PDHonline Course E274 (3 PDH)

Passive Solar Heating – Principles & Calculations

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Passive Solar Heating – Principles & Calculations

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COURSE CONTENT

1. A Definition for Passive Solar Heating

A passive solar system for space heating converts the sun's radiant energy to heat upon absorption by a building. The absorbed thermal energy (heat) is stored in components of the building and/or used directly to heat the building. In a strictly passive system energy flow within the building is by natural means (conduction, natural convection and radiation). In comparison, an active solar heating system uses fans, blowers, and/or pumps to move heated fluid from the collectors to thermal storage, from the collectors to the heated space, and from thermal storage to the heated space.

2. Components of a Passive Solar Heating System

The components making up a passive solar system are similar to those for an active solar system: **aperture** (collector), **absorber**, **thermal mass** (storage), **distribution system**, **controls**, and a **backup heating system**.

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

In an active system, the absorber is typically part of the collector and there is a separate heat storage system. In a passive system, the **absorber** and the **storage** or **thermal mass** are both part of the same unit(s), such as floors and walls, which are in the direct path of sunlight. The typically dark colored surface absorbs solar radiation converting it to heat, which is stored in the material making up the floors and walls.

The **distribution system** is the means by which heat circulates from the collection and storage points to different areas of the house. In a strictly passive system, heat will be circulated solely by the three natural means of heat flow, conduction, convection, and radiation. Sometimes fans, and/or blowers are used to help with the distribution of heat throughout the house.

Controls include items such as moveable window insulation, operable vents or dampers, roof overhangs or awnings that shade the aperture during summer months and electronic sensing devices, such as a differential thermostat that signals a fan to turn on or a damper to open.

The **backup heating system** can be any type of non-solar system.

3. Basic Types of Passive Solar Heating Systems

There are five basic types of passive solar heating systems, **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 roof, attached sunspace and thermal storage roof, are sometimes referred to as indirect gain systems. The five types will each be described briefly here.

Direct Gain is the simplest approach for passive solar heating. During the daytime, sunlight enters the living space through south facing windows. When solar radiation strikes the floor, walls, or ceiling or is reflected to them, it is absorbed and converted to heat. During the daytime, when the room temperature is high enough and the storage surface temperature is high enough, heat will be conducted from the hot surface to the interior of the walls and floor, where it is stored. When the surface of the walls and floor are no longer being heated by the suns rays, the room and the wall and floor surface temperatures will decrease and heat will be conducted from the heated interior of the walls and floor to the cooler surface and will heat the living space by convection and radiation. This is illustrated in Figure 1, below.

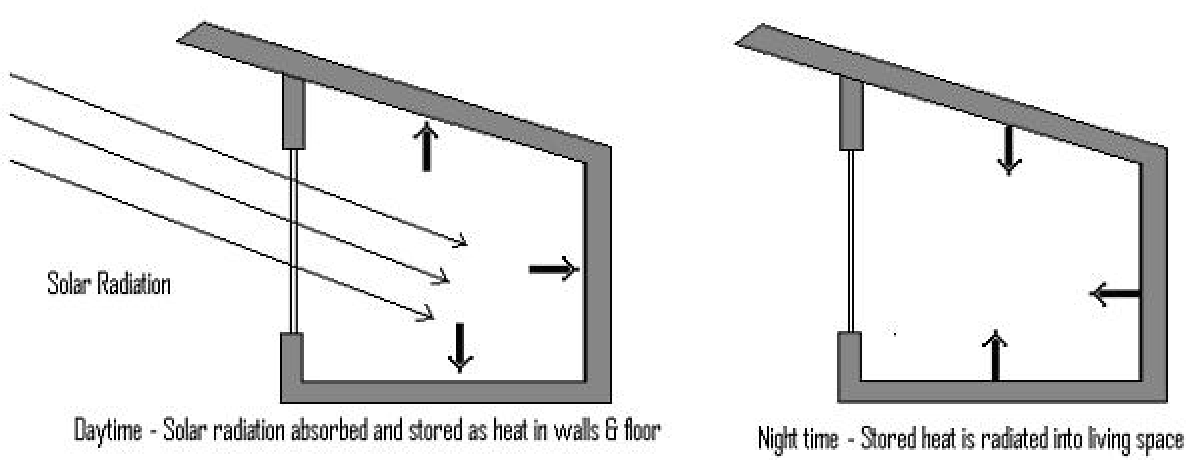


Figure 1. Direct Gain Passive Solar Heating

The fundamental requirements for a direct gain passive solar heating system are plenty of south facing glass and adequate thermal storage capacity in the living space. One guideline for thermal storage capacity is that one-half to two-thirds of the total interior surface area should be constructed of thermal storage materials. Typically this is masonry, such as concrete, adobe, brick, etc, but water walls are sometimes used as well. Water walls can be made of water in plastic or metal containers placed in the direct path of the sunlight. Water walls have the advantage of heating more quickly and more evenly than masonry, but may not be as aesthetically pleasing. Dark colored masonry surfaces may become quite high in temperature if they receive direct sunlight. A refinement, which helps to alleviate this, is use of a diffusing glazing material which scatters sunlight, thus distributing it more evenly over walls, ceiling, and floor. This does not reduce the total amount of solar energy entering the space, but distributes it more evenly. This is illustrated in Figure 2, below. Moveable insulation, such as insulated drapes, to cover the south facing windows at night, will decrease the nighttime heat loss.

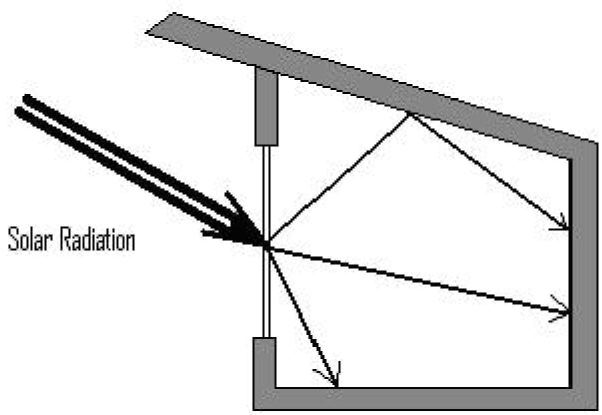


Figure 2. Direct Gain with Diffusing Glazing Material

The **Thermal Storage Wall** is illustrated in Figures 3, below. The wall may be made of masonry or of water filled containers. It is often referred to as a Trombe Wall, named after the engineer, Felix Trombe, who popularized the design together with architect, Jacques Michel, in the 1960's. The design was patented by Edward Morse in 1881. The key feature of the Trombe wall system is placement of thermal storage material between the interior habitable space and the sun, so that the dark colored storage wall is heated by sunshine during day and the stored heat in the wall provides heat to the living space at night. Use of vents near the top and the bottom of the wall, which are opened during the day and closed at night, provides natural convection* heating of the living space from the heated air between the storage wall and glazing during sunlight hours. As with the direct gain system, movable insulation for the glazing will reduce nighttime heat loss.

***NOTE**: Natural convection (also called free convection) is the movement of a fluid due to decreased 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 example, the heated air between the glazing and the storage wall will rise and enter the living space through the upper vent, thus drawing cool air from the bottom of the living area into the space between the glazing and storage wall through the lower vent.

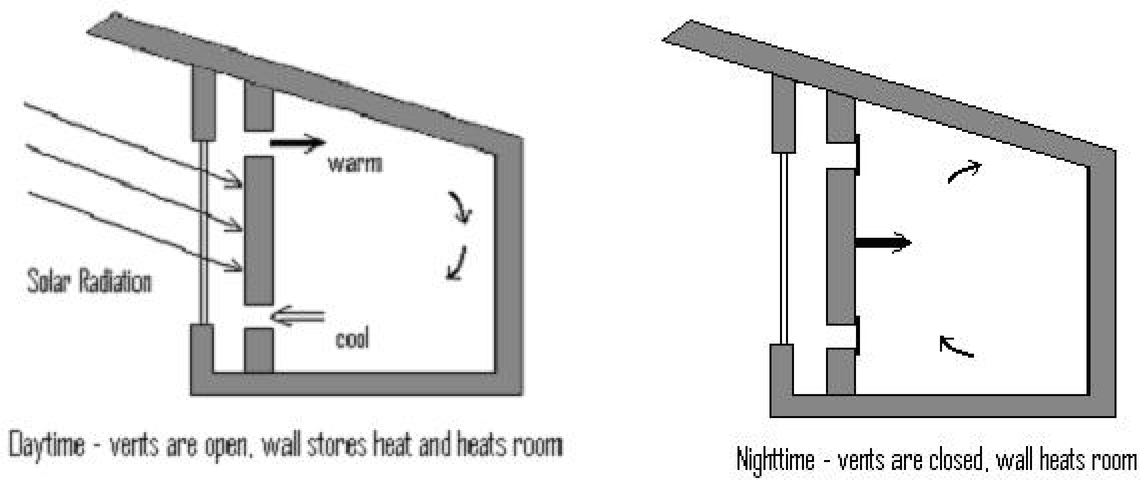


Figure 3. Thermal Storage (Trombe) Wall, daytime and nighttime configurations

The **Attached Sunspace** is a passive solar heating system that can be added to an existing building, making it more suitable for retrofit than some of the other systems. It is a combination of direct gain in the sunspace (sometimes referred to, and sometimes used as, a greenhouse) and a solar wall for heating the adjacent living space. Including vents as shown in Figure 4, will provide more heat to the adjacent living space.

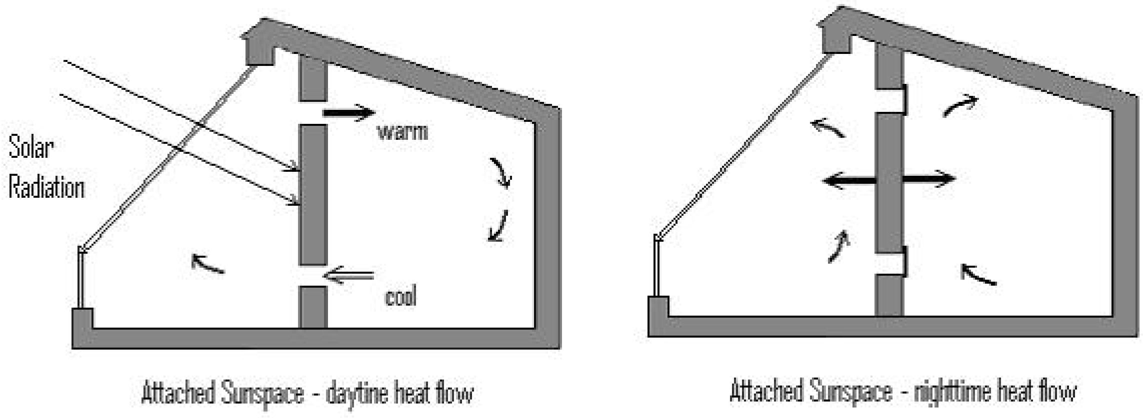


Figure 4. Attached Sunspace, Daytime & Nighttime Heat Flows

The **Thermal Storage Roof,** or solar roof**,** uses water encased in plastic on the roof, with moveable insulation to cover the roof and reduce heat loss during the night. This system is also called a roof pond or solar pond. The pond (water encased in plastic) can also be placed in an attic, under pitched roof glazing. Daytime and nighttime heat flows for a thermal storage roof system are shown in Figure 5, below. It is worth noting, 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.

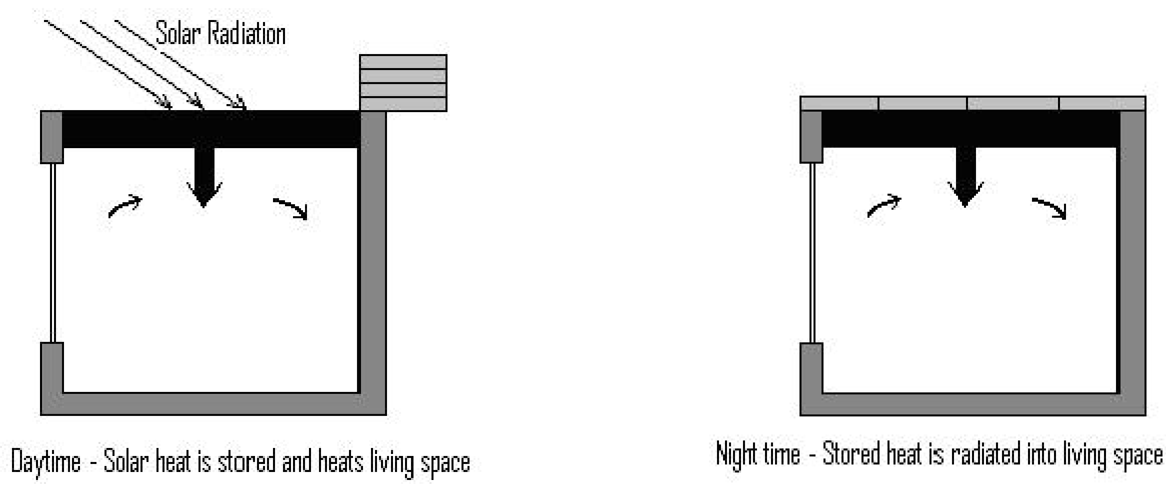
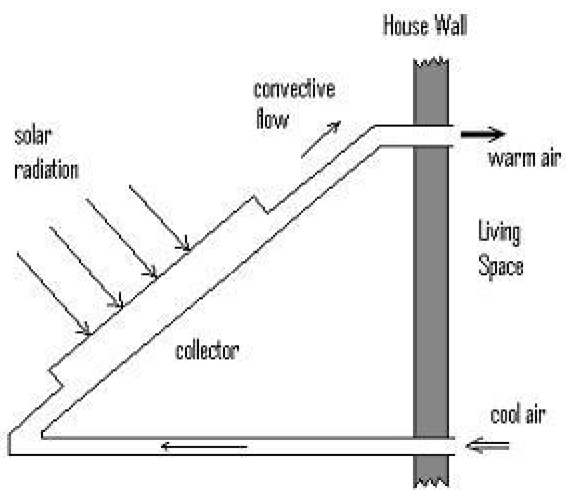
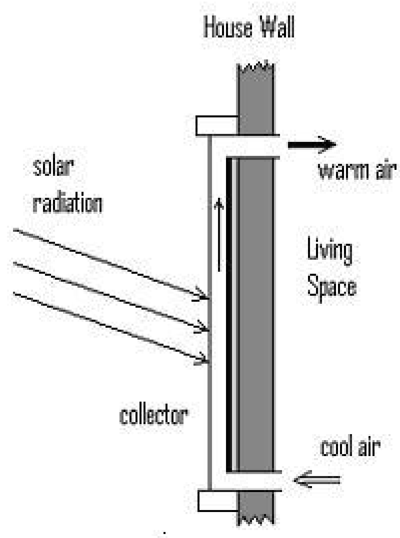


Figure 5. Solar Roof, covered with insulation at night, uncovered during day

The **convective loop** (also called isolated gain or thermosiphon) system heats water or air in a flat plate solar collector. The fluid then flows by natural convection to a heat storage area or to a space to be heated directly. Figure 6 shows convective loop systems for heating a living space, one with the collector mounted at a tilt and the other with a vertically mounted collector. These systems are quite suitable for retrofit on an existing building, as they can be mounted directly on an existing wall. There must be an opening into the building at the top of the collector for heated air flow into the building, and an opening through the building to the bottom of the collector for cool air flow into the collector. In some cases the upper opening uses a window on one floor of the building and/or the lower opening uses a window on a lower floor. The vertically mounted collector, convective loop, shown at the right in Figure 6, is sometimes also called a solar chimney. Figure 7 shows a convective loop used for a hot water system.



Collector mounted at a tilt



Vertical Collector (solar chimney)

Figure 6. Convective loops to heat living space

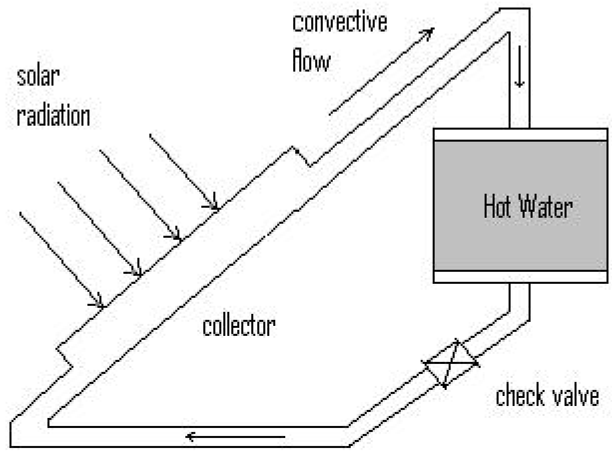


Figure 7. Convective loop, used for heating water

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

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

i) 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. Two sources, specifically for passive solar applications, will be discussed here. Additional information on sources for and interpretation of solar radiation data is available through the PDHcenter on-line course, E273, *Solar Radiation Data from the Internet*.

A very good source of solar radiation 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://www.nrel.gov/docs/legosti/old/7904.pdf . This publication includes data on monthly average and yearly average incident solar radiation on horizontal surfaces and on vertical surfaces facing north, east, south and west. A portion of the table for Des Moines, IA, is shown below. 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 the portion of the global radiation that is made up of sky radiation and ground reflected radiation. The rest 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 suns rays.

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	630	890	1200	1550	1840	2060	2050	1790	1410	1030	650	520	1300
	Std.Dev.	45	60	97	121	122	122	132	112	122	90	55	43	40
	Minimum	530	770	950	1350	1510	1850	1820	1550	1140	880	550	430	1230
	Maximum	700	1010	1410	1770	2110	2390	2300	2000	1730	1230	780	620	1430
	Diffuse	300	420	560	680	790	800	770	670	550	400	310	270	550
	Clear-Day Global	850	1200	1690	2190	2520	2640	2550	2260	1810	1300	900	740	1720
North	Global	190	260	350	440	550	630	600	480	370	270	200	170	380
	Diffuse	190	260	350	420	500	530	510	450	360	270	200	170	350
	Clear-Day Global	170	230	320	420	580	690	630	470	340	250	180	150	370
East	Global	440	590	740	920	1050	1140	1150	1040	860	680	440	370	790
	Diffuse	240	330	420	510	590	630	620	550	450	340	240	210	430
	Clear-Day Global	660	870	1130	1350	1470	1500	1460	1360	1170	910	690	590	1100
South	Global	1090	1160	1100	990	880	840	890	1020	1150	1230	1010	930	1020
	Diffuse	350	430	490	530	570	580	570	550	500	420	340	310	470
	Clear-Day Global	1910	1990	1840	1470	1140	990	1040	1300	1660	1870	1870	1820	1570
West	Global	450	580	740	920	1060	1170	1180	1070	890	670	450	370	800
	Diffuse	240	330	420	520	600	640	630	560	460	340	250	210	430
	Clear-Day Global	660	870	1130	1350	1470	1500	1460	1360	1170	910	690	590	1100

Also included in this publication are monthly and yearly average transmitted radiation with double glazing for horizontal and each of the four vertical surfaces mentioned above. A portion of table for Des Moines, IA, giving transmitted radiation values, is shown below. 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.

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	400	600	840	1110	1330	1500	1490	1300	1000	710	420	330	920
North	Unshaded	130	180	240	300	360	410	390	320	250	190	140	120	250
	Shaded	120	160	210	260	320	360	350	280	230	170	120	100	220
East	Unshaded	300	420	530	650	740	810	820	740	610	480	310	250	560
	Shaded	270	360	450	560	620	680	680	620	520	420	270	220	470
South	Unshaded	820	860	770	650	550	510	540	650	780	890	750	700	710
	Shaded	800	790	600	410	350	350	350	380	540	770	720	680	560
West	Unshaded	310	410	520	650	750	840	850	770	630	470	310	250	560
	Shaded	270	360	450	550	630	700	710	650	540	410	270	220	480

Illuninance data and some data on average climatic conditions are also provided in this publication. The data is available for 239 locations in the United States and its territories, based on data collected from 1961-1990 for those 239 sites.

The second source for solar radiation data, to be considered here, is the second reference in the "Related Links and References" for this course. That is, *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 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 21st 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 a map 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. Anderson & Wells also provide an estimate of 82% for the average portion of incident radiation that will be transmitted through each layer of glass.

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 20.

Example #1: 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 St. Louis, MO, in January using each of the two references discussed above.

Solution: From *Solar Radiation Data Manual for Buildings*, page 119, (p 21 of this course) the average daily incident global solar radiation on a south-facing surface in St. Louis, MO is 1080 Btu/ft^2/day. For the 6 ft^2 window in the example, the daily incident radiation would thus be: (1080 Btu/ft^2/day)(6 ft^2) = **6480 Btu/day**

NOTE: from page 119 of *Solar Radiation Data Manual for Buildings*, it can be found that the latitude for St. Louis, MO is **38.75^o north**. This information can also be found by doing a "Google search" or "Yahoo search" for "St. Louis 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 22 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 38.75^o N latitude can be found by interpolation, as follows:

$$1726 + [(40 – 38.75)/(40 – 32)] (1779 – 1726) = \underline{1734\ Btu/day/ft^2}$$

From the map on the first page of Appendix 3 (p 23 of this course), the average % time that the sun is shining in St. Louis, MO, in January, is about 50%, thus the average daily solar radiation striking the south-facing window would be:

$$(0.5)(1734\ Btu/ft^2/day)(6\ ft^2) = \mathbf{5202\ Btu/day}$$

You may have noticed that the numbers from the two sources are not quite the same. 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 21st of the month, so they can be expected to be somewhat different for that reason.

Example #2: From the same two sources used in **Example #1**, 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 St. Louis, MO, in January.

Solution: : From *Solar Radiation Data Manual for Buildings*, page 119 (page 21 of this course), the average daily solar radiation transmitted through an unshaded, south-facing, double pane, glass window, in St. Louis, MO is 810 Btu/ft^2/day. For the 6 ft^2 window in the example, the daily incident radiation would thus be:

$$(810\ Btu/ft^2/day)(6\ ft^2) = \mathbf{4860\ Btu/day}$$

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 5202 Btu/day of incident solar radiation calculated above, as follows:

(0.82)(0.82)(5202 Btu/day) = **3498 Btu/day**

For this example also, the two estimates differ, because of differences between the two databases used.

ii) Heating requirements (degree days) during the heating season at the site of interest: Data on heating degree days is available in both of the references discussed in the previous section. Monthly average and yearly average values for heating degree days are given in *Solar Radiation Data Manual for Buildings*, for each of the 239 sites covered in that publication.

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

NOTE: Degree days indicate heating and 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^o F or 18.3^o C). If the average temperature is less than the base temperature, then the difference is called heating degree days. If the average is greater than the base temperature, then the difference is called cooling degree days.

Example #3: Compare the values given in the above two references for annual heating degree days and for January heating degree days for St. Louis, MO.

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

From *Solar Radiation Data Manual for Buildings*, page 119 (p 21 of this course), for St. Louis, MO:

Annual heating degree days = 4758 ^{o}F days

January heating degree days = 1107 ^{o}F days

From *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, page 157 (p 24 of this course), for St. Louis, MO:

Annual heating degree days = 4900 ^{o}F days

January heating degree days = 1026 ^{o}F days

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

iii) Information on the rate of heat loss from the house: A useful way of expressing the rate of heat loss is 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 a super-insulated home, the heat loss rate would be less, and for an older home, which is not well insulated and weather-stripped, it would be more than the above guideline. For an existing home, which 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% for 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 from a building per degree-day can be estimated from information about the building construction, such as insulation thickness, roof area, wall area, glass area, number of glazing layers, etc. This type of calculation is covered in various HVAC texts and publications and in another PDHcenter on-line course, so it will not be covered in this course.

Another approach to estimating rate of heat loss from an existing home is from fuel consumption information. 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: A gallon of fuel oil has an energy content of 135,00 to 140,000 Btus. Multiplying by the furnace efficiency (typically 40 to 70 %) gives the heat supplied to the house per gallon of fuel oil used. For electric resistance heating, one kwh of electricity is equivalent to 3400 Btu and electric resistance heating has an efficiency of 100%. A heat pump can supply as much as 6800 Btus per kwh of electricity used to operate it. 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. This information together with an estimate of the amount of fuel used to heat the home from power bills, can be used to estimate the amount of heat supplied to the house during any month, which, by the first law of thermodynamics, is the amount of heat lost from the house.

Example #4: Data on monthly natural gas consumption for a 2500 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/^{o}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	340	232	119	91	33	18	22	20	20	36	114	233	1278
Heating ^{o}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:

(18 + 22 + 20)/3 = <u>20 ccf/month</u>

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

= 1278 – (18 + 22 + 20) = 1218 ccf

Calculate the annual gas consumption for heating by subtracting the baseline (non-heating) gas consumption of 20 ccf/month:

Gas consumption for heating = 1218 – 9*20 = <u>1038 ccf</u>

Converting to Btu: Gas consumption for heating = $1038*10^5$ = $1.038*10^8$ Btu

Heat delivered to house (60% efficiency) = $0.6*1.038*10^8$ = $6.228*10^7$ Btu

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

Heat loss rate in Btu/^{o}F-day/ft^2 = $6.228*10^7$/4425/2500 = **<u>5.6 Btu/^{o}F-day/ft^2</u>**

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

5. Size and Performance Calculations for Passive Solar Systems

For a passive solar heating system, the primary parameter to be determined in order to size the system is the area of south-facing glazing. The rest of the system, primarily heat storage, then can be sized to match the area of glazing. A larger area of glazing, will result in larger solar savings fraction (the fraction of the building heating load that is taken care of by the passive solar system(s)). Anderson & Wells (ref #2 under "Related Links & References" for this course) provide some rules of thumb and guidelines for deciding upon the size for a passive solar heating system. That approach will be discussed and illustrated with examples here. More detailed, sophisticated calculation procedures are available, for example in Goswami, Krieth, & Krieder (ref #1 under "Related Links & References" for this course).

Anderson & Wells suggest that the optimum passive heating system size will supply the same percentage of the building heating load as the average percentage of daytime hours that the sun is shining during the heating season (from the maps in Appendix 3 of their book) at the location of interest. This figure 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 gallon 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 southwest 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 #4**.

Solution: From Appendix 3 of Anderson & Wells' book, (pp 23 & 24 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 # 4,** the estimated heat requirement for heating the house in a season is 6.228*10^7 Btu. The required glazing to deliver 60% of this heat is thus estimated as:

$$(0.6)(6.228*10^7 \text{ Btu})/120{,}000 \text{ Btu/ft}^2 = 311 \text{ ft}^2$$

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 311 ft^2 glazing area calculated in **Example #5** for the 2500 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 #4** 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 26 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 2500 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 ^{o}F-days	Solar Input Btu /day/ft^2	Heating Requirement Btus	Solar Heat Input (315 ft^2) Btus	Solar %
Jan	955	1220	13,370,000	11,913,300	89.1%
Feb	700	1110	9,800,000	9,790,200	99.9%
Mar	561	800	7,854,000	7,812,000	99.5%
Apr	301	490	4,214,000	4,630,500	109.9%
May	89	360	1,246,000	3,515,400	282.1%
June	0				
July	0				
Aug	0				
Sept	18	650	252,000	6,142,500	2437.5%
Oct	259	1040	3,626,000	10,155,600	280.1%
Nov	621	1200	8,694,000	11,340,000	130.4%
Dec	921	1200	12,894,000	11,718,000	90.9%

Discussion of Results: The solar percentage results are quite high, indicating that the 315 ft^2 glazing area is more than required for this area of the country. Thus the calculations will be repeated with 200 ft^2 of south-facing glazing instead of 315 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 56% and 83%.

Albuquerque, NM

Month	heating °F-days	Solar Input Btu /day/ft^2	Heating Requirement Btus	Solar Heat Input (200 ft^2) Btus	Solar %
Jan	955	1220	13,370,000	7,564,000	56.6%
Feb	700	1110	9,800,000	6,216,000	63.4%
Mar	561	800	7,854,000	4,960,000	63.2%
Apr	301	490	4,214,000	2,940,000	69.8%
May	89	360	1,246,000	2,232,000	179.1%
June	0				
July	0				
Aug	0				
Sept	18	650	252,000	3,900,000	1547.6%
Oct	259	1040	3,626,000	6,448,000	177.8%
Nov	621	1200	8,694,000	7,200,000	82.8%
Dec	921	1200	12,894,000	7,440,000	57.7%

Example #7: To illustrate the effect of climate in a different part of the country repeat the last set of calculations for St. Louis, MO. Use 200 ft^2 of glazing, 2500 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 119 of the NREL publication, *Solar Radiation Data Manual for Buildings*. (p 21 of this course) The other columns were calculated just the same as above.

St. Louis, MO

Month	heating °F-days	Solar Input Btu /day/ft²	Heating Requirement Btus	Solar Heat Input (200 ft²) Btus	Solar %
Jan	1107	790	15,498,000	4,898,000	31.6%
Feb	871	750	12,194,000	4,200,000	34.4%
Mar	617	590	8,638,000	3,658,000	42.3%
Apr	266	420	3,724,000	2,520,000	67.7%
May	111	350	1,554,000	2,170,000	139.6%
June	0				
July	0				
Aug	0				
Sept	21	550	294,000	3,300,000	1122.4%
Oct	237	770	3,318,000	4,774,000	143.9%
Nov	564	730	7,896,000	4,380,000	55.5%
Dec	964	680	13,496,000	4,216,000	31.2%

As was the case for Albuquerque, there is more than enough solar input from 200 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 68% for St. Louis, as compared with 56% to 83% for Albuquerque. There are indeed less clouds in the sky in the southwestern U.S.

The glazing area decided upon by this method can be taken as an approximate value. More 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 do, 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.

6. 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, attached sunspace and convective loop (solar chiminey) are especially suitable. Also addition of more south-facing windows or upgrading existing south-facing windows to enhance direct gain is a possibility. If a thermal storage wall were to be used for retrofit, it would probably be a "water wall" rather than a masonry wall. 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. Beware, 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 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.

7. Sizing Solar Storage

Guidelines for required quantity of thermal storage are given in both of the references mentioned in the previous couple of sections. Goswami, Krieth, & Krieder (ref #1 under "Related Links & References" for this course) give a rule of thumb that there should be 613 kJ/^{o}C for each m^2 of glazing, if the sunlight shines directly on the storage material. Four times as much is needed if the sunlight does not shine directly on the storage mass. Converting units, this rule of thumb is equivalent to 30 Btu/^{o}F 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.

The volume of any of the materials in Table 1, needed per ft^2 of glazing can be found by dividing 30 Btu/^{o}F by the volumetric heat capacity (Btu/ft^3/^{o}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.

Table 1. Thermal Properties of Some Materials

Material	Specific Heat (Btu/lb/°F)	Density lb/ft³	Volumetric Heat Capacity Btu/ft³/°F
Air (75°F)	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 other book that is being used in this course, *Passive Solar Energy: The Homeowners Guide to Natural Heating and Cooling*, by Anderson & Wells (ref #2 under "Related Links & References" for this course), gives 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. They also state that four times that much is required if the sun heats air, which in turn heats the thermal storage material. As you can see, Anderson & Wells give a more conservative thermal storage requirement than Goswami, Krieth, & Krieder.

8. Controls - Summer Shading of Passive Solar Glazing

The NREL publication, *Solar Radiation Data Manual for Buildings*, provides design information 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. This is illustrated in Figure 9, below.

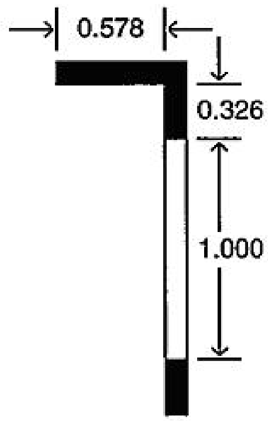


Figure 8. Recommended Shading Geometry

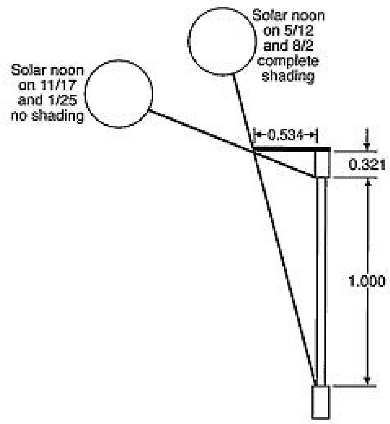


Figure 9. Effect of Winter & Summer Solar Altitude Angle

9. 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 third reference below has information and plans for many DIY passive solar projects.

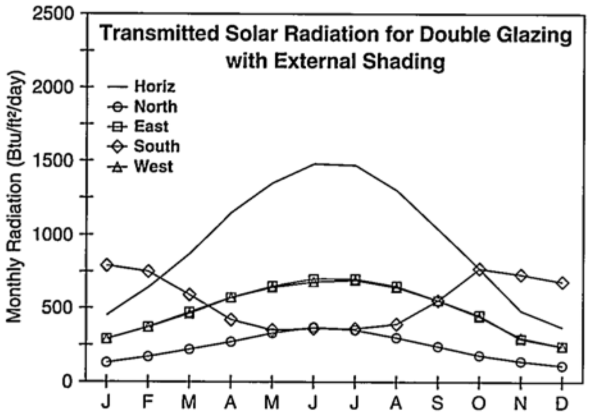
10. Related Links & References

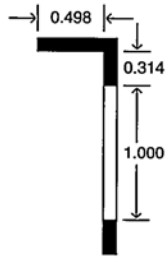
1. Goswami, D. Y., Krieth, Frank, and Kreider, Jan F., *Principles of Solar Engineering*, Philadelphia: Taylor & Francis, 2000.

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

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

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





Shading Geometry
(Not to Scale)

St. Louis, MO

WBAN NO. 13994

LATITUDE: 38.75° N
LONGITUDE: 90.38° W
ELEVATION: 564 feet
MEAN PRESSURE: 14.5 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	690	930	1230	1590	1860	2030	2020	1800	1460	1100	720	580	1340
	Std.Dev.	56	69	98	135	138	114	120	110	112	98	69	57	42
	Minimum	550	800	1060	1370	1550	1830	1750	1570	1190	870	590	490	1280
	Maximum	780	1070	1430	1930	2180	2350	2240	1960	1690	1250	870	710	1480
	Diffuse	340	460	590	710	810	840	810	730	600	430	350	300	580
	Clear-Day Global	950	1300	1760	2230	2520	2630	2550	2290	1870	1400	1000	840	1780
North	Global	210	280	360	440	550	630	600	490	380	290	220	190	390
	Diffuse	210	280	360	430	500	530	520	460	380	290	220	190	370
	Clear-Day Global	190	250	330	430	580	680	630	470	360	270	200	170	380
East	Global	460	590	750	920	1060	1140	1130	1050	880	710	470	390	800
	Diffuse	260	340	440	530	600	640	620	570	470	360	270	230	440
	Clear-Day Global	710	910	1150	1340	1440	1460	1430	1340	1170	940	730	640	1110
South	Global	1080	1110	1060	970	830	780	820	950	1110	1220	1020	940	990
	Diffuse	370	440	500	540	560	570	570	560	520	440	360	330	480
	Clear-Day Global	1930	1970	1770	1380	1040	890	950	1210	1580	1840	1870	1860	1520
West	Global	470	600	740	920	1040	1110	1120	1030	880	700	480	390	790
	Diffuse	260	340	440	530	610	650	630	580	480	360	270	230	450
	Clear-Day Global	710	910	1150	1340	1440	1460	1430	1340	1170	940	730	640	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	870	1150	1350	1480	1470	1300	1040	770	480	370	950
North	Unshaded	150	190	250	300	370	410	390	330	260	200	150	130	260
	Shaded	130	170	220	270	330	370	350	300	240	180	140	110	230
East	Unshaded	320	410	530	660	750	810	810	750	620	500	320	270	560
	Shaded	290	370	470	570	650	700	700	650	550	450	290	240	490
South	Unshaded	810	810	740	630	510	470	490	600	750	870	760	700	680
	Shaded	790	750	590	420	350	360	360	390	550	770	730	680	560
West	Unshaded	320	420	520	650	740	790	800	740	620	490	330	270	560
	Shaded	290	370	460	570	640	680	690	640	550	440	300	240	490

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°F)	29.3	33.9	45.1	56.7	66.1	75.4	79.8	77.6	70.2	58.4	46.2	33.9	56.1
Daily Minimum Temp	20.8	25.1	35.5	46.4	56.0	65.7	70.4	67.9	60.5	48.3	37.7	26.0	46.7
Daily Maximum Temp	37.7	42.6	54.6	66.9	76.1	85.2	89.3	87.3	79.9	68.5	54.7	41.7	65.4
Record Minimum Temp	-18.0	-10.0	-5.0	22.0	31.0	43.0	51.0	47.0	36.0	23.0	1.0	-16.0	-18.0
Record Maximum Temp	76.0	85.0	89.0	93.0	93.0	102.0	107.0	107.0	104.0	94.0	85.0	76.0	107.0
HDD, Base 65°F	1107	871	617	266	111	0	0	0	21	237	564	964	4758
CDD, Base 65°F	0	0	0	17	145	312	459	391	177	33	0	0	1534
Humidity Ratio (#w/#da)	0.0026	0.0030	0.0044	0.0063	0.0091	0.0125	0.0145	0.0138	0.0112	0.0072	0.0049	0.0033	0.0077
Wind Speed (mph)	10.9	10.8	11.9	11.6	9.6	9.1	8.4	8.0	8.4	9.1	10.2	10.7	9.9
Clearness Index, Kt	0.48	0.49	0.49	0.51	0.53	0.55	0.56	0.55	0.53	0.52	0.46	0.44	0.52

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	40/23	73/45	82/52	64/40	26/16	48/32	84/61	101/76	96/71	67/49	29/17	68/42	86/58	78/53	47/31	16/9	42/25	48/28	30/17	2/2
North	10/9	14/16	15/17	13/14	8/7	19/15	16/18	17/19	17/19	15/16	9/7	14/15	16/18	15/17	12/12	6/4	10/10	11/11	8/7	1/1
East	75/25	56/30	15/17	13/14	8/7	78/40	72/49	31/27	17/19	15/16	65/23	70/36	28/23	15/17	12/12	42/11	39/18	11/11	8/7	1/1
South	40/17	73/36	82/43	64/32	26/12	12/12	31/26	45/37	41/33	19/18	21/11	57/31	75/45	67/41	37/21	39/10	82/29	88/32	63/20	6/2
West	10/9	14/16	24/21	67/33	64/22	12/12	16/18	17/19	53/41	78/50	9/7	14/15	16/18	54/35	74/35	6/4	10/10	22/14	50/17	9/2
M. Clr (%hrs)	32	28	27	28	29	43	39	32	29	34	47	47	41	41	43	31	30	30	30	32

Appendix 2

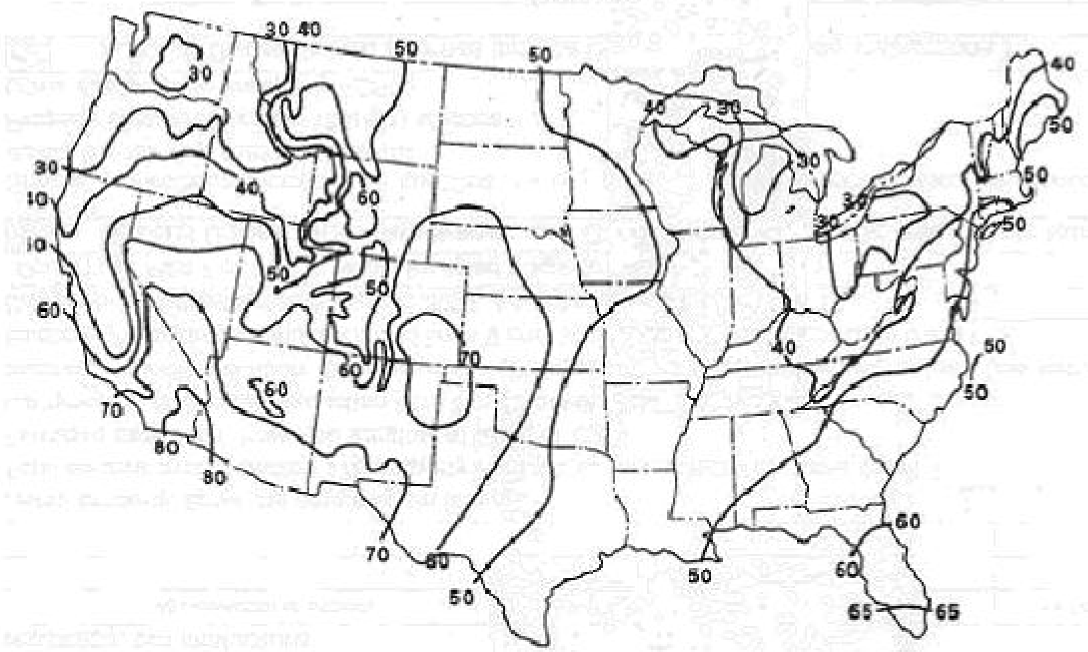
Solar Radiation on South Walls on Sunny Days *

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

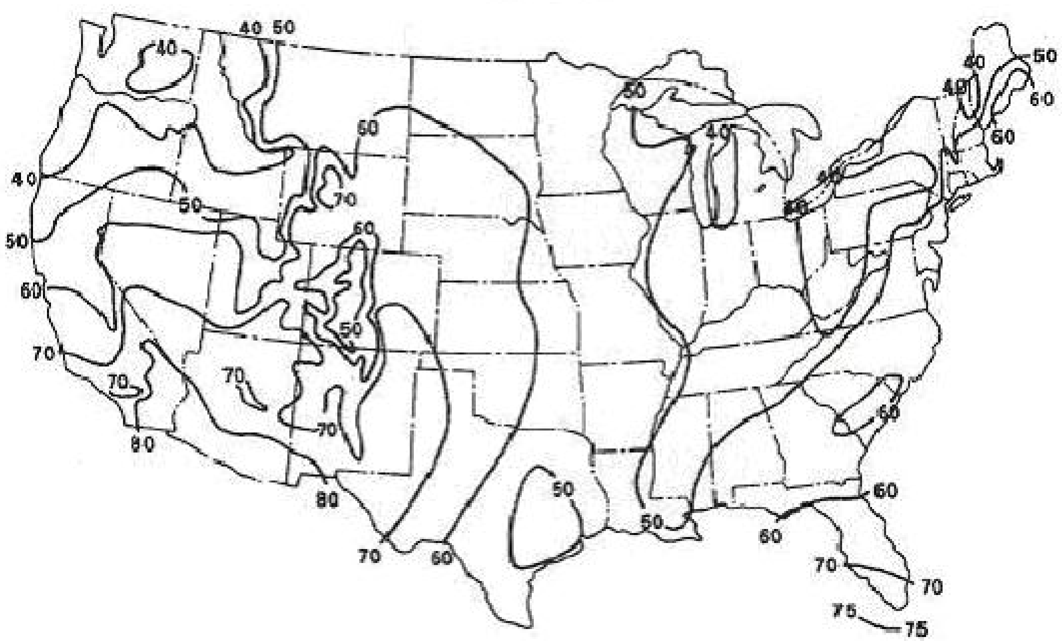
* Courtesy ASHRAE, *Handbook of Fundamentals.*

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

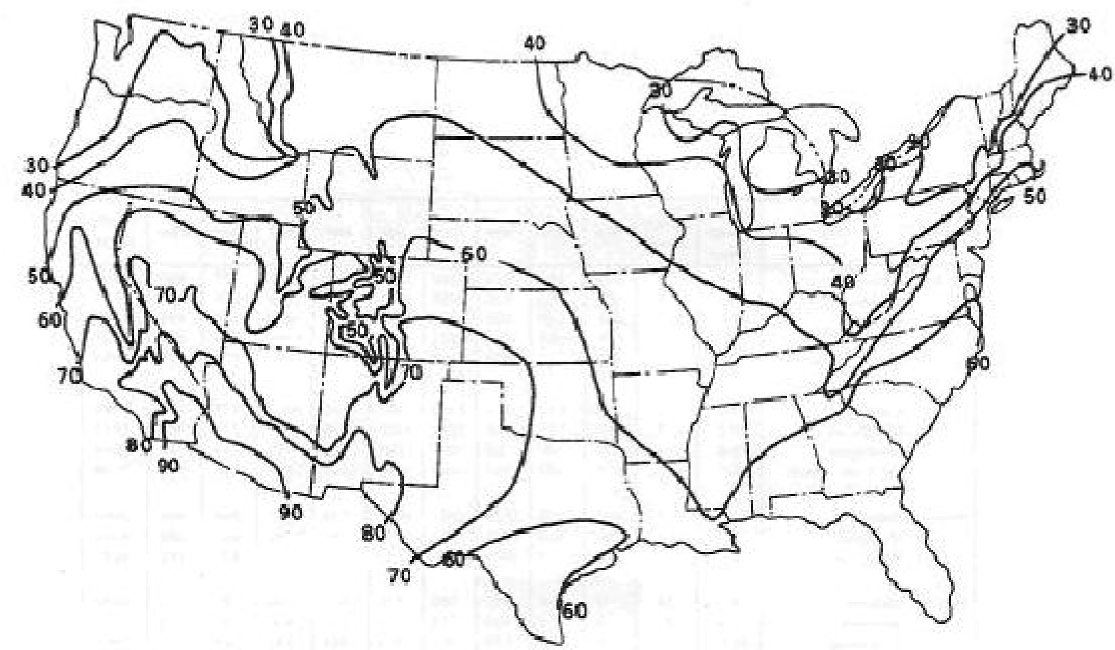
JANUARY



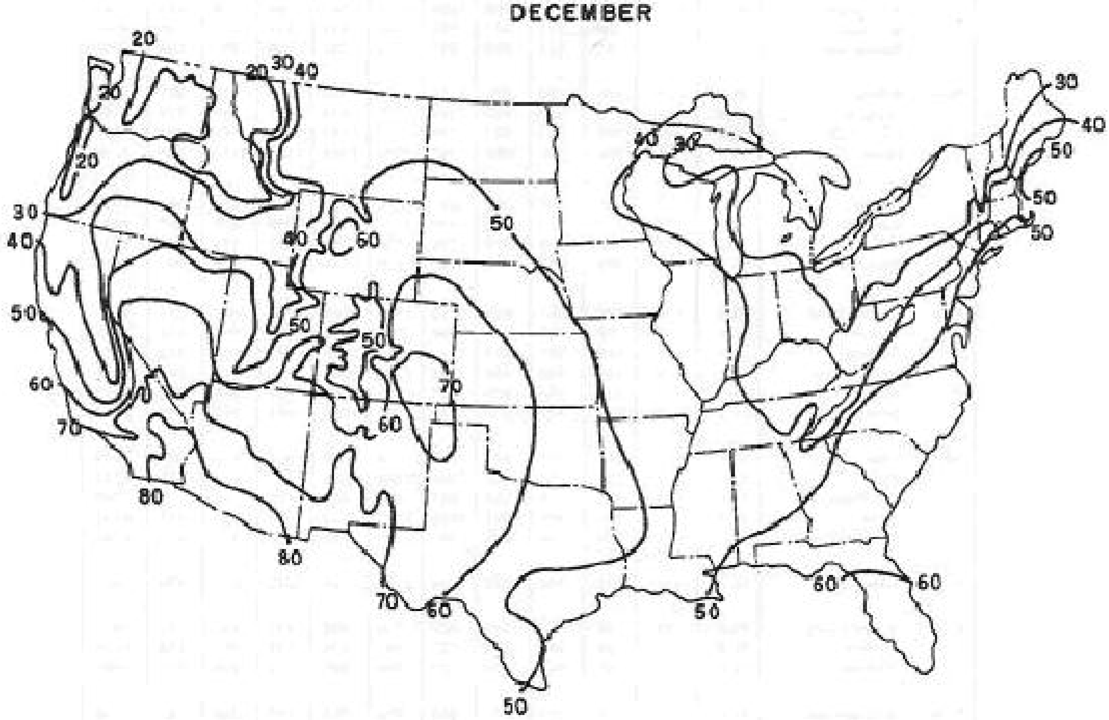
FEBRUARY



NOVEMBER



DECEMBER



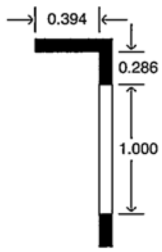
State	City	Avg. Winter Temp	Design Temp	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Yearly Total
Mich.	Alpena	29.7	− 5	273	580	912	1268	1404	1299	1218	777	446	8506
	Detroit	37.2	4	87	360	738	1088	1181	1058	936	522	220	6232
	Escanaba	29.6	− 7	243	539	924	1293	1445	1296	1203	777	456	8481
	Flint	33.1	− 1	159	465	843	1212	1330	1198	1066	639	319	7377
	Grand Rapids	34.9	2	135	434	804	1147	1259	1134	1011	579	279	6894
	Lansing	34.8	2	138	431	813	1163	1262	1142	1011	579	273	6909
	Marquette	30.2	− 8	240	527	936	1268	1411	1268	1187	771	468	8393
	Muskegon	36.0	4	120	400	762	1088	1209	1100	995	594	310	6696
	Sault Ste. Marie	27.7	−12	279	580	951	1367	1525	1380	1277	810	477	9048
Minn.	Duluth	23.4	−19	330	632	1131	1581	1745	1518	1355	840	490	10000
	Minneapolis	28.3	−14	189	505	1014	1454	1631	1380	1166	621	288	8382
	Rochester	28.8	−17	186	474	1005	1438	1593	1366	1150	630	301	8295
Miss.	Jackson	55.7	21	0	65	315	502	546	414	310	87	0	2239
	Meridian	55.4	20	0	81	339	518	543	417	310	81	0	2289
	Vicksburg	56.9	23	0	53	279	462	512	384	282	69	0	2041
Mo.	Columbia	42.3	2	54	251	651	967	1076	874	716	324	121	5046
	Kansas City	43.9	4	39	220	612	905	1032	818	682	294	109	4711
	St. Joseph	40.3	− 1	60	285	708	1039	1172	949	769	348	133	5484
	St. Louis	43.1	4	60	251	627	936	1026	848	704	312	121	4900
	Springfield	44.5	5	45	223	600	877	973	781	660	291	105	4900
Mont.	Billings	34.5	−10	186	487	897	1135	1296	1100	970	570	285	7049
	Glasgow	26.4	−25	270	608	1104	1466	1711	1439	1187	648	335	8996
	Great Falls	32.8	−20	258	543	921	1169	1349	1154	1063	642	384	7750
	Havre	28.1	−22	306	595	1065	1367	1584	1364	1181	657	338	8700
	Helena	31.1	−17	294	601	1002	1265	1438	1170	1042	651	381	8129
	Kalispell	31.4	− 7	321	654	1020	1240	1401	1134	1029	639	397	8191
	Miles City	31.2	−19	174	502	972	1296	1504	1252	1057	579	276	7723
	Missoula	31.5	− 7	303	651	1035	1287	1420	1120	970	621	391	8125
Neb.	Grand Island	36.0	− 6	108	381	834	1172	1314	1089	908	462	211	6530
	Lincoln	38.8	− 4	75	301	726	1066	1237	1016	834	402	171	5864
	Norfolk	34.0	−11	111	397	873	1234	1414	1179	983	498	233	6979
	North Platte	35.5	− 6	123	440	885	1166	1271	1039	930	519	248	6684
	Omaha	35.6	− 5	105	357	828	1175	1355	1126	939	465	208	6612
	Scottsbluff	35.9	− 8	138	459	876	1128	1231	1008	921	552	285	6673
Nev.	Elko	34.0	−13	225	561	924	1197	1314	1036	911	621	409	7433
	Ely	33.1	− 6	234	592	939	1184	1308	1075	977	672	456	7733
	Las Vegas	53.5	23	0	78	387	617	688	487	335	111	6	2709
	Reno	39.3	2	204	490	801	1026	1073	823	729	510	357	6332
	Winnemucca	36.7	1	210	536	876	1091	1172	916	837	573	363	6761
N. H.	Concord	33.0	−11	177	505	822	1240	1358	1184	1032	636	298	7383
N. J.	Atlantic City	43.2	14	39	251	549	880	936	848	741	420	133	4812
	Newark	42.8	11	30	248	573	921	983	876	729	381	118	4589
	Trenton	42.4	12	57	264	576	924	989	885	753	399	121	4980
N. M.	Albuquerque	45.0	14	12	229	642	868	930	703	595	288	81	4348
	Raton	38.1	− 2	126	431	825	1048	1116	904	834	543	301	6228
	Roswell	47.5	16	18	202	573	806	840	641	481	201	31	3793
	Silver City	48.0	14	6	183	525	729	791	605	518	261	87	3705

Albuquerque, NM

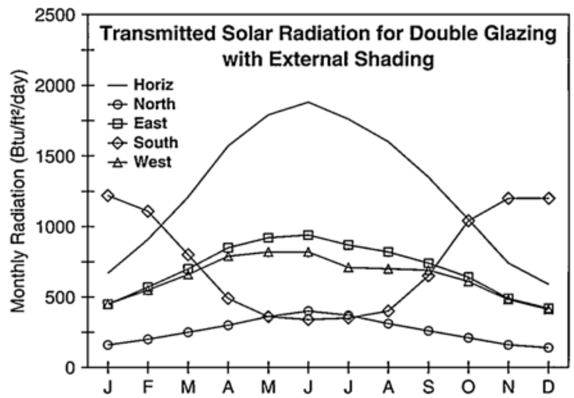
WBAN NO. 23050

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

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