored masonry surfaces may become quite high if they receive direct sunlight. One way to avoid this, is to use a diffusing glazing material which scatters sunlight, thus distributing it more evenly over walls, ceiling, and floor. This approach distributes the incoming solar radiation more evenly but doesn't reduce the total amount of solar energy entering the space. The effect of using a diffusing glazing material is illustrated in Figure 2, below. Nighttime heat loss can be reduced by the use of moveable insulation, such as insulated drapes, to cover the south facing windows at night.

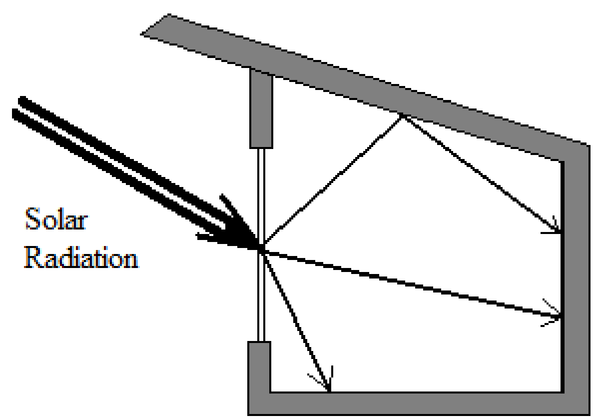
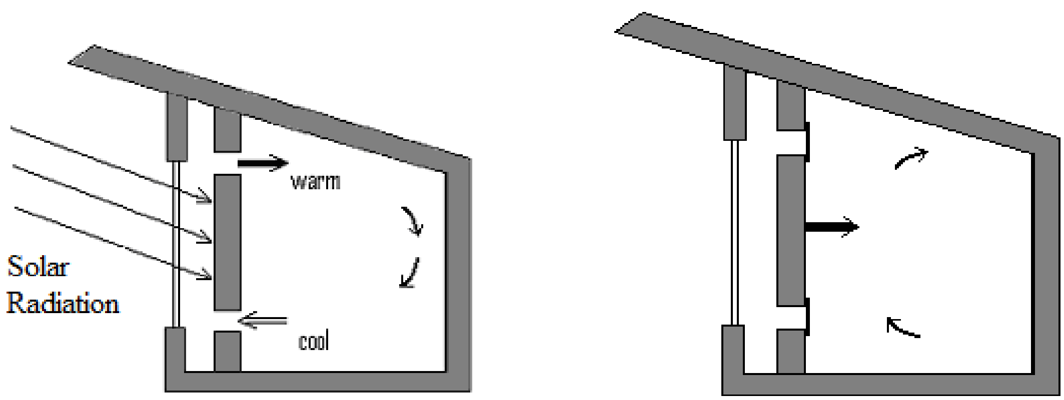



Figure 2. Direct Gain with Diffusing Glazing Material

A **Thermal Storage Wall** is shown in Figure 3 below. These walls are typically made of masonry or of water filled containers. This type of wall is sometimes called a Trombe Wall. It is named after the engineer, Felix Trombe, who popularized the design together with architect, Jacques Michel, in the 1960's. In 1881, this design was patented by Edward Morse. The key feature of the thermal storage (Trombe) wall system is the presence of thermal storage material between the interior living space and the sun. As a result of this wall placement, the dark colored storage wall will be heated by sunshine during day and the stored heat in the wall will provide heat to the living space at night. Vents are typically placed near the top and the bottom of the wall, as shown in Figure 3. These vents should be opened during the day and closed at night, to provide natural convection* heating of the living space from the heated air between the storage wall and glazing during sunlight hours and to minimize heat loss from the heated space at night. As with the direct gain system, use of movable insulation for the glazing at night will reduce nighttime heat loss.

***NOTE**: Natural convection (also called free convection) is the movement of a fluid because of the reduced density of a heated portion of the fluid. That is, as a portion of a fluid is heated, its density decreases and it rises. This will cause movement of other portions of a fluid mass as well. In the thermal storage wall, for example, the heated air between the glazing and the storage wall will rise and enter the living space through the upper vent. This will draw cool air from the bottom of the living area into the space between the glazing and storage wall through the lower vent.




Daytime - vents are open, wall stores heat and heats room

Nighttime - vents are closed, wall heats room

Figure 3. Thermal Storage (Trombe) Wall, daytime and nighttime configurations

Figure 4 shows an **Attached Sunspace** passive solar heating system. A useful feature of this type of system is that it can be added to an existing building. This makes it more suitable for retrofit than some of the other types of passive heating systems. This type of system uses direct gain in the sunspace, which is sometimes called a solar greenhouse, and may, in fact, be used as a greenhouse. Another important part of the attached sunspace system is a thermal storage wall between the sunspace and the rest of the living space, as shown in Figure 4. Vents are typically included at the top and bottom of the thermal storage wall, as described above for a thermal storage (Trombe) wall.

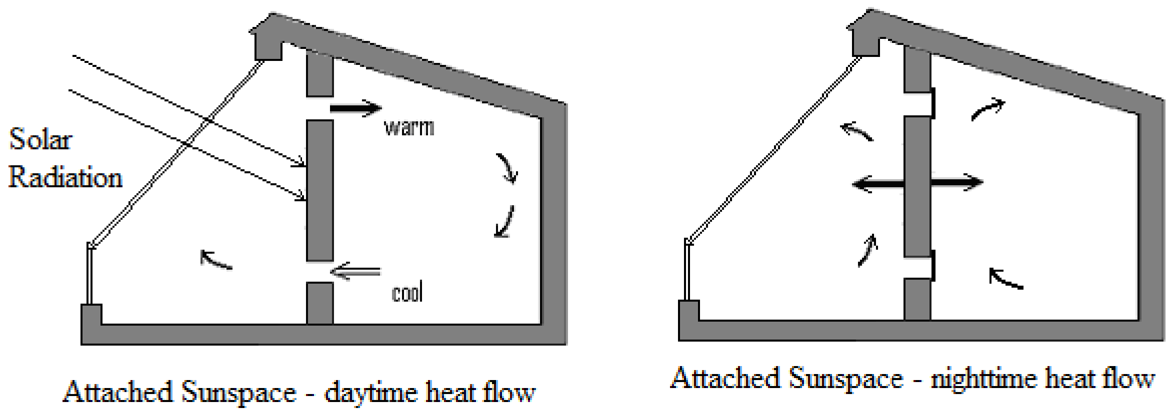



Figure 4. Attached Sunspace, Daytime & Nighttime Heat Flows

The **Thermal Storage Roof,** also called a solar roof, solar pond, or roof pond, uses water encased in plastic on the roof. Moveable insulation is used to cover the roof and reduce heat loss during the night, but the roof must be uncovered during the daytime to allow the sunshine to strike the pond. The pond (water encased in plastic) can also be placed in an attic, under glazing in a pitched roof. Figure 5 shows typical daytime and nighttime heat flows for a thermal storage roof system. On the minus side, however, a thermal storage roof requires a somewhat elaborate drainage system, movable insulation to cover and uncover the water at appropriate times, and a structural system to support up to 65 lbs/sq ft dead load.

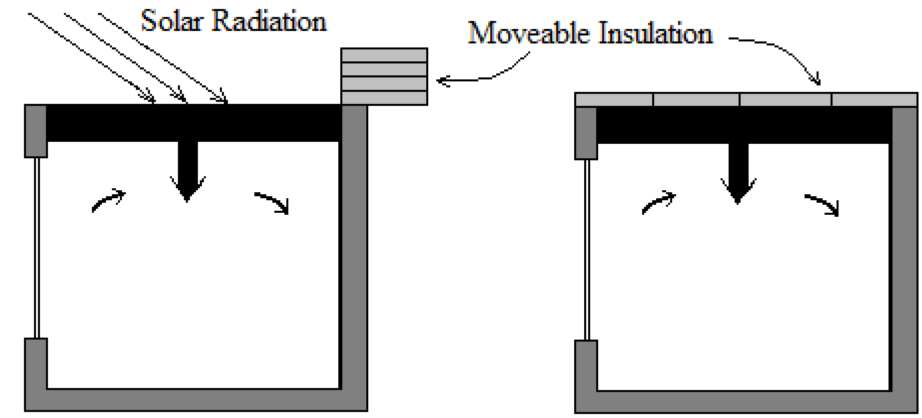


Figure 5. Solar Roof, covered with insulation at night, uncovered during day

A convective loop system uses a flat plate solar collector to heat air or water. The heater air or water then flows by natural convection to directly heat a living space or to a thermal storage area. Two convective loop configurations for space heating are shown in Figure 6. One of the systems has a vertically mounted collector, and the other has the collector mounted at a tilt. Either of these systems can be mounted on an existing wall, so they are quite suitable for retrofit applications. Either of these systems needs two openings into the building, one at the top of the collector for heated air flow into the building, and one at the bottom of the collector for cool air flow from the building into the collector. Some applications use a window on one floor for the upper opening and a window on a lower floor for the bottom opening. The vertically mounted collector, as shown at the right in Figure 6, is also referred to as a solar chimney. Other names used for any of the convective loop systems are isolated gain and thermosiphon system. This type of system can also be used for a passive water heating system as shown in Figure 7.

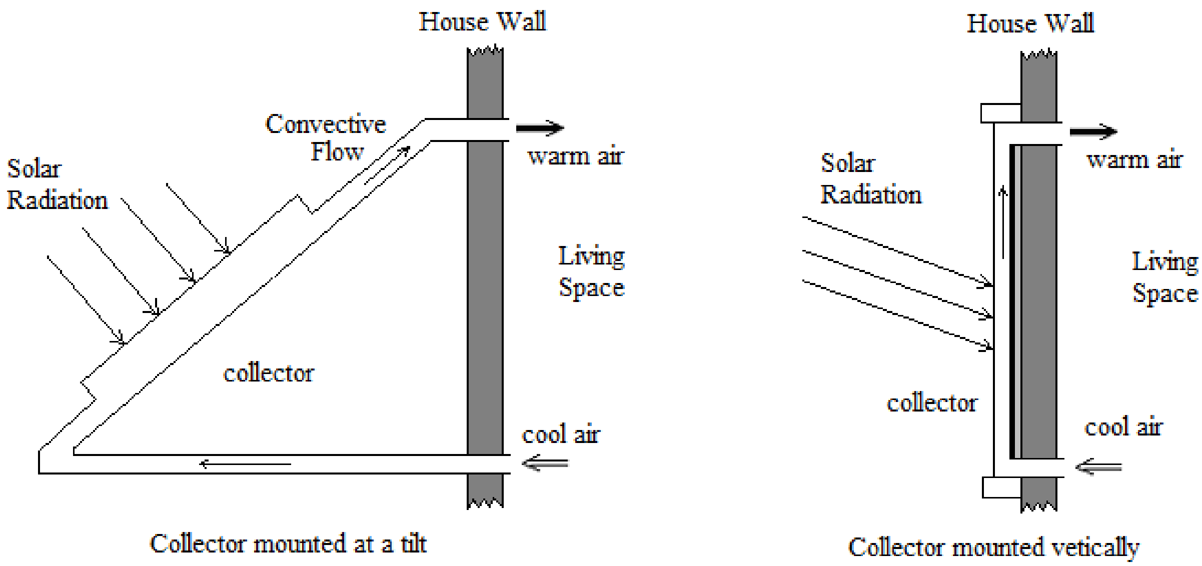



Figure 6. Convective loops to heat living space

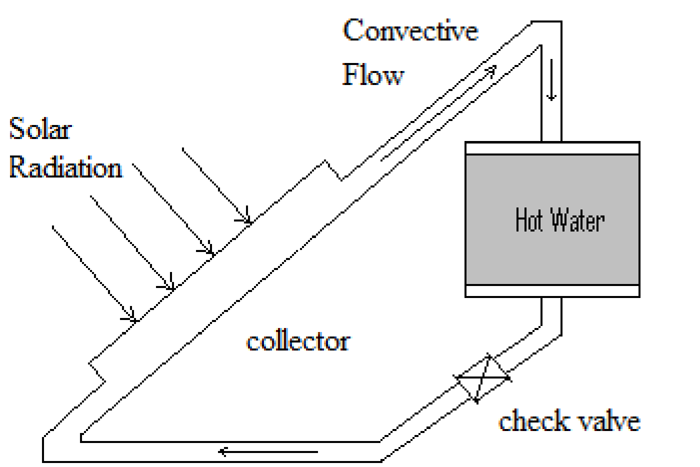



Figure 7. Convective loop, used for heating water

## 7. Inputs Needed to Estimate Size/Performance of a Passive Solar Heating System

In planning and designing a passive solar heating system, it is often helpful to estimate the performance of a particular passive solar heating system, or to estimate the size system needed to provide a specified percentage of the heating requirements for a building. In order to do either of these, information is typically needed on each of the following: i) heating requirements (degree days) during the heating season at the site of interest, ii) information on the rate of heat loss from the house, and iii) available solar radiation at the site of interest. Sources of information for, or means of estimating those three items, will be discussed in this section. Then the use of that information for sizing and performance calculations will be covered in the next section.

**i) Heating requirements (degree days) during the heating season at the site of interest:** Data on heating degree days is available from a variety of sources. Two such sources will be discussed here. One very good source of data for passive solar heating applications is *Solar Radiation Data Manual for Buildings,* published by the National Renewable Energy Laboratory (NREL), and available for free download at the website: http://rredc.nrel.gov/solar/pubs/bluebook/. This publication includes data for 239 locations in the United States and its territories, based on data collected from 1961-1990 for those 239 sites. Monthly average and yearly average values for heating degree days are given in the *Solar Radiation Data Manual for Buildings* for each of the 239 sites covered in that publication.

The other source for passive solar heating data that will be discussed in this section, is the second reference in the "Related Links and References" for this course, *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling,* by Bruce Anderson and Malcolm Wells. It is available for free download from the website:
http://www.builditsolar.com/Projects/SolarHomes/PasSolEnergyBk/PSEbook.htm.

Appendix 5 of *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, contains data for 236 U.S. Cities based on ASHRAE, *Handbook of Fundamentals*, 1972. Information is given on monthly average heating degree days for the period from September through May, and the yearly total for each of the 236 U.S. cities.

**NOTE:** Degree days data provides information on heating or cooling requirements for buildings at a given location. The value of degree days for a given day is defined as the difference between the average temperature for the day (calculated by averaging the maximum and minimum temperature for the day) and a base temperature (typically 65° F or 18.3° C). The difference is called heating degree days if the average temperature is less than the base temperature. It is called cooling degree days if the average is greater than the base temperature.

**Example #1:** Compare the values given in the above two references for annual heating degree days and for January heating degree days for Colorado Springs, CO.

**Solution:** This simply requires looking up values in the tables in the two references.

From *Solar Radiation Data Manual for Buildings*, page 47 (p 25 of this course), for Colorado Springs, CO:

Annual heating degree days = 6415 °F days

January heating degree days = 1122 °F days

From *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, page 155 (p 26 of this course), for Colorado Springs, CO:

Annual heating degree days = 6423 °F days

January heating degree days = 938 °F days

The agreement between the two sources is pretty good, although the data came from databases covering different timeframes.

**ii) Information on the rate of heat loss from the house:** A useful way of expressing the rate of heat loss is Btu per heating degree-day per square foot of building floor area. For conventional building design, a heating load of 6 to 8 Btu/$^{o}$F-day/ft$^2$ is considered an energy conservative design. For an older home that is not well insulated and weather-stripped, the heat loss rate would be greater. For a super-insulated home, it would be less than the above guideline. For an existing home that is not well insulated and weather-stripped, it is typically cost-effective to add insulation and/or weather-stripping before adding passive solar components. Goswami, Krieth, & Krieder (ref #1 under "Related Links & References" for this course) suggest reducing the nonsolar rate of heat loss by 20% in conjunction with solarizing of the south-facing wall of a building with passive solar systems. This gives a range of 4.8 to 6.4 Btu/$^{o}$F-day/ft$^2$, as an estimate for the rate of heat loss from a well-insulated and weather-stripped home with passive solar heating system(s) added.

The rate of heat loss per degree-day from a building can be estimated from information about the construction of the building, such as roof area, wall area, insulation thickness, glass area, number of glazing layers, etc. This type of calculation is covered in various HVAC texts and publications and will not be covered here.

Another approach to estimating rate of heat loss from an existing home is through the use of fuel consumption information for that home. Anderson & Wells (ref #2 under "Related Links & References" for this course) discuss this approach on pages 112 & 113 of their book. That discussion is summarized here for several types of heating: fuel oil furnace, natural gas furnace, electric resistance heating and heat pump.

i) **Fuel Oil Furnace:** A gallon of fuel oil has an energy content of 135,00 to 140,000 Btus. If this is multiplied by the furnace efficiency (typically 40 to 70 %) that gives the heat supplied to the house per gallon of fuel oil used.

ii) **Natural Gas Furnace:** One cubic foot of natural gas contains 1000 Btus of energy. Natural gas consumption is often expressed as hundreds of cubic feet (ccf) or thousands of cubic feet (mcf). As with fuel oil, the amount of energy in the natural gas consumed must be multiplied by the furnace efficiency to get the amount of heat delivered to the house.

iii) **Electric Resistance Heating:** For electric resistance heating, one kwh of electricity is equivalent to 3400 Btu with electric resistance heating having an efficiency of 100%.

iv) **Heat Pump:** A heat pump can supply as much as 6800 Btus per kwh of electricity used to operate it.

This information can be used together with an estimate of the amount of fuel or electricity used to heat the home from power bills, to estimate the amount of heat supplied to the house during any month. By the first law of thermodynamics, that must be the amount of heat lost from the house.

**Example #2:** Data on monthly natural gas consumption for a 2000 $ft^2$ home in Albuquerque, NM is given in the table below. Also given in the table are monthly heating degree-days for Albuquerque, NM from the NREL publication, *Solar Radiation Data Manual for Buildings*. Estimate the rate of heat loss from this home in Btu/°F-day/$ft^2$ based on this data. Assume 60% efficiency for the furnace.

| Month | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nat'l Gas Consump., ccf | 272 | 186 | 95 | 73 | 27 | 15 | 18 | 17 | 17 | 28 | 91 | 186 | 1025 |
| Heating °F-days | 955 | 700 | 561 | 301 | 89 | 0 | 0 | 0 | 18 | 259 | 621 | 921 | 4425 |

**Solution:** Ave. gas consumption for June – August (zero heating degree-day months) is:

$$(15 + 18 + 17)/3 = 17 \underline{\text{ ccf/month}}$$

Total gas consumption for heating season (Sept – May):

$$= 1025 - (15 + 18 + 17) = 975 \text{ ccf}$$

Calculate the annual gas consumption for heating by subtracting the baseline (non-heating) gas consumption of 17 ccf/month:

Gas consumption for heating = 975 – 9*17 = <u>822 ccf</u>

Converting to Btu: Gas consumption for heating = $822*10^5$ = $8.22*10^7$ Btu

Heat delivered to house (60% efficiency) = $0.6*8.22*10^7$ = $4.93*10^7$ Btu

Dividing by the average annual heating degree-days for Albuquerque and the floor area of the house:

Heat loss rate in Btu/°F-day/ft$^2$ = $4.93*10^7$/4425/2000 = **<u>5.6 Btu/°F-day/ft$^2$</u>**

This seems reasonable. It is in the range of 4.8 to 6.4 Btu/°F-day/ft$^2$ given above for a house that is receiving some solar input from south-facing windows.

**iii) Available solar radiation at the site of interest:** Data on incident solar radiation in the United States and around the world are available from various publications and internet websites. The two sources that were introduced in the previous section are especially useful for passive solar heating applications, and will be discussed here.

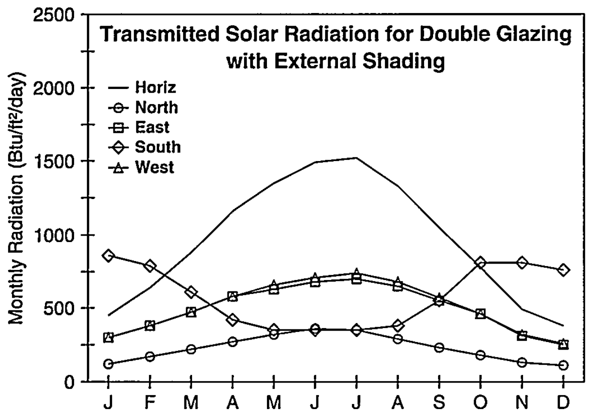
The first of the two references, *Solar Radiation Data Manual for Buildings,* includes data on monthly average and yearly average incident solar radiation on horizontal surfaces and on vertical surfaces facing north, east, south and west. Page 117 of this reference, giving data for Kansas City, MO, is shown on the next page.

The first table near the top of the page gives the information about incident radiation. The "global" monthly radiation values given in the table are the average total solar radiation striking the surface, including the effect of cloudiness. "Diffuse" monthly radiation is that part of the global radiation that is made up of ground reflected radiation and sky radiation. The remainder of the global monthly radiation is "direct beam" radiation reaching the surface directly from the sun. The "clear day global" radiation given in the table is the daily amount that would strike the surface on a clear day, when there are no clouds interfering with the path of the sun's rays.

The second table in the example gives monthly and yearly average transmitted radiation with double glazing for horizontal and each of the four vertical surfaces mentioned above. The "shaded" transmitted radiation is for the shading geometry shown at the top of the page for each location. The "unshaded" transmitted radiation is for the case with no awning or overhang above the window. This is discussed further in Section 8, near the end of this course.

Illuninance data and some data on average climatic conditions are given in the last two tables on the page. The example page for Kansas City, MO shows the format for the data available for all 239 locations in the United States and its territories that are included in the publication.

The second source for solar radiation data that was introduced above is *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling,* by Bruce Anderson and Malcolm Wells. Appendix 2 contains data on hourly solar radiation (Btu/hr/ft$^2$ on south walls on sunny days from 7:00 a.m. to 5:00 p.m. solar time for the 21$^{st}$ of each month for six latitudes ranging from 24 to 64 degrees north. Daily totals for solar radiation are also given for each month, at each latitude. Appendix 3 in the same book provides maps of the U.S. showing average percentage of the time that the sun is shining during daylight hours for each month. Information from these two appendices can be used to estimate the average rate of incident solar radiation on a south-facing window for any month at any location in the U.S. Also given by Anderson & Wells is an estimate of 82% for the average portion of incident radiation that will be transmitted through each layer of glass.

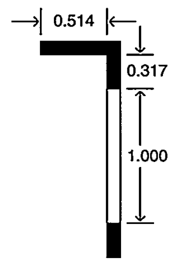



# Kansas City, MO

## WBAN NO. 03947

LATITUDE: 39.30° N
LONGITUDE: 94.72° W
ELEVATION: 1034 feet
MEAN PRESSURE: 14.3 psia

STATION TYPE: Secondary




Shading Geometry (Not to Scale)

### Average Incident Solar Radiation (Btu/ft²/day), Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Global | 700 | 940 | 1240 | 1610 | 1870 | 2050 | 2080 | 1830 | 1460 | 1120 | 740 | 590 | 1360 |
| | Std.Dev. | 57 | 71 | 114 | 112 | 128 | 127 | 144 | 129 | 130 | 107 | 73 | 53 | 42 |
| | Minimum | 560 | 790 | 980 | 1330 | 1560 | 1750 | 1800 | 1550 | 1060 | 930 | 590 | 490 | 1280 |
| | Maximum | 820 | 1100 | 1410 | 1870 | 2130 | 2360 | 2350 | 2040 | 1760 | 1390 | 890 | 700 | 1490 |
| | Diffuse | 300 | 420 | 560 | 680 | 790 | 810 | 760 | 680 | 560 | 410 | 320 | 280 | 550 |
| | Clear-Day Global | 940 | 1280 | 1760 | 2230 | 2530 | 2640 | 2560 | 2290 | 1870 | 1390 | 990 | 820 | 1780 |
| North | Global | 200 | 270 | 350 | 440 | 550 | 630 | 600 | 480 | 380 | 290 | 210 | 180 | 380 |
| | Diffuse | 200 | 270 | 350 | 430 | 500 | 530 | 510 | 450 | 370 | 290 | 210 | 180 | 360 |
| | Clear-Day Global | 190 | 240 | 320 | 420 | 580 | 680 | 630 | 460 | 350 | 270 | 200 | 160 | 380 |
| East | Global | 480 | 610 | 760 | 940 | 1040 | 1110 | 1130 | 1040 | 880 | 730 | 500 | 400 | 800 |
| | Diffuse | 240 | 330 | 430 | 520 | 590 | 630 | 620 | 550 | 460 | 350 | 260 | 220 | 430 |
| | Clear-Day Global | 700 | 900 | 1140 | 1350 | 1450 | 1470 | 1440 | 1350 | 1180 | 950 | 740 | 630 | 1110 |
| South | Global | 1170 | 1170 | 1100 | 990 | 850 | 780 | 840 | 980 | 1130 | 1280 | 1120 | 1030 | 1040 |
| | Diffuse | 350 | 420 | 490 | 530 | 560 | 560 | 560 | 550 | 500 | 430 | 350 | 320 | 470 |
| | Clear-Day Global | 1940 | 1980 | 1800 | 1400 | 1060 | 910 | 960 | 1220 | 1610 | 1870 | 1900 | 1870 | 1540 |
| West | Global | 480 | 610 | 760 | 940 | 1070 | 1160 | 1190 | 1080 | 910 | 730 | 500 | 420 | 820 |
| | Diffuse | 250 | 330 | 430 | 530 | 600 | 640 | 630 | 570 | 470 | 360 | 260 | 220 | 440 |
| | Clear-Day Global | 700 | 900 | 1140 | 1350 | 1450 | 1470 | 1440 | 1350 | 1180 | 950 | 740 | 630 | 1110 |

### Average Transmitted Solar Radiation (Btu/ft²/day) for Double Glazing, Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Unshaded | 450 | 640 | 880 | 1160 | 1350 | 1490 | 1520 | 1330 | 1050 | 780 | 490 | 380 | 960 |
| North | Unshaded | 140 | 190 | 240 | 300 | 360 | 410 | 390 | 320 | 260 | 200 | 150 | 120 | 260 |
| | Shaded | 120 | 170 | 220 | 270 | 320 | 360 | 350 | 290 | 230 | 180 | 130 | 110 | 230 |
| East | Unshaded | 330 | 430 | 540 | 670 | 740 | 790 | 810 | 740 | 620 | 510 | 350 | 280 | 570 |
| | Shaded | 300 | 380 | 470 | 580 | 630 | 680 | 700 | 650 | 550 | 460 | 310 | 250 | 500 |
| South | Unshaded | 880 | 850 | 760 | 640 | 520 | 470 | 500 | 610 | 760 | 920 | 840 | 780 | 710 |
| | Shaded | 860 | 790 | 610 | 420 | 350 | 350 | 350 | 380 | 550 | 810 | 810 | 760 | 590 |
| West | Unshaded | 330 | 430 | 540 | 670 | 760 | 830 | 850 | 780 | 650 | 510 | 350 | 280 | 580 |
| | Shaded | 300 | 380 | 470 | 580 | 660 | 710 | 740 | 680 | 570 | 460 | 320 | 260 | 510 |

### Average Climatic Conditions

| Element | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°F) | 25.7 | 31.2 | 42.7 | 54.5 | 64.1 | 73.2 | 78.5 | 76.1 | 67.5 | 56.6 | 43.1 | 30.4 | 53.6 |
| Daily Minimum Temp | 16.7 | 21.8 | 32.6 | 43.8 | 53.9 | 63.1 | 68.2 | 65.7 | 56.9 | 45.7 | 33.6 | 21.9 | 43.7 |
| Daily Maximum Temp | 34.7 | 40.6 | 52.8 | 65.1 | 74.3 | 83.3 | 88.7 | 86.4 | 78.1 | 67.5 | 52.6 | 38.8 | 63.6 |
| Record Minimum Temp | -17.0 | -19.0 | -10.0 | 12.0 | 30.0 | 42.0 | 52.0 | 43.0 | 33.0 | 21.0 | 1.0 | -23.0 | -23.0 |
| Record Maximum Temp | 69.0 | 76.0 | 86.0 | 93.0 | 92.0 | 105.0 | 107.0 | 109.0 | 102.0 | 92.0 | 82.0 | 70.0 | 109.0 |
| HDD, Base 65°F | 1218 | 946 | 691 | 325 | 135 | 7 | 0 | 6 | 56 | 279 | 657 | 1073 | 5393 |
| CDD, Base 65°F | 0 | 0 | 0 | 10 | 107 | 253 | 419 | 350 | 131 | 18 | 0 | 0 | 1288 |
| Humidity Ratio (#w/#da) | 0.0023 | 0.0027 | 0.0040 | 0.0060 | 0.0090 | 0.0125 | 0.0143 | 0.0135 | 0.0107 | 0.0068 | 0.0045 | 0.0029 | 0.0074 |
| Wind Speed (mph) | 10.9 | 10.9 | 12.2 | 12.0 | 10.3 | 9.7 | 9.2 | 9.0 | 9.2 | 10.0 | 10.7 | 10.8 | 10.4 |
| Clearness Index, Kt | 0.50 | 0.50 | 0.50 | 0.52 | 0.53 | 0.55 | 0.58 | 0.56 | 0.54 | 0.54 | 0.48 | 0.46 | 0.53 |

### Average Incident Illuminance (klux-hr) for Mostly Clear/Mostly Cloudy Conditions, Uncertainty ±9%

| Orientation | March | | | | | June | | | | | September | | | | | December | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm |
| Horizontal | 34/20 | 69/42 | 82/51 | 68/42 | 32/20 | 42/27 | 81/55 | 101/70 | 98/72 | 73/53 | 23/13 | 63/37 | 85/53 | 81/53 | 53/34 | 11/7 | 39/23 | 48/29 | 33/20 | 4/3 |
| North | 9/8 | 13/15 | 15/17 | 13/15 | 9/8 | 20/14 | 16/17 | 17/19 | 17/19 | 16/16 | 7/6 | 13/14 | 16/17 | 15/17 | 12/13 | 4/3 | 9/9 | 10/11 | 8/8 | 2/2 |
| East | 73/24 | 62/31 | 15/17 | 13/15 | 9/8 | 75/35 | 76/46 | 38/30 | 17/19 | 16/16 | 61/18 | 73/34 | 35/25 | 15/17 | 12/13 | 36/9 | 43/18 | 10/11 | 8/8 | 2/2 |
| South | 35/15 | 70/34 | 83/43 | 69/34 | 33/15 | 11/10 | 28/23 | 45/35 | 43/35 | 24/21 | 17/8 | 53/27 | 75/41 | 71/41 | 43/25 | 30/8 | 79/27 | 92/34 | 70/24 | 13/4 |
| West | 9/8 | 13/15 | 16/17 | 63/32 | 71/26 | 11/10 | 16/17 | 17/19 | 46/37 | 78/50 | 7/6 | 13/14 | 16/17 | 48/31 | 75/37 | 4/3 | 9/9 | 16/13 | 49/18 | 18/5 |
| M. Clr (%hrs) | 34 | 32 | 31 | 30 | 32 | 39 | 40 | 39 | 38 | 41 | 46 | 47 | 47 | 46 | 47 | 35 | 36 | 35 | 36 | 37 |

As noted, *Solar Radiation Data Manual for Buildings* and *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling* are available for free download, however all of the pages from these two references needed for the examples in this course and for the quiz are included at the end of the course materials, starting on page 25.

**Example #3**: Find an estimate of the average amount of solar radiation per day (in Btu/day), which will strike a 24" by 36" south facing window in Kansas City, MO, in January using each of the two references discussed above.

**Solution:** From *Solar Radiation Data Manual for Buildings*, page 117, (p 14 of this course) the average daily incident global solar radiation on a south-facing surface in Kansas City, MO in January is 1170 Btu/ft$^2$/day. For the 6 ft$^2$ window in the example, the daily incident radiation would thus be: (1170 Btu/ft$^2$/day)(6 ft$^2$) = **7020 Btu/day**

**NOTE:** from page 117 of *Solar Radiation Data Manual for Buildings*, it can be found that the latitude for Kansas City, MO is **39.30$^o$ north**. This information can also be found by doing a "Google search" or "Yahoo search" for "Kansas City, MO latitude". Note that you may find a slightly different value for latitude if your source gives the latitude for a different part of the city.

As found in *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, Appendix 2, first page (p 27 of this course): The sunny day solar radiation rate on a south wall for January 21, is 1779 Btu/day/ft$^2$ for 32$^o$ N latitude and 1726 Btu/day/ft$^2$ for 40$^o$ N latitude. The value for 39.30$^o$ N latitude can be found by interpolation, as follows:

$$1726 + [(40 - 39.30)/(40 - 32)]\ (1779 - 1726) = \underline{1731 \text{ Btu/day/ft}^2}$$

From the map on the first page of Appendix 3 (p 28 of this course), the average % time that the sun is shining in Kansas City, MO, in January, is about 50%, thus the average daily solar radiation striking the south-facing window would be:

$$(0.5)(1731 \text{ Btu/ft}^2\text{/day})(6 \text{ ft}^2) = \mathbf{5193\ Btu/day}$$

You may have noticed that the numbers from the two sources differ by quite a bit. The data in the two sources come from different databases. The NREL publication uses U.S. Weather Bureau data for the period 1961 – 1990. Anderson & Wells, in their 1981 book, use data from ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) *Handbook of Fundamentals*, 1972. Also, the NREL data is monthly averages, and the ASHRAE data is for the 21$^{st}$ of the month, so they can be expected to be somewhat different for that reason.

**Example #4:** From the same two sources used in **Example #3**, find an estimate of the average amount of solar radiation per day (in Btu/day), which will be transmitted through an unshaded 24" by 36" south facing, double pane, glass window in Kansas City, MO, in January.

**Solution: :** From *Solar Radiation Data Manual for Buildings*, page 117 (page 14 of this course), the average daily solar radiation transmitted through an unshaded, south-facing, double pane, glass window, in Kansas City, MO is 880 Btu/ft$^2$/day. For the 6 ft$^2$ window in the example, the daily incident radiation would thus be:

(880 Btu/ft$^2$/day)(6 ft$^2$) = **5280 Btu/day**

From *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, page 43, approximately 82% of the incident solar radiation will be transmitted through a single layer of glass. Thus, for a double pane window, an estimate of the solar radiation transmitted through the glass can be calculated from the 5193 Btu/day of incident solar radiation calculated above, as follows:

(0.82)(0.82)(5193 Btu/day) = **3492 Btu/day**

Once again the two estimates differ, because of differences between the two databases used.

## 8. Size and Performance Calculations for Passive Solar Systems

The primary parameter to be determined in order to size a passive solar heating system, is the area of south-facing glazing. The other major component, heat storage, then can be sized to match the area of glazing. The fraction of a building's heating load that is handled by solar heating is a parameter often used in some way when designing or sizing a passive solar system. A larger area of glazing, will result in larger solar savings fraction for a given building. Anderson & Wells (ref #2 under "Related Links & References" for this course) provide some rules of thumb and guidelines for preliminary sizing of a passive solar heating system. Calculations to check more closely on the preliminary sizing decision can then be made. That approach will be discussed and illustrated with examples here. Another, more detailed, sophisticated calculation procedure is available in Goswami, Krieth, & Krieder (ref #1 under "Related Links & References" for this course).

Anderson & Wells suggest that the average percentage of daytime hours that the sun is shining during the heating season at the location of interest can be used as an estimate of the optimum percentage of the building heating load to be provided by a passive heating system. The average percentage of daytime hours that the sun is shining during the heating season can be obtained from the maps in Appendix 3 of Anderson & Wells' book. Looking at those maps shows that this percentage is approximately 50% for much of the United States. The fraction is notably higher in the southwest and lower in the northwest.

Anderson & Wells also suggest that on the average each square foot of south-facing glazing will supply about the same amount of heat over a heating season as a barrel of fuel oil, about 60,000 Btu. This figure will be lower in very cloudy areas, perhaps as low as half, or 30,000 Btu. In the sunny southwestern U.S., it will be higher, perhaps as high as twice or 120,000 Btu.

**Example #5:** Using Anderson & Wells' guidelines given above, estimate the approximate glazing area that would be optimum for a passive solar heating system for the Albuquerque house described in **Example #2**.

**Solution:** From Appendix 3 of Anderson & Wells' book, (pp 28 & 29 of this course) the average percentage of daytime that the sun is shining in Albuquerque, NM is 60 to 65% for Nov, Dec, Jan, & Feb (most of the heating season). Choose a target of 60% solar reduction in heating fuel consumption. From Anderson & Wells' rules of thumb for Btu/sq. ft. of glazing, try 120,000 Btu/ft$^2$ as an estimate for the Albuquerque area.

From **Example # 2,** the estimated heat requirement for heating the house in a season is $4.93*10^7$ Btu. The required glazing to deliver 60% of this heat is thus estimated as:

$$(0.6)(4.93*10^7 \text{ Btu})/120{,}000 \text{ Btu/ft}^2 = 246 \text{ ft}^2$$

**Example #6:** Using data for heating degree days and rate of solar radiation transmitted through south-facing, double layer glazing in Albuquerque, NM, estimate the percentage of the heating load that would be provided by the 246 ft$^2$ glazing area calculated in **Example #5** for the 2000 ft$^2$ home in **Example #4**, for each month of the heating season. Use the heat loss rate of 5.6 Btu/$^o$F-day/ft$^2$, calculated in **Example #2** for this house.

**Solution:** The data and calculations are summarized in the spreadsheet table copied below. The second and third columns give monthly values for heating degree-days and solar radiation transmitted through a shaded, double glazed, south-facing window in Albuquerque, NM, from page 148 of the NREL publication, *Solar Radiation Data Manual for Buildings*. (see p 30 of this course) The fourth column was calculated by multiplying the monthly heating degree-days from column 2 times 5.6 Btu/$^o$F-day/ft$^2$ times the 2000 ft$^2$ floor area of the house. The monthly solar % given in the sixth column is simply column 5 divided by column 4, expressed as a percentage.

**Albuquerque, NM**

| Month | heating °F-days | Solar Input Btu /day/ft² | Heating Requirement Btus | Solar Heat Input (246 ft²) Btus | Solar % |
|---|---|---|---|---|---|
| Jan | 955 | 1220 | 10,696,000 | 9,303,720 | 87.0% |
| Feb | 700 | 1110 | 7,840,000 | 8,464,860 | 108.0% |
| Mar | 561 | 800 | 6,283,200 | 6,100,800 | 97.1% |
| Apr | 301 | 490 | 3,371,200 | 3,736,740 | 110.8% |
| May | 89 | 360 | 996,800 | 2,745,360 | 275.4% |
| June | 0 | | | | |
| July | 0 | | | | |
| Aug | 0 | | | | |
| Sept | 18 | 650 | 201,600 | 4,956,900 | 2458.8% |
| Oct | 259 | 1040 | 2,900,800 | 7,931,040 | 273.4% |
| Nov | 621 | 1200 | 6,955,200 | 9,151,200 | 131.6% |
| Dec | 921 | 1200 | 10,315,200 | 9,151,200 | 88.7% |

**Discussion of Results:** The solar percentage results are quite high, indicating that the 246 $ft^2$ glazing area is more than required for this area of the country. Thus the calculations will be repeated with 170 $ft^2$ of south-facing glazing instead of 246 $ft^2$. The results are summarized in the table below. These results are much closer to the target level of 60% of heating requirement to be supplied by the solar system. There is more than enough solar input for the heating requirements in May, September and October. For the rest of the heating season, the solar percentage is between 57% and 86%.

**Albuquerque, NM**

| Month | heating °F-days | Solar Input Btu /day/ft² | Heating Requirement Btus | Solar Heat Input (160 ft²) Btus | Solar % |
|---|---|---|---|---|---|
| Jan | 955 | 1220 | 10,696,000 | 6,051,200 | 56.6% |
| Feb | 700 | 1110 | 7,840,000 | 5,505,600 | 70.2% |
| Mar | 561 | 800 | 6,283,200 | 3,968,000 | 63.2% |
| Apr | 301 | 490 | 3,371,200 | 2,430,400 | 72.1% |
| May | 89 | 360 | 996,800 | 1,785,600 | 179.1% |
| June | 0 | | | | |
| July | 0 | | | | |
| Aug | 0 | | | | |
| Sept | 18 | 650 | 201,600 | 3,224,000 | 1599.2% |
| Oct | 259 | 1040 | 2,900,800 | 5,158,400 | 177.8% |
| Nov | 621 | 1200 | 6,955,200 | 5,952,000 | 85.6% |
| Dec | 921 | 1200 | 10,315,200 | 5,952,000 | 57.7% |

**Example #7:** To illustrate the effect of climate in a different part of the country repeat the last set of calculations for Kansas City, MO. Use 160 $ft^2$ of glazing, 2000 $ft^2$ floor area and 5.6 Btu/°F-day/$ft^2$ as the heat loss rate for the house.

**Solution:** The calculations are summarized in the table below. The data for heating degree-days and solar input through south-facing glazing came from page 117 of the NREL publication, *Solar Radiation Data Manual for Buildings*. (p 14 of this course) The other columns were calculated just the same as above.

**Kansas City, MO**

| Month | heating °F-days | Solar Input Btu /day/ft² | Heating Requirement Btus | Solar Heat Input (200 ft²) Btus | Solar % |
|---|---|---|---|---|---|
| Jan | 1218 | 880 | 13,641,600 | 4,364,800 | 32.0% |
| Feb | 946 | 850 | 10,595,200 | 4,216,000 | 39.8% |
| Mar | 691 | 760 | 7,739,200 | 3,769,600 | 48.7% |
| Apr | 325 | 640 | 3,640,000 | 3,174,400 | 87.2% |
| May | 135 | 520 | 1,512,000 | 2,579,200 | 170.6% |
| June | 7 | | | | |
| July | 0 | | | | |
| Aug | 6 | | | | |
| Sept | 56 | 760 | 627,200 | 3,769,600 | 601.0% |
| Oct | 279 | 920 | 3,124,800 | 4,563,200 | 146.0% |
| Nov | 657 | 840 | 7,358,400 | 4,166,400 | 56.6% |
| Dec | 1073 | 780 | 12,017,600 | 3,868,800 | 32.2% |

As was the case for Albuquerque, there is more than enough solar input from 160 $ft^2$ of south-facing glazing to provide the heating requirements for May, September and October. For the rest of the heating season, however, the solar percentage is between 32% and 87% for Kansas City, as compared with 56% to 83% for Albuquerque. The solar percentage is significantly lower in Kansas City than in Albuquerque for all of the months except April. There are indeed less clouds in the sky in the southwestern U.S.

The glazing area determined by this method can be taken as an approximate value. More area or less area may be used to accommodate convenient sizes of components actually used for the passive solar heating system. In fact, Anderson & Wells (ref #2 under "Related Links & References" for this course), suggest that your answer to the question, "How large do you want the system to be?" is a common, direct, and useful method of determining size. The calculations illustrated above, however, provide a means of estimating solar % of heating requirement for a given size passive solar system, at a given location, with given building heat loss characteristics.

## 9. Choice of the Type(s) of Passive Solar System to Use

After deciding upon an approximate total area of glazing, it is necessary to choose from among the five basic passive solar heating systems discussed above, **direct gain, thermal storage wall, attached sunspace, thermal storage roof, and convective loop.** Any combination can be used to come up with the desired total area of glazing.

For retrofit on an existing home, the attached sunspace and the convective loop (solar chiminey) are especially suitable. Also, one may add more south-facing windows or upgrade existing south-facing windows to increase direct gain. If a thermal storage wall were to be used for retrofit, the choice would probably be made for a "water wall" rather than a masonry wall, because of the difficulty of inserting a masonry wall for retrofit.. A thermal storage roof (roof pond) is another possibility to go onto a flat roof or into an attic under glazing on a pitched roof. Remember, however, that a thermal storage roof requires a somewhat elaborate drainage system, movable insulation to cover and uncover the water at appropriate times, and a structural system to support up to 65 lbs/sq ft dead load.

For new construction, any combination of the five types of systems can be used. Maximizing southern exposure for the building and using a lot of south-facing windows would be typical in order to obtain direct gain of solar heat. A masonry thermal storage wall in front of some of the south-facing glazing, could readily be included for new construction. An attached sunspace works best if the back of the house faces south.

## 10. Sizing Solar Storage

Both of the references mentioned in the previous couple of sections include guidelines for required quantity of thermal storage. Anderson & Wells, in *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, (ref #2 under "Related Links & References" for this course), give a rule of thumb for thermal storage requirement as 2 cubic feet of concrete, brick or stone for each square foot of glazing, if the sun shines directly upon the storage material. If the sun heats air, which in turn heats the thermal storage material, then the requirement is given as four times that much, or 8 cubic feet of masonry storage per square foot of glazing.

Goswami, Krieth, & Krieder (ref #1 under "Related Links & References" for this course) give a rule of thumb that there should be 613 kJ/ºC for each $m^2$ of glazing, if the sunlight shines directly on the storage material. They also give a requirement of four times that much if the sunlight does not shine directly on the storage mass. Converting units, this rule of thumb is equivalent to 30 Btu/ºF for each $ft^2$ of glazing. This can be converted to the volume of material needed for thermal storage in $ft^3$ using the information in table 1, below.

Table 1. Thermal Properties of Some Materials

| Material | Specific Heat (Btu/lb/ºF) | Density lb/$ft^3$ | Volumetric Heat Capacity Btu/$ft^3$/ºF |
|---|---|---|---|
| Air (75ºF) | 0.24 | 0.075 | 0.018 |
| Sand | 0.191 | 94.6 | 18.1 |
| White Pine | 0.67 | 27 | 18.1 |
| Gypsum | 0.26 | 78 | 20.3 |
| Adobe | 0.24 | 106 | 25 |
| White Oak | 0.57 | 47 | 26.8 |
| Concrete | 0.2 | 140 | 28 |
| Brick | 0.21 | 140 | 28 |
| Heavy Stone | 0.21 | 180 | 38 |
| Water | 1 | 62.5 | 62.5 |

The volume of any of the materials in Table 1, needed per $ft^2$ of glazing can be found by dividing 30 Btu/°F by the volumetric heat capacity (Btu/$ft^3$/°F) for that material. For example (30/28) $ft^3$ of concrete or brick (or approximately 1 $ft^3$) is needed for thermal storage per square foot of glazing based on the above rule of thumb. By comparison, only 30/62.5, or about ½ cubic foot of water is needed per square foot of glazing.

As you can see, Anderson & Wells give a more conservative thermal storage requirement than Goswami, Krieth, & Krieder.

## 11. Controls - Summer Shading of Passive Solar Glazing

In order to reduce unwanted heat gain in the summer, it is helpful to provide shading above south-facing solar glazing. The NREL publication, *Solar Radiation Data Manual for Buildings*, provides recommendatiohns for summertime shading of south-facing vertical passive solar glazing. Near the top of the page for each of the 239 stations represented in the publication, there is a figure similar to Figure 8, below, showing the length of overhang and height of overhang above the top of the glazing for each foot of vertical height of the glazing. The recommended shading geometry provides a balance between the need for maximum heat gain during the heating season without creating unreasonable heat gain during the cooling season. This can be done because the sun is much lower in the sky in the winter than in the summer, as illustrated in Figure 9, below.

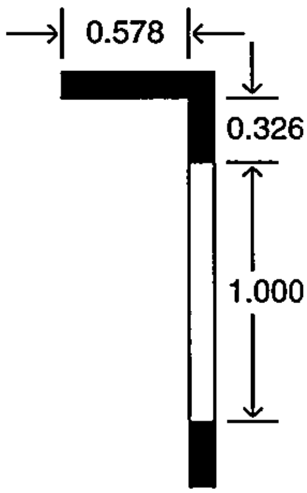



Figure 8. Recommended Shading Geometry

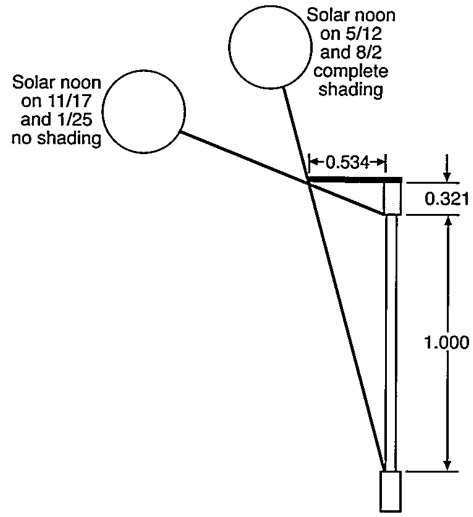



Figure 9. Effect of Winter & Summer Solar Altitude Angle

## 12. Construction Details

Information on construction details is available from various sources. For example in *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, by Anderson & Wells (ref #2 under "Related Links & References" for this course). Also the first website listed under "Related Links & References" for this course, http://www.builditsolar.com/Projects/SpaceHeating/Space_Heating.htm#Basics , has information and plans for many DIY passive solar projects.

## 13. Related Links and References

**References:**

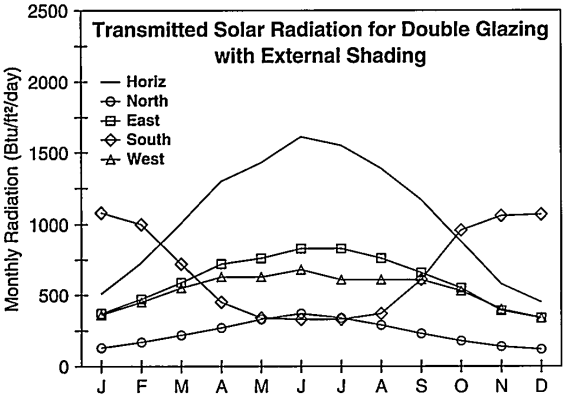
1. Goswami, D. Y., Krieth, Frank, and Kreider, Jan F., *Principles of Solar Engineering,* Philadelphia: Taylor & Francis, 2000.

2. Anderson, Bruce & Wells, Malcolm, *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling,* Andover MA: Brickhouse Publishing Co., 1981 (available for free download at the website given below:)
http://www.builditsolar.com/Projects/SolarHomes/PasSolEnergyBk/PSEbook.htm

**Websites:**

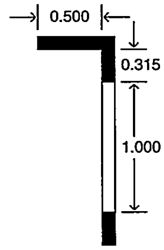
1. Solar DIY Space Heating Projects
http://www.builditsolar.com/Projects/SpaceHeating/Space_Heating.htm#Basics

2. Passive Solar Heating & Cooling – Arizona Solar Center
http://www.azsolarcenter.com/technology/pas-2.html




# Colorado Springs, CO

## WBAN NO. 93037




**Shading Geometry (Not to Scale)**

LATITUDE: 38.82° N
LONGITUDE: 104.72° W
ELEVATION: 6172 feet
MEAN PRESSURE: 11.8 psia

STATION TYPE: Secondary

### Average Incident Solar Radiation (Btu/ft²/day), Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Global | 800 | 1070 | 1420 | 1790 | 1960 | 2200 | 2110 | 1910 | 1630 | 1270 | 880 | 720 | 1480 |
| | Std.Dev. | 49 | 54 | 97 | 97 | 113 | 136 | 117 | 107 | 104 | 97 | 49 | 42 | 41 |
| | Minimum | 690 | 950 | 1170 | 1530 | 1740 | 1950 | 1930 | 1650 | 1360 | 1010 | 800 | 640 | 1410 |
| | Maximum | 890 | 1150 | 1610 | 2000 | 2210 | 2440 | 2350 | 2120 | 1820 | 1420 | 990 | 800 | 1550 |
| | Diffuse | 260 | 350 | 500 | 610 | 710 | 670 | 660 | 600 | 470 | 350 | 280 | 240 | 480 |
| | Clear-Day Global | 1010 | 1370 | 1870 | 2380 | 2680 | 2790 | 2710 | 2430 | 2000 | 1500 | 1080 | 900 | 1900 |
| North | Global | 200 | 260 | 350 | 440 | 560 | 640 | 590 | 470 | 360 | 280 | 220 | 180 | 380 |
| | Diffuse | 200 | 260 | 350 | 420 | 480 | 500 | 480 | 430 | 360 | 280 | 220 | 180 | 350 |
| | Clear-Day Global | 180 | 230 | 310 | 420 | 600 | 730 | 660 | 470 | 330 | 260 | 190 | 160 | 380 |
| East | Global | 580 | 740 | 940 | 1140 | 1220 | 1340 | 1340 | 1220 | 1050 | 860 | 620 | 530 | 970 |
| | Diffuse | 250 | 320 | 430 | 520 | 570 | 580 | 570 | 530 | 440 | 350 | 270 | 230 | 420 |
| | Clear-Day Global | 780 | 990 | 1250 | 1470 | 1580 | 1600 | 1560 | 1470 | 1290 | 1050 | 810 | 710 | 1210 |
| South | Global | 1450 | 1450 | 1300 | 1090 | 860 | 790 | 820 | 1000 | 1270 | 1510 | 1450 | 1430 | 1200 |
| | Diffuse | 360 | 420 | 490 | 530 | 540 | 520 | 520 | 520 | 480 | 420 | 370 | 330 | 460 |
| | Clear-Day Global | 2110 | 2120 | 1900 | 1440 | 1050 | 880 | 940 | 1230 | 1670 | 2010 | 2080 | 2060 | 1620 |
| West | Global | 580 | 710 | 870 | 1010 | 1030 | 1110 | 1000 | 990 | 960 | 840 | 630 | 530 | 860 |
| | Diffuse | 250 | 330 | 440 | 530 | 580 | 590 | 580 | 530 | 450 | 350 | 270 | 230 | 430 |
| | Clear-Day Global | 780 | 990 | 1250 | 1470 | 1580 | 1600 | 1560 | 1470 | 1290 | 1050 | 810 | 710 | 1210 |

### Average Transmitted Solar Radiation (Btu/ft²/day) for Double Glazing, Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Unshaded | 510 | 730 | 1010 | 1300 | 1430 | 1610 | 1550 | 1390 | 1170 | 880 | 580 | 450 | 1050 |
| North | Unshaded | 140 | 180 | 240 | 300 | 360 | 410 | 380 | 310 | 250 | 200 | 150 | 130 | 250 |
| | Shaded | 130 | 170 | 220 | 270 | 330 | 370 | 340 | 290 | 230 | 180 | 140 | 120 | 230 |
| East | Unshaded | 400 | 520 | 670 | 820 | 870 | 960 | 970 | 880 | 750 | 610 | 430 | 360 | 690 |
| | Shaded | 370 | 470 | 590 | 720 | 760 | 830 | 830 | 760 | 660 | 550 | 390 | 340 | 610 |
| South | Unshaded | 1100 | 1070 | 900 | 700 | 520 | 460 | 480 | 620 | 850 | 1080 | 1090 | 1080 | 830 |
| | Shaded | 1080 | 1000 | 720 | 450 | 340 | 330 | 330 | 370 | 610 | 960 | 1060 | 1070 | 690 |
| West | Unshaded | 400 | 500 | 610 | 720 | 730 | 790 | 710 | 700 | 680 | 590 | 430 | 370 | 600 |
| | Shaded | 360 | 450 | 550 | 630 | 630 | 680 | 610 | 610 | 610 | 530 | 400 | 340 | 530 |

### Average Climatic Conditions

| Element | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°F) | 28.8 | 32.0 | 37.3 | 46.4 | 55.4 | 65.0 | 70.8 | 68.3 | 60.4 | 49.9 | 37.8 | 29.8 | 48.5 |
| Daily Minimum Temp | 16.1 | 19.3 | 24.6 | 33.0 | 42.1 | 51.1 | 57.1 | 55.2 | 47.1 | 36.3 | 24.9 | 17.4 | 35.4 |
| Daily Maximum Temp | 41.4 | 44.6 | 50.0 | 59.8 | 68.7 | 79.0 | 84.4 | 81.3 | 73.6 | 63.5 | 50.7 | 42.2 | 61.6 |
| Record Minimum Temp | -26.0 | -27.0 | -11.0 | -3.0 | 21.0 | 32.0 | 42.0 | 43.0 | 22.0 | 5.0 | -8.0 | -24.0 | -27.0 |
| Record Maximum Temp | 72.0 | 76.0 | 81.0 | 83.0 | 93.0 | 100.0 | 100.0 | 99.0 | 94.0 | 86.0 | 78.0 | 77.0 | 100.0 |
| HDD, Base 65°F | 1122 | 924 | 859 | 558 | 302 | 87 | 6 | 18 | 164 | 468 | 816 | 1091 | 6415 |
| CDD, Base 65°F | 0 | 0 | 0 | 0 | 0 | 87 | 186 | 120 | 26 | 0 | 0 | 0 | 419 |
| Humidity Ratio (#w/#da) | 0.0018 | 0.0020 | 0.0024 | 0.0033 | 0.0051 | 0.0070 | 0.0089 | 0.0089 | 0.0064 | 0.0038 | 0.0025 | 0.0019 | 0.0045 |
| Wind Speed (mph) | 9.2 | 9.6 | 10.6 | 11.3 | 10.8 | 9.7 | 8.9 | 8.5 | 9.2 | 9.5 | 9.4 | 8.9 | 9.6 |
| Clearness Index, Kt | 0.56 | 0.57 | 0.57 | 0.58 | 0.56 | 0.60 | 0.59 | 0.58 | 0.59 | 0.60 | 0.56 | 0.55 | 0.58 |

### Average Incident Illuminance (klux-hr) for Mostly Clear/Mostly Cloudy Conditions, Uncertainty ±9%

| Orientation | March | | | | | June | | | | | September | | | | | December | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm |
| Horizontal | 44/29 | 76/51 | 84/59 | 66/45 | 28/18 | 52/35 | 87/65 | 102/78 | 97/66 | 69/46 | 33/19 | 71/47 | 87/60 | 80/54 | 48/32 | 18/12 | 45/31 | 50/35 | 31/21 | 2/2 |
| North | 10/10 | 13/15 | 14/17 | 12/14 | 8/7 | 18/15 | 15/17 | 16/17 | 16/17 | 13/14 | 8/8 | 13/15 | 15/17 | 14/16 | 11/11 | 6/5 | 10/10 | 10/11 | 8/8 | 1/1 |
| East | 83/39 | 57/36 | 14/17 | 12/14 | 8/7 | 87/45 | 72/52 | 28/26 | 16/17 | 13/14 | 79/29 | 72/42 | 26/23 | 14/16 | 11/11 | 52/20 | 41/24 | 10/11 | 8/8 | 1/1 |
| South | 45/24 | 76/45 | 84/53 | 66/39 | 28/14 | 11/11 | 30/27 | 44/37 | 39/30 | 17/16 | 25/12 | 59/36 | 75/48 | 68/43 | 39/22 | 49/19 | 90/45 | 95/52 | 69/33 | 8/3 |
| West | 10/10 | 13/15 | 25/22 | 70/41 | 74/28 | 11/11 | 15/17 | 16/17 | 53/38 | 82/48 | 8/8 | 13/15 | 15/17 | 56/37 | 81/39 | 6/5 | 10/10 | 24/18 | 55/27 | 11/4 |
| M. Clr (%hrs) | 42 | 42 | 34 | 31 | 31 | 60 | 59 | 52 | 36 | 31 | 58 | 59 | 56 | 49 | 45 | 47 | 47 | 44 | 45 | 50 |

| State | City | Avg. Winter Temp | Design Temp | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Yearly Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ala. | Birmingham | 54.2 | 19 | 6 | 93 | 363 | 555 | 592 | 462 | 363 | 108 | 9 | 2551 |
| | Huntsville | 51.3 | 13 | 12 | 127 | 426 | 663 | 694 | 557 | 434 | 138 | 19 | 3070 |
| | Mobile | 59.9 | 26 | 0 | 22 | 213 | 357 | 415 | 300 | 211 | 42 | 0 | 1560 |
| | Montgomery | 55.4 | 22 | 0 | 68 | 330 | 527 | 543 | 417 | 316 | 90 | 0 | 2291 |
| Alaska | Anchorage | 23.0 | −25 | 516 | 930 | 1284 | 1572 | 1631 | 1316 | 1293 | 879 | 592 | 10864 |
| | Fairbanks | 6.7 | −53 | 642 | 1203 | 1833 | 2254 | 2359 | 1901 | 1739 | 1068 | 555 | 14279 |
| | Juneau | 32.1 | − 7 | 483 | 725 | 921 | 1135 | 1237 | 1070 | 1073 | 810 | 601 | 9075 |
| | Nome | 13.1 | −32 | 693 | 1094 | 1455 | 1820 | 1879 | 1666 | 1770 | 1314 | 930 | 14171 |
| Ariz. | Flagstaff | 35.6 | 0 | 201 | 558 | 867 | 1073 | 1169 | 991 | 911 | 651 | 437 | 7152 |
| | Phoenix | 58.5 | 31 | 0 | 22 | 234 | 415 | 474 | 328 | 217 | 75 | 0 | 1765 |
| | Tucson | 58.1 | 29 | 0 | 25 | 231 | 406 | 471 | 344 | 242 | 75 | 6 | 1800 |
| | Winslow | 43.0 | 9 | 6 | 245 | 711 | 1008 | 1054 | 770 | 601 | 291 | 96 | 4782 |
| | Yuma | 64.2 | 37 | 0 | 0 | 108 | 264 | 307 | 190 | 90 | 15 | 0 | 974 |
| Ark. | Fort Smith | 50.3 | 9 | 12 | 127 | 450 | 704 | 781 | 596 | 456 | 144 | 22 | 3292 |
| | Little Rock | 50.5 | 19 | 9 | 127 | 465 | 716 | 756 | 577 | 434 | 126 | 9 | 3219 |
| | Texarkana | 54.2 | 22 | 0 | 78 | 345 | 561 | 626 | 468 | 350 | 105 | 0 | 2533 |
| Calif. | Bakersfield | 55.4 | 31 | 0 | 37 | 282 | 502 | 546 | 364 | 267 | 105 | 19 | 2122 |
| | Burbank | 58.6 | 36 | 6 | 43 | 177 | 301 | 366 | 277 | 239 | 138 | 81 | 1646 |
| | Eureka | 49.9 | 32 | 258 | 329 | 414 | 499 | 546 | 470 | 505 | 438 | 372 | 4643 |
| | Fresno | 53.3 | 28 | 0 | 84 | 354 | 577 | 605 | 426 | 335 | 162 | 62 | 2611 |
| | Long Beach | 57.8 | 36 | 9 | 47 | 171 | 316 | 397 | 311 | 264 | 171 | 93 | 1803 |
| | Los Angeles | 57.4 | 41 | 42 | 78 | 180 | 291 | 372 | 302 | 288 | 219 | 158 | 2061 |
| | Oakland | 53.5 | 35 | 45 | 127 | 309 | 481 | 527 | 400 | 353 | 255 | 180 | 2870 |
| | Sacramento | 53.9 | 30 | 0 | 56 | 321 | 546 | 583 | 414 | 332 | 178 | 72 | 2502 |
| | San Diego | 59.5 | 42 | 21 | 43 | 135 | 236 | 298 | 235 | 214 | 135 | 90 | 1458 |
| | San Francisco | 55.1 | 42 | 102 | 118 | 231 | 388 | 443 | 336 | 319 | 279 | 239 | 3001 |
| | Santa Maria | 54.3 | 32 | 96 | 146 | 270 | 391 | 459 | 370 | 363 | 282 | 233 | 2967 |
| Colo. | Alamosa | 29.7 | −17 | 279 | 639 | 1065 | 1420 | 1476 | 1162 | 1020 | 696 | 440 | 8529 |
| | Colorado Springs | 37.3 | − 1 | 132 | 456 | 825 | 1032 | 1128 | 938 | 893 | 582 | 319 | 6423 |
| | Denver | 37.6 | − 2 | 117 | 428 | 819 | 1035 | 1132 | 938 | 887 | 558 | 288 | 6283 |
| | Grand Junction | 39.3 | 8 | 30 | 313 | 786 | 1113 | 1209 | 907 | 729 | 387 | 146 | 5641 |
| | Pueblo | 40.4 | − 5 | 54 | 326 | 750 | 986 | 1085 | 871 | 772 | 429 | 174 | 5462 |
| Conn. | Bridgeport | 39.9 | 4 | 66 | 307 | 615 | 986 | 1079 | 966 | 853 | 510 | 208 | 5617 |
| | Hartford | 37.3 | 1 | 117 | 394 | 714 | 1101 | 1190 | 1042 | 908 | 519 | 205 | 6235 |
| | New Haven | 39.0 | 5 | 87 | 347 | 648 | 1011 | 1097 | 991 | 871 | 543 | 245 | 5897 |
| Del. | Wilmington | 42.5 | 12 | 51 | 270 | 588 | 927 | 980 | 874 | 735 | 387 | 112 | 4930 |
| D. C. | Washington | 45.7 | 16 | 33 | 217 | 519 | 834 | 871 | 762 | 626 | 288 | 74 | 4224 |
| Fla. | Daytona Beach | 64.5 | 32 | 0 | 0 | 75 | 211 | 248 | 190 | 140 | 15 | 0 | 879 |
| | Fort Myers | 68.6 | 38 | 0 | 0 | 24 | 109 | 146 | 101 | 62 | 0 | 0 | 442 |
| | Jacksonville | 61.9 | 29 | 0 | 12 | 144 | 310 | 332 | 246 | 174 | 21 | 0 | 1239 |
| | Key West | 73.1 | 55 | 0 | 0 | 0 | 28 | 40 | 31 | 9 | 0 | 0 | 108 |
| | Lakeland | 66.7 | 35 | 0 | 0 | 57 | 164 | 195 | 146 | 99 | 0 | 0 | 661 |
| | Miami | 71.1 | 44 | 0 | 0 | 0 | 65 | 74 | 56 | 19 | 0 | 0 | 214 |
| | Miami Beach | 72.5 | 45 | 0 | 0 | 0 | 40 | 56 | 36 | 9 | 0 | 0 | 141 |
| | Orlando | 65.7 | 33 | 0 | 0 | 72 | 198 | 220 | 165 | 105 | 6 | 0 | 766 |
| | Pensacola | 60.4 | 29 | 0 | 19 | 195 | 353 | 400 | 277 | 183 | 36 | 0 | 1463 |
| | Tallahassee | 60.1 | 25 | 0 | 28 | 198 | 360 | 375 | 286 | 202 | 36 | 0 | 1485 |

# Appendix 2

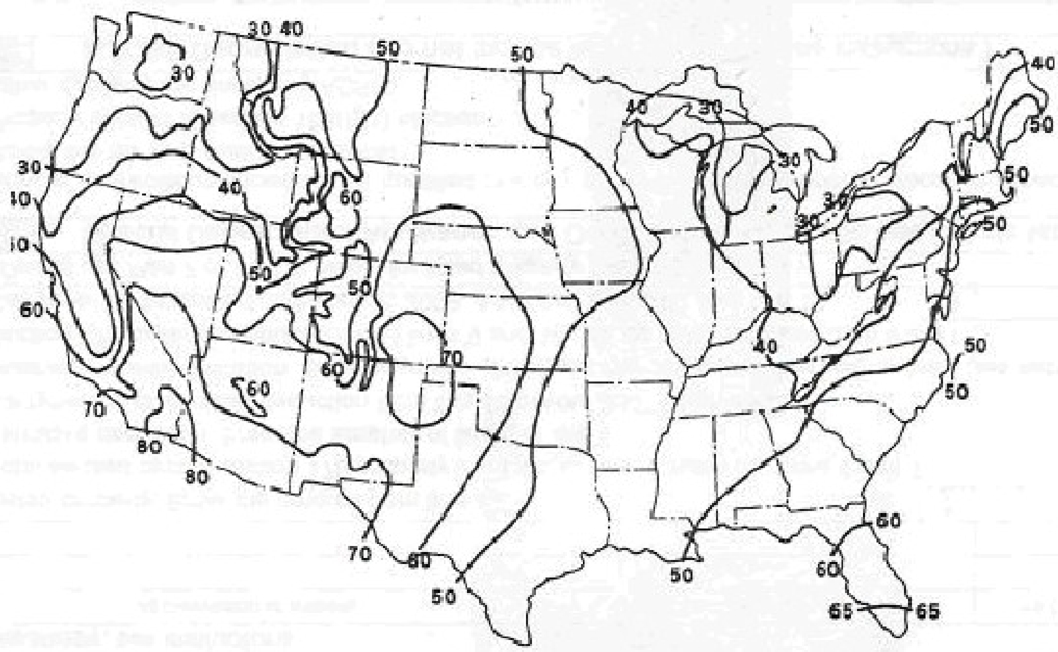
## Solar Radiation on South Walls on Sunny Days *

| Date | Solar Time AM | Solar Time PM | Solar Radiation, Btus per hour per square foot — Latitude (North) 24 | 32 | 40 | 48 | 56 | 64 |
|---|---|---|---|---|---|---|---|---|
| Jan 21 | 7 | 5 | 31 | 1 | 0 | 0 | 0 | 0 |
| | 8 | 4 | 127 | 115 | 84 | 22 | 0 | 0 |
| | 9 | 3 | 176 | 181 | 171 | 139 | 60 | 0 |
| | 10 | 2 | 207 | 221 | 223 | 206 | 153 | 20 |
| | 11 | 1 | 226 | 245 | 253 | 243 | 201 | 81 |
| | 12 | | 232 | 253 | 263 | 255 | 217 | 103 |
| | Daily Totals | | 1766 | 1779 | 1726 | 1478 | 1044 | 304 |
| Feb 21 | 7 | 5 | 46 | 38 | 22 | 4 | 0 | 0 |
| | 8 | 4 | 102 | 108 | 107 | 96 | 69 | 19 |
| | 9 | 3 | 141 | 158 | 167 | 167 | 151 | 107 |
| | 10 | 2 | 168 | 193 | 210 | 217 | 208 | 173 |
| | 11 | 1 | 185 | 214 | 236 | 247 | 243 | 213 |
| | 12 | | 191 | 222 | 245 | 259 | 255 | 226 |
| | Daily Totals | | 1476 | 1644 | 1730 | 1720 | 1598 | 1252 |
| March 31 | 7 | 5 | 27 | 32 | 35 | 35 | 32 | 25 |
| | 8 | 4 | 64 | 78 | 89 | 96 | 97 | 89 |
| | 9 | 3 | 95 | 119 | 138 | 152 | 154 | 153 |
| | 10 | 2 | 120 | 150 | 176 | 195 | 205 | 203 |
| | 11 | 1 | 135 | 170 | 200 | 223 | 236 | 235 |
| | 12 | | 140 | 177 | 208 | 232 | 246 | 246 |
| | Daily Totals | | 1022 | 1276 | 1484 | 1632 | 1700 | 1656 |

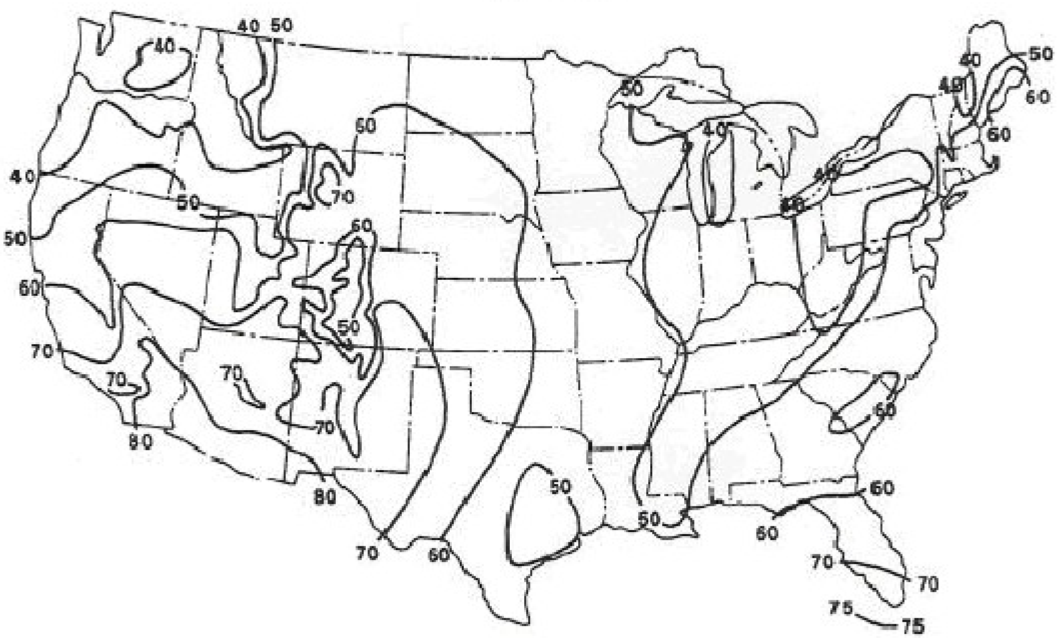
* Courtesy ASHRAE, *Handbook of Fundamentals*.

Appendix 3: Maps of the Average Percentage of the Time the Sun is Shining

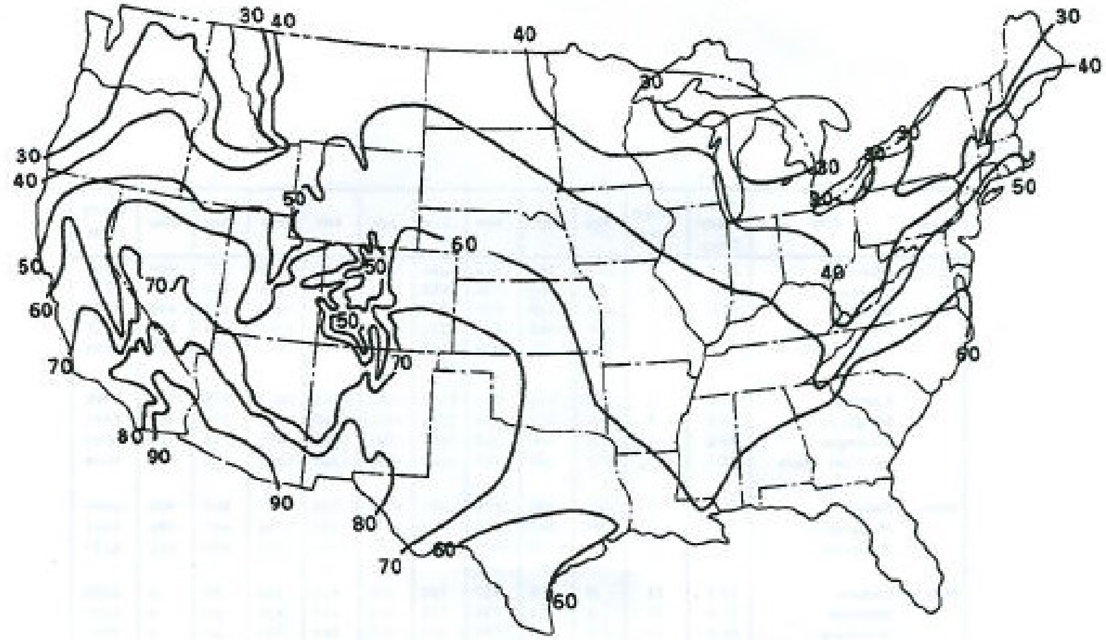
JANUARY



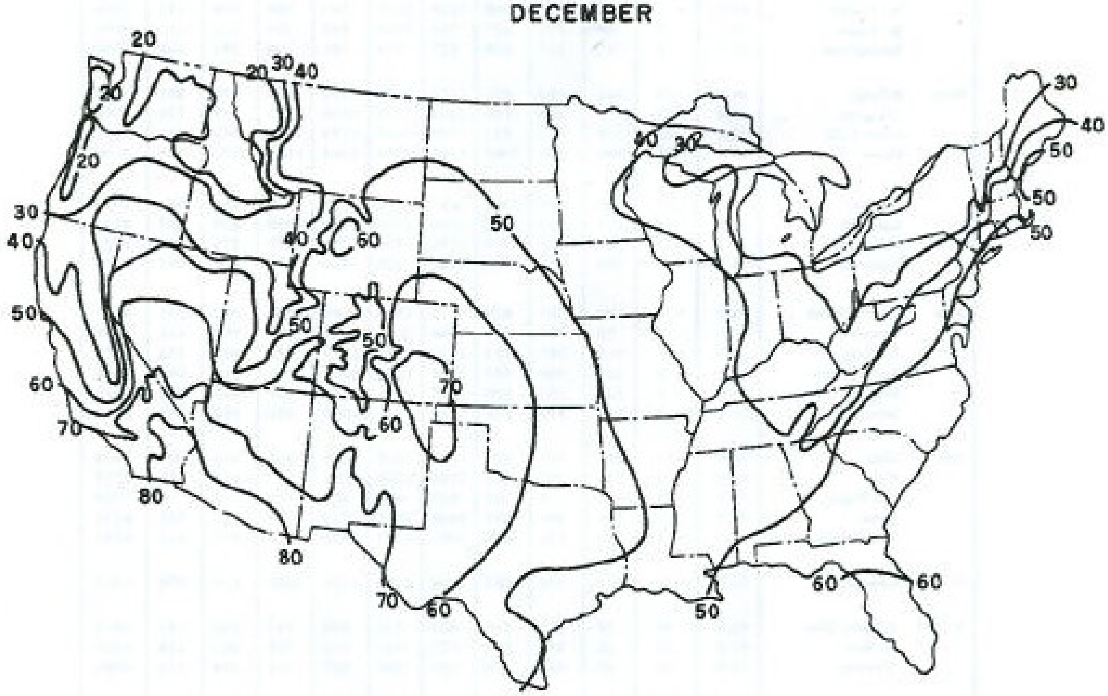

FEBRUARY



**NOVEMBER**




**DECEMBER**

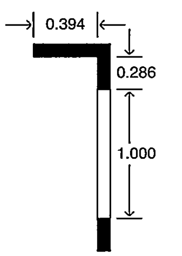


# Albuquerque, NM

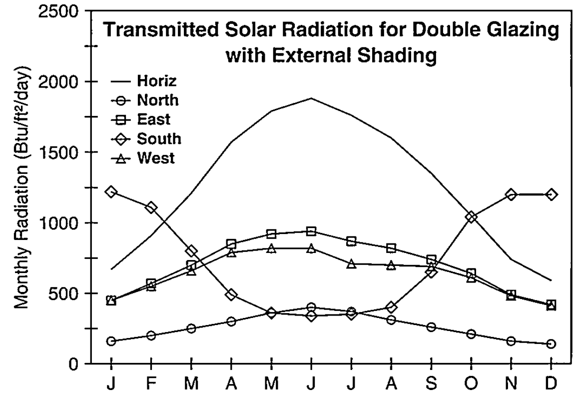
## WBAN NO. 23050

LATITUDE: 35.05° N
LONGITUDE: 106.62° W
ELEVATION: 5312 feet
MEAN PRESSURE: 12.2 psia

STATION TYPE: Primary




Shading Geometry
(Not to Scale)




### Average Incident Solar Radiation (Btu/ft²/day), Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Global | 1010 | 1320 | 1700 | 2160 | 2430 | 2560 | 2380 | 2180 | 1860 | 1500 | 1100 | 910 | 1760 |
| | Std.Dev. | 79 | 96 | 121 | 91 | 119 | 105 | 81 | 93 | 95 | 101 | 79 | 74 | 56 |
| | Minimum | 830 | 1100 | 1410 | 1950 | 2170 | 2350 | 2160 | 1870 | 1700 | 1270 | 890 | 710 | 1630 |
| | Maximum | 1140 | 1470 | 1930 | 2310 | 2630 | 2720 | 2510 | 2350 | 2070 | 1680 | 1220 | 1030 | 1850 |
| | Diffuse | 310 | 400 | 540 | 600 | 650 | 640 | 700 | 640 | 520 | 390 | 310 | 280 | 500 |
| | Clear-Day Global | 1200 | 1550 | 2020 | 2490 | 2740 | 2830 | 2730 | 2490 | 2120 | 1660 | 1250 | 1080 | 2020 |
| North | Global | 240 | 300 | 390 | 480 | 620 | 700 | 630 | 500 | 400 | 320 | 250 | 220 | 420 |
| | Diffuse | 240 | 300 | 390 | 450 | 510 | 520 | 520 | 470 | 400 | 320 | 250 | 220 | 380 |
| | Clear-Day Global | 210 | 260 | 330 | 430 | 620 | 750 | 680 | 480 | 350 | 280 | 220 | 190 | 400 |
| East | Global | 700 | 870 | 1070 | 1310 | 1430 | 1460 | 1360 | 1270 | 1130 | 970 | 750 | 650 | 1080 |
| | Diffuse | 300 | 380 | 480 | 560 | 610 | 610 | 620 | 570 | 490 | 400 | 310 | 270 | 470 |
| | Clear-Day Global | 870 | 1070 | 1300 | 1490 | 1580 | 1580 | 1540 | 1470 | 1320 | 1110 | 900 | 810 | 1250 |
| South | Global | 1640 | 1620 | 1430 | 1170 | 900 | 760 | 810 | 1020 | 1320 | 1620 | 1640 | 1610 | 1290 |
| | Diffuse | 410 | 470 | 540 | 550 | 540 | 530 | 540 | 540 | 520 | 470 | 410 | 380 | 490 |
| | Clear-Day Global | 2190 | 2130 | 1830 | 1330 | 930 | 760 | 820 | 1110 | 1580 | 1990 | 2130 | 2160 | 1580 |
| West | Global | 690 | 850 | 1010 | 1220 | 1290 | 1290 | 1140 | 1120 | 1060 | 940 | 740 | 630 | 1000 |
| | Diffuse | 300 | 380 | 480 | 570 | 620 | 620 | 620 | 580 | 500 | 400 | 320 | 270 | 470 |
| | Clear-Day Global | 870 | 1070 | 1300 | 1490 | 1580 | 1580 | 1540 | 1470 | 1320 | 1110 | 900 | 810 | 1250 |

### Average Transmitted Solar Radiation (Btu/ft²/day) for Double Glazing, Uncertainty ±9%

| Orientation | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontal | Unshaded | 670 | 910 | 1210 | 1570 | 1790 | 1880 | 1760 | 1600 | 1350 | 1050 | 740 | 590 | 1260 |
| North | Unshaded | 170 | 210 | 270 | 320 | 390 | 440 | 400 | 330 | 270 | 220 | 170 | 150 | 280 |
| | Shaded | 160 | 200 | 250 | 300 | 360 | 400 | 370 | 310 | 260 | 210 | 160 | 140 | 260 |
| East | Unshaded | 490 | 610 | 770 | 940 | 1020 | 1050 | 970 | 910 | 810 | 690 | 520 | 450 | 770 |
| | Shaded | 450 | 570 | 700 | 850 | 920 | 940 | 870 | 820 | 740 | 640 | 490 | 420 | 700 |
| South | Unshaded | 1230 | 1170 | 970 | 720 | 510 | 430 | 460 | 600 | 860 | 1140 | 1220 | 1210 | 880 |
| | Shaded | 1220 | 1110 | 800 | 490 | 360 | 340 | 350 | 400 | 650 | 1040 | 1200 | 1200 | 760 |
| West | Unshaded | 480 | 600 | 720 | 870 | 920 | 920 | 800 | 790 | 750 | 660 | 510 | 440 | 700 |
| | Shaded | 450 | 550 | 660 | 790 | 820 | 820 | 710 | 700 | 690 | 610 | 480 | 410 | 640 |

### Average Climatic Conditions

| Element | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°F) | 34.2 | 40.0 | 46.9 | 55.2 | 64.2 | 74.2 | 78.5 | 75.9 | 68.6 | 57.0 | 44.3 | 35.3 | 56.2 |
| Daily Minimum Temp | 21.7 | 26.4 | 32.2 | 39.6 | 48.6 | 58.3 | 64.4 | 62.6 | 55.2 | 43.0 | 31.2 | 23.1 | 42.2 |
| Daily Maximum Temp | 46.8 | 53.5 | 61.4 | 70.8 | 79.7 | 90.0 | 92.5 | 89.0 | 81.9 | 71.0 | 57.3 | 47.5 | 70.1 |
| Record Minimum Temp | -17.0 | -5.0 | 8.0 | 19.0 | 28.0 | 40.0 | 52.0 | 52.0 | 37.0 | 21.0 | -7.0 | -7.0 | -17.0 |
| Record Maximum Temp | 69.0 | 76.0 | 85.0 | 89.0 | 98.0 | 105.0 | 105.0 | 101.0 | 100.0 | 91.0 | 77.0 | 72.0 | 105.0 |
| HDD, Base 65°F | 955 | 700 | 561 | 301 | 89 | 0 | 0 | 0 | 18 | 259 | 621 | 921 | 4425 |
| CDD, Base 65°F | 0 | 0 | 0 | 7 | 64 | 279 | 419 | 338 | 126 | 11 | 0 | 0 | 1244 |
| Humidity Ratio (#w/#da) | 0.0025 | 0.0027 | 0.0028 | 0.0031 | 0.0042 | 0.0058 | 0.0092 | 0.0097 | 0.0077 | 0.0049 | 0.0033 | 0.0027 | 0.0049 |
| Wind Speed (mph) | 8.3 | 8.8 | 10.1 | 11.0 | 10.7 | 10.0 | 9.0 | 8.4 | 8.6 | 8.1 | 8.1 | 7.9 | 9.1 |
| Clearness Index, Kt | 0.62 | 0.63 | 0.64 | 0.68 | 0.69 | 0.70 | 0.66 | 0.66 | 0.65 | 0.65 | 0.62 | 0.61 | 0.66 |

### Average Incident Illuminance (klux-hr) for Mostly Clear/Mostly Cloudy Conditions, Uncertainty ±9%

| Orientation | March | | | | | June | | | | | September | | | | | December | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm | 9am | 11am | 1pm | 3pm | 5pm |
| Horizontal | 45/31 | 82/61 | 93/71 | 76/55 | 34/23 | 49/39 | 88/73 | 109/91 | 104/83 | 75/57 | 31/20 | 74/54 | 94/75 | 87/67 | 54/40 | 22/15 | 52/36 | 60/43 | 40/28 | 5/4 |
| North | 10/11 | 14/17 | 15/18 | 14/16 | 9/9 | 23/19 | 15/18 | 16/19 | 16/19 | 14/16 | 8/8 | 14/16 | 16/19 | 15/18 | 12/13 | 7/6 | 11/12 | 12/13 | 9/10 | 2/2 |
| East | 85/44 | 63/44 | 15/18 | 14/16 | 9/9 | 85/56 | 75/60 | 33/32 | 16/19 | 14/16 | 75/32 | 76/49 | 31/29 | 15/18 | 12/13 | 58/25 | 47/28 | 12/13 | 9/10 | 2/2 |
| South | 41/25 | 74/50 | 83/60 | 67/45 | 31/17 | 11/12 | 24/25 | 39/37 | 35/33 | 15/17 | 21/13 | 55/38 | 73/56 | 67/49 | 40/26 | 51/22 | 91/48 | 99/57 | 77/39 | 17/7 |
| West | 10/11 | 14/17 | 23/23 | 73/48 | 81/36 | 11/12 | 15/18 | 16/19 | 53/45 | 85/58 | 8/8 | 14/16 | 16/19 | 55/42 | 83/48 | 7/6 | 11/12 | 23/19 | 60/32 | 25/9 |
| M. Clr (%hrs) | 53 | 47 | 42 | 40 | 42 | 76 | 77 | 75 | 60 | 49 | 64 | 65 | 64 | 59 | 50 | 54 | 54 | 49 | 50 | 51 |