CHAPTER 7

Solar Energy for Buildings

The single biggest demand for energy in the building sector is residential space heating, the next largest is lighting for commercial buildings, and the third most important is residential water heating. In this chapter we will explore the use of solar energy to satisfy a significant fraction of these energy loads. We will also pay attention to cooling loads by seeing how buildings can be designed to minimize the impact of unwanted solar gains in those hot summer months. Building orientation, use of overhangs to shade windows, and selection of window coatings that admit natural daylight while rejecting unwanted thermal gains, are important techniques used to minimize cooling loads.

7.1 The Solar Resource

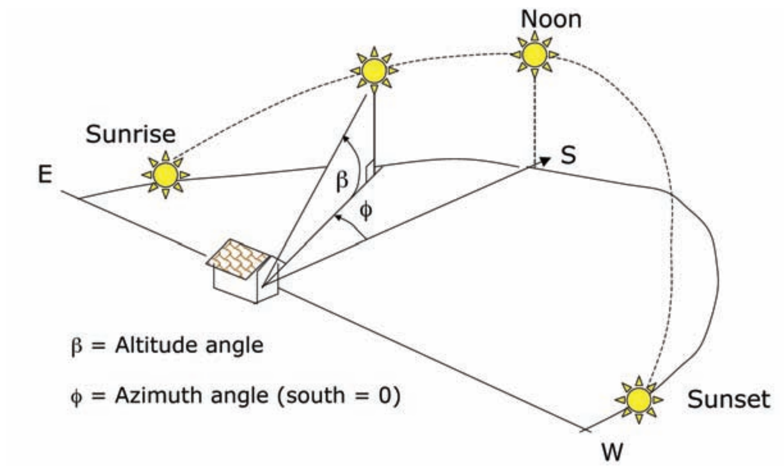
With just a rudimentary understanding of where the sun is, season-by-season, at various times of the day, we can both let it help heat our buildings in the winter and keep it from overheating our buildings in the summer. With a little more effort, we can quantitatively evaluate its impact on building energy demand.

7.1.1 Solar Angles to Help Design Overhangs

For starters, let's locate the sun in the sky. It rises in the east, reaches some maximum height in the sky when it is along our own line of longitude (that time is called *solar noon*), and it sets somewhere in the west. Figure 7.1 identifies the two key angles of interest: the sun's altitude angle β and its azimuth angle ϕ.

Of particular interest is the altitude angle of the sun at solar noon; that is, when it is either due south or due north of your location. We know this altitude angle will vary considerably as the seasons change and we want to learn how to take advantage of that variation. Equation 7.1 tells us just what we want to know:

figure 7.1



The sun's position can be described in terms of its altitude angle β and its azimuth angle ϕ.

Eq. 7.1

$$\beta_N = 90 - L + \delta$$

where β_N = the altitude angle of the sun at solar noon
L = the local latitude
δ = the solar declination

The solar declination δ is the line of latitude over which the sun revolves on that particular day; that is, if you drew a line from the center of the sun to the center of the Earth it would pass through that line of latitude all day long. The equation for δ is given below. The only variable is n, which is the day number (where $n = 1$ is January 1, and $n = 365$ is December 31).

Eq. 7.2

$$\delta = 23.5 \sin\left[\frac{360^\circ}{365^\circ}(n - 81)\right]$$

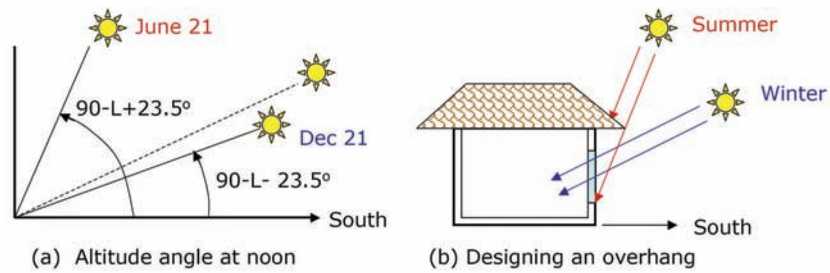
Notice the solar declination varies sinusoidally between ±23.5 and on day number 81, which corresponds to the spring equinox, March 21, $\delta = 0$ and the sun is directly over the equator. (Notice, by the way, that we simplify the narrative of solar angles by assuming we are in the northern hemisphere.) The sun reaches its highest point at solar noon on the summer solstice, June 21, and its lowest noon angle occurs on the winter solstice, December 21. Figure 7.2 shows this range of angles.

The analysis of overhangs is especially simple for south-facing surfaces, which is convenient because that's where you want to place solar-gain windows that will help heat your house in the winter. As shown in Figure 7.3, an overhang that projects out a distance P casts a shadow that ends at a distance y down the south-facing vertical surface. At solar noon, we can easily write that

Eq. 7.3

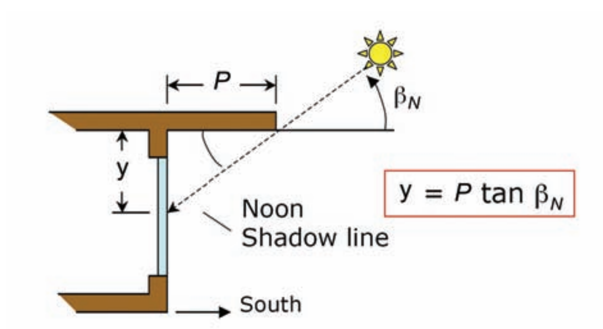
$$y = P \tan \beta_N$$

figure 7.2



We can use the altitude angle of the sun at noon to design overhangs that allow sunlight to hit south-facing windows in the winter while blocking unwanted sun in the summer.

figure 7.3



Locating the shadow line at solar noon for a south-facing window.

The example shown in Solution Box 7.1 illustrates the use of Equation 7.3 to design an overhang.

7.1.2 Site Surveys Using Sun-Path Diagrams

The equations used to locate the sun at any time of day, any day of the year are fairly cumbersome (see for example Masters, 2004, for a more careful analysis), but graphs that show the sun's location are readily available on the Internet. The University of Oregon Web site is especially handy: http://solardat.uoregon.edu/SunChartProgram.html. Just enter your location either by zip code or latitude and longitude (longitude matters only if you want to adjust for local time). Figure 7.4 shows a sample sun-path diagram along with some potential obstructions that shade the site at certain times of the year.

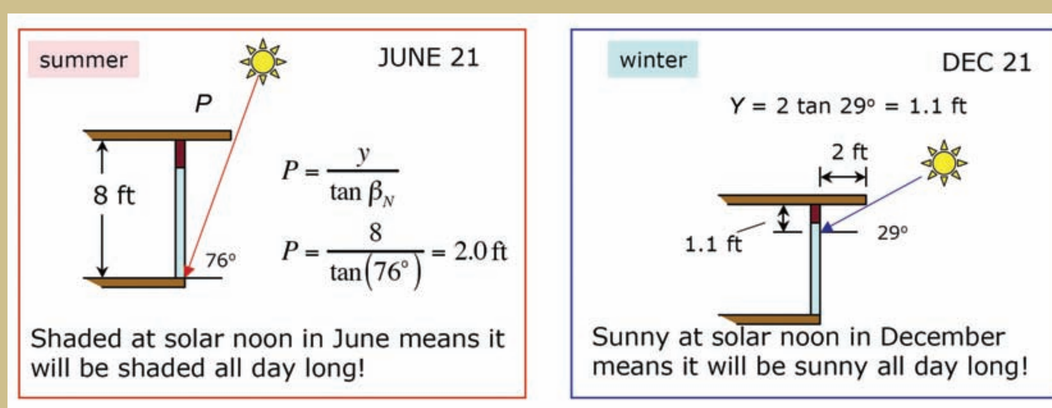
Sun-path diagrams are especially useful for doing a quick site analysis to determine whether obstructions such as trees or buildings may cast shadows onto your proposed location. The altitude and azimuth angles of potential obstructions can be measured using a simple protractor and plumb bob along with a compass (corrected for local magnetic declination) as

SOLUTION BOX 7.1

Design an Overhang

Design an overhang for Palo Alto, California, latitude 37.5°, that will completely shade south-facing, sliding-glass doors at noon on the summer solstice, June 21. Check the shadow line on the winter solstice, December 21.

On the solstices, the declination is ±23.5°, so using Equation 7.1 the altitude angle of the sun at solar noon will be β_N (June 21) = 90 – 37.5 + 23.5 = 76° while on December 21 it is 90 – 37.5 – 23.5 = 29°. It is now easy to figure out the overhang and its impact in the winter:



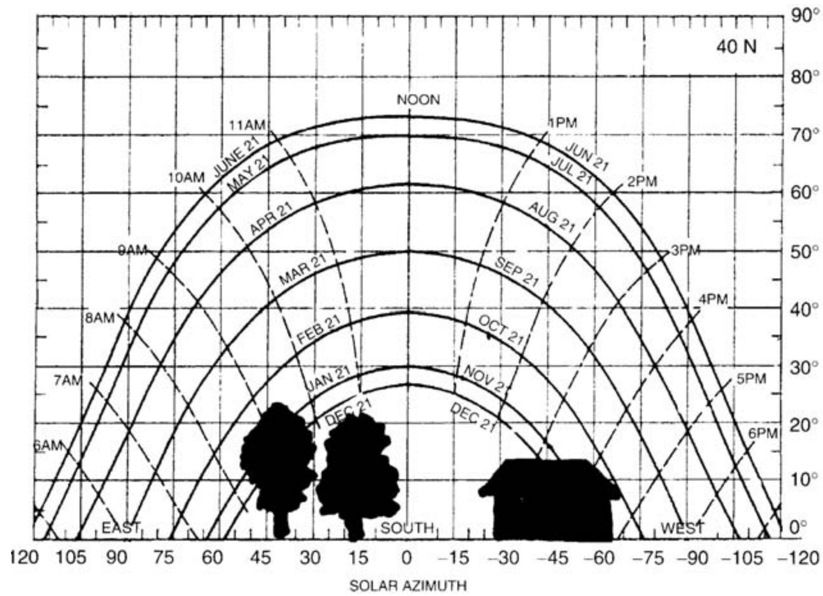
So, a 2-foot overhang completely shades the glass doors at noon in June and completely exposes the windows to the warm rays from the sun at noon in December. Designing overhangs for solar noon provides the fortuitous result that a south-facing window shaded at noon in the summer will be shaded all day long, and a window exposed to the sun in winter at noon will be exposed to the sun all day long.

suggested in Figure 7.5. Sketching the obstructions directly onto a sun-path diagram makes it easy to determine the monthly hour-by-hour shading problems at the site. For example, the site diagramed in Figure 7.4 will have full sun from February through October, but will be shaded from roughly 8:30 to 9:45 a.m., and after about 3:00 p.m., from November through January.

7.1.3 Incident Solar Radiation (Insolation)

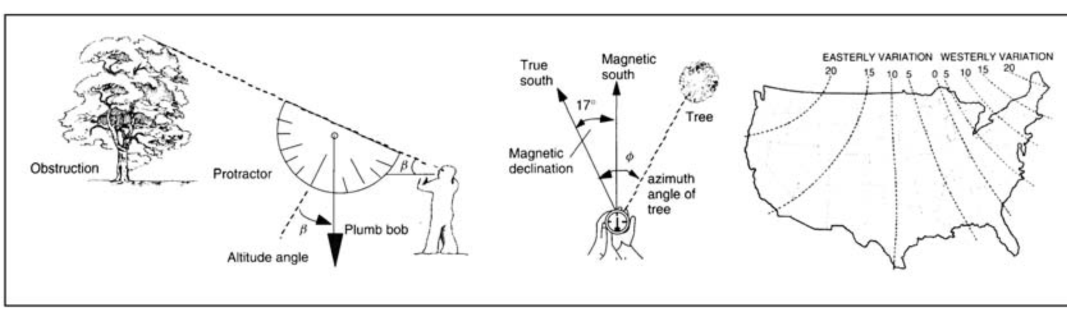
Sun angles and site surveys are very useful, but in most circumstances what we really need to know is how much solar energy is available to generate electricity and to heat our buildings

figure
7.4



A sun-path diagram showing obstructions that shade the site in the morning and late afternoon from November through January.

figure
7.5



A solar site survey can be made using a simple compass, protractor, and plumb bob. The example shows the compass correction for San Francisco, which has a declination of 17°E.

and hot water. In addition, we need to know how much extra cooling our building will need because too much sun is coming through the windows. The **in**cident **sol**ar radi**ation** on a collector, referred to as the *insolation*, is often measured in kW or kWh for photovoltaic calculations and Btu or Btu/hr for solar thermal applications. Table 7.1 provides conversion factors between these and other insolation units. Notice one of the entries is based on the idea that the solar intensity on a surface normal to the incoming rays in mid-afternoon on a clear day is very close to 1 kW/m^2. That is defined as “1-sun” insolation. A site with say 5 kWh/m^2 per day of insolation is said to have 5 hours of 1-sun insolation (this will be very handy in Chapter 11 when we look at generating power with photovoltaics).

table 7.1 Conversion Factors for Various Insolation Units

1 kW/m^2	=	316.95 Btu/hr-ft^2
	=	1.433 langley/min
	=	"1-sun" of insolation
1 kWh/m^2	=	316.95 Btu/ft^2
	=	85.98 langleys
	=	3.60×10^6 joules/m^2

In some circumstances, especially for summer air-conditioning load calculations, clear sky insolation is all we need to know. These values can be calculated for any spot on Earth at any time of any day using a rather cumbersome set of equations (see, for example, Masters, 2004). Whereas clear-sky insolations are useful for a number of purposes, more often what is needed is actual data for a given location. There are, perhaps surprisingly, only 56 primary data-collection stations around the United States for which long-term solar measurements have been made. Those have been supplemented with estimates made from meteorological models for another 183 sites. All of these data have been compiled by the National Renewable Energy Laboratory and are readily available on the Internet.[1] Table 7.2 presents representative insolation data for several cities, just to give you a sense of what is available.

7.2 Passive Solar Heating

As Figure 6.3 pointed out, simple heating of houses is the biggest single category of energy demand in the entire building sector. So, why not let the sun do some of that job? There are two ways to try to do that. The *passive solar* approach is based on encouraging sunlight to pass through windows and other solar apertures to provide needed heat. Passive solar systems are simple, cheap, and reliable. The second approach, *active solar*, uses special solar-thermal collectors to collect heat, which is then moved to storage and distribution systems using pumps and blowers. Although active systems provide greater control of heat flow, their high cost and uncertain reliability have led to less widespread acceptance.

The basic design guidelines for passive solar are pretty simple.

1. Maximize envelope efficiency (we did that in Chapter 6).
2. Try to orient the building along an east-west axis to control solar gains.

[1] *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* (http://rredc.nrel.gov/solar/pubs/redbook/) and *The Solar Radiation Data Manual for Buildings* (http://rredc.nrel.gov/solar/old_data/nsrdb/bluebook/).

table 7.2 **Average Daily Insolation (Btu/ft²-day) on South-facing Surfaces for Various Tilt Angles (Latitude –15°, Latitude, Latitude +15°, and 90°)**

LOS ANGELES, CA: LATITUDE, 33.93 N

TILT	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	YEAR
LAT −15°	1204	1426	1743	2028	2028	2028	2250	2155	1870	1585	1331	1141	1743
LAT	1395	1585	1807	1997	1933	1902	2092	2092	1902	1712	1490	1331	1775
LAT +15°	1490	1616	1775	1870	1712	1648	1838	1902	1807	1743	1585	1426	1712
90	1299	1299	1204	1046	792	697	761	951	1141	1331	1363	1299	1109

BOULDER, CO: LATITUDE, 40.02 N

TILT	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	YEAR
LAT −15°	1204	1458	1712	1933	1965	2092	2092	1997	1870	1616	1268	1109	1712
LAT	1395	1616	1775	1902	1870	1933	1933	1933	1902	1775	1458	1331	1743
LAT +15°	1521	1680	1775	1775	1648	1648	1680	1743	1838	1807	1521	1426	1680
90	1426	1458	1363	1141	887	824	856	1014	1268	1458	1395	1363	1204

BOSTON, MA: LATITUDE, 42.37 N

TILT	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	YEAR
LAT −15°	951	1204	1458	1648	1807	1902	1902	1807	1585	1299	887	792	1426
LAT	1078	1331	1490	1585	1680	1743	1775	1743	1616	1363	983	919	1458
LAT +15°	1141	1363	1458	1490	1490	1521	1553	1585	1553	1395	1046	983	1395
90	1078	1236	1173	983	887	824	887	983	1109	1141	951	919	1014

ATLANTA, GA: LATITUDE, 33.65 N

TILT	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	YEAR
LAT −15°	1078	1331	1616	1902	1965	1997	1933	1870	1680	1553	1204	1014	1585
LAT	1204	1458	1680	1838	1838	1838	1807	1807	1712	1648	1331	1173	1616
LAT +15°	1299	1490	1616	1712	1648	1616	1585	1648	1616	1680	1553	1236	1553
90	1109	1173	1109	951	761	697	697	856	1014	1268	1204	1109	983

Source: Masters, 2004, based on NREL data

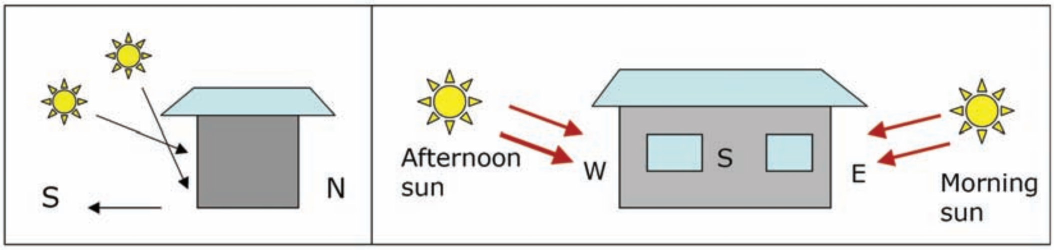
3. Provide south-facing glazing systems to admit solar energy.
4. Design proper overhangs to protect south-facing windows in the summer.
5. Provide sufficient thermal mass to absorb solar energy in excess of daytime needs.

We will now explore these important concepts.

7.2.1 The Importance of Building Orientation

The orientation of a building will greatly affect our dual goals of letting the sun get into a building in the winter, while minimizing excessive solar gain during the summer. We have

figure 7.6

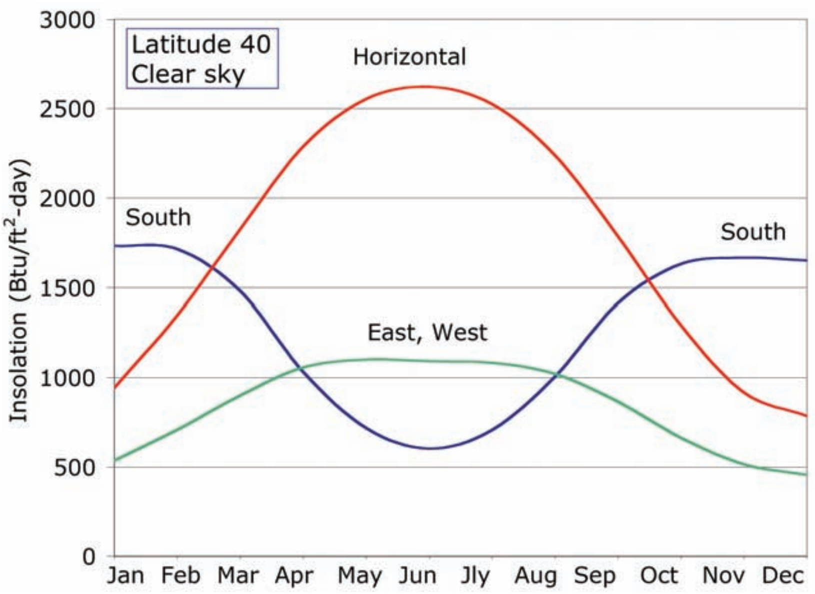


Solar gains through south-facing windows are easy to control using overhangs, but east- and west-facing windows can cause overheating in the summer.

already seen how easy it is for overhangs to be designed for south-facing windows (north-facing for those of you in the southern hemisphere) to do just that. But what about east- and west-facing windows? As shown in Figure 7.6 those windows are exposed to nearly horizontal morning and afternoon solar radiation, so overhangs don't do much good to protect the building from summer overheating.

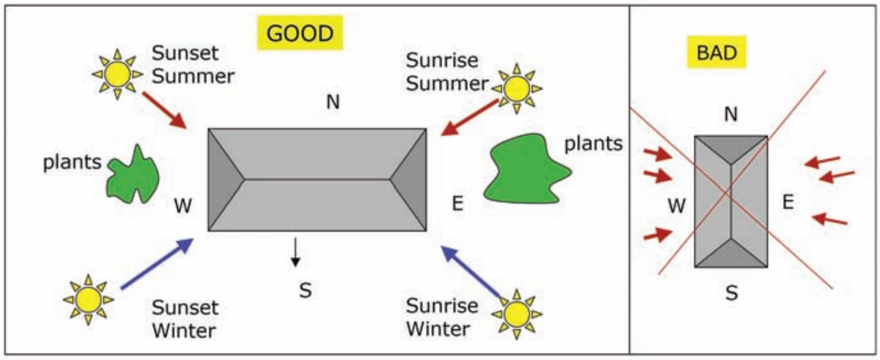
To help introduce the importance of orientation, consider Figure 7.7, which compares monthly clear-sky insolation striking south-facing windows with amounts hitting east and west windows as well as horizontal surfaces (at 40° latitude). Solar energy in the winter helps heat your building, but in the summer it drives up air-conditioning costs. In that sense,

figure 7.7



South-facing windows provide solar gains in the winter when you want it; east and west windows provide it when you don't. Horizontal skylights are the worst for air-conditioning loads.

figure 7.8

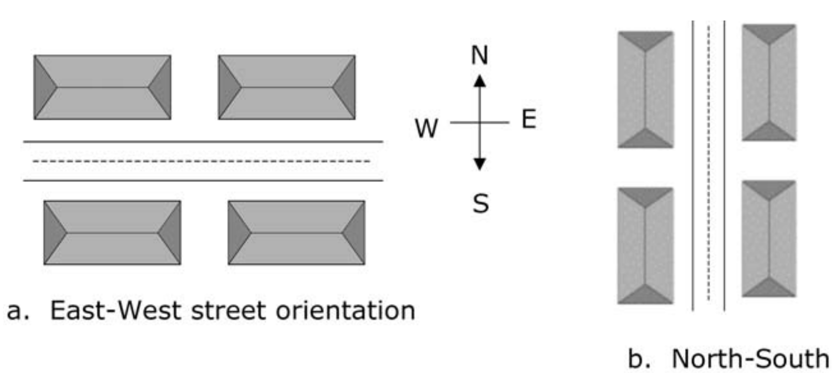


A building with its long axis along the east-west direction helps maximize solar gains in the winter while minimizing morning and afternoon solar exposure in the summer. Vegetation along the east and west sides can help control summer overheating without affecting winter solar gains.

south-facing windows are pretty ideal. East and west windows, on the other hand, can cause overheating in the summer and they're not very helpful in the winter. Also note how problematic horizontal skylights are in the summer.

The best starting point to satisfy the simultaneous needs of providing winter heat and minimizing summer cooling loads is to orient the building with its main axis along the east-west direction as shown in Figure 7.8. That maximizes the amount of wall area available for easily controlled solar gains and minimizes the area of wall and windows exposed to morning and afternoon summer heating. Vegetation along those east and west walls can beautifully and effectively control those summer gains. One way to encourage proper orientation of houses is to plan neighborhood streets to run in the east-west direction rather than north-south, as suggested in Figure 7.9.

figure 7.9



East-west street orientation increases the potential for passive solar and decreases cooling loads.

7.2.2 South-Facing Windows for Solar Gains

It is true that south-facing windows can bring in a lot of solar energy during a sunny day, but they also lose energy all day and all night all winter long. The question of whether they can be net energy providers is important, and easily answered.

We know how to calculate thermal losses using the U-factor of the window. To find solar gains we need a measure of the fraction of solar energy that hits the window that is transmitted into the interior of the building, called the *solar heat gain coefficient* (SHGC). A high SHGC is desirable for passive solar heating, whereas a low value is especially important in commercial buildings with significant cooling loads. The National Fenestration Rating Council (NFRC) labels provide both the U-factor and SHGC as well as a measure of the transmittance of visible wavelengths and the air leakage of the window, an example of which is shown in Figure 7.10. Solution Box 7.2 illustrates the usefulness of several of these important factors.

Virtually anywhere in the country, solar gains for double-glazed, south-facing windows exceed thermal losses all winter long. That suggests putting in a lot of them. There is some risk, however, if too much south-window area is provided. For one, recall from Chapter 6 how cold those windows may feel at night when you are sitting next to them. The other reason is that you may actually overheat the house in the daytime with so much solar power coming in. That can be avoided by adding extra thermal mass, such as a concrete floor, to absorb some of that heat in the daytime so it can be given back at night. Providing enough thermal mass is one of the principal challenges in passive solar design.

figure 7.10 Sample of a National Fenestration Rating Council (NFRC) Window Label

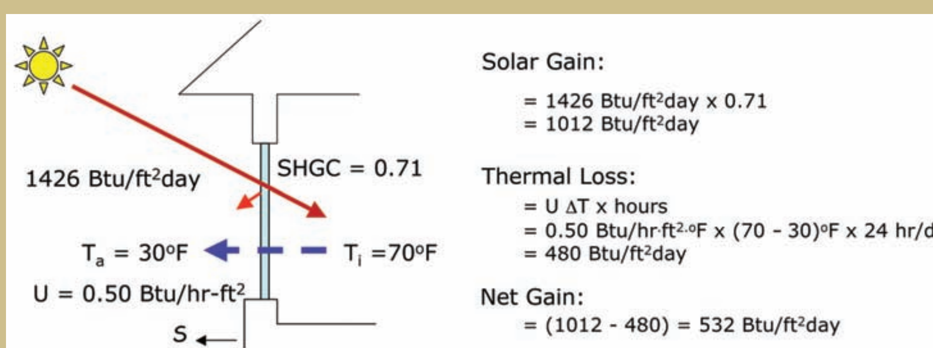
SOLUTION BOX 7.2

Net Gain for a Solar Window in Boulder, Colorado

Compare the average January solar gain for a clear, double-glazed, south-facing window with its average thermal losses. The window has a U-factor of 0.50 and an SHGC of 0.71. It is located in Boulder, Colorado, where the month-long average January temperature is 30°F. Assume the interior of the house is kept at 70°F.

Solution:

From Table 7.2 we find the insolation hitting the window in January averages 1426 Btu/ft²-day. The solar gains and thermal losses are easy to find:



That means every square foot of this window acts like a little furnace providing a net positive 532 Btu/ft² per day—better than the best possible insulated wall, which will always lose some energy.

7.2.3 A "Sun-Tempered" House

A natural question is, How much south glass can we put into an ordinary lightweight framed house that has no extra thermal mass before we risk causing overheating on sunny days? One rule of thumb suggests that as long as the solar gain area is less than about 7% of the floor space area, the inherent mass of the house itself is probably sufficient. A simple, conservative way to analyze such *sun-tempered* houses is to ignore the south window area when doing heat-loss calculations. That is, find the UA-value of the house as if the south-facing windows have infinite R-value. We'll call that $(UA)_{ST}$. Table 7.3 demonstrates this procedure using the "House #1" spreadsheet developed in Table 6.10. For this particular 1500 ft² house, the 100 ft² of south-facing solar-gain windows provide enough heat to drop the annual fuel bill about 20% from $1108 per year down to $897. That's a sizable chunk for such a simple thing to do.

7.2.4 The Importance of Thermal Mass

Because we can imagine south-facing windows as net sources of heat, it is tempting to add more and more of them in a passive solar house design. However, as the area of south-facing glass increases, there will come a point when the inherent house mass will be insufficient to avoid excessive indoor temperature swings. For example, a computer simulation of an

table 7.3 Building Efficiency: Sun-Tempered UA-Value House #1 with 100 ft² of south window out of total 250 ft²

Component	Area (ft²)	Insulation	*R*	*U* = 1/R*	UA*	% of Total*
Ceiling	1500	R-30 #13	30.3	0.033	49.5	12%
South Windows	100	dbl Al #21	Infinite	0.000	0.0	0%
Non-S Windows	150	dbl Al #21	1.4	0.714	107.1	26%
Doors	60	No storm #19	2.6	0.385	23.1	6%
Walls	970	R-21 #3	19.2	0.052	50.5	12%
Floors	1500	R-21 #7	29.3	0.034	51.2	12%
	ACH	**Volume (ft³)**	**Efficiency**			
Infiltration	0.6	12,000	0		129.6	32%
Ventilation	0	12,000	70%		0	0%
				TOTAL $(UA)_{ST}$ = 411 Btu/hr°F		

The fuel bill for this "sun-tempered" house drops about 20% when the solar gains of its 100 ft² of south-facing windows are accounted for. Compare this with the original house in Table 6.10.
* Columns are calculated values. All other information is data entry.

ANNUAL FUEL CONSUMPTION

Fuel Price	$12	per million Btu (Table 6.9)	
Furnace Efficiency	80%		
Distribution Efficiency	75%		
Internal gains, q_{int}	3000	Btu/hr	
Indoor set point, T_i	70	°F	
HDD65	5052	°F-d/yr for Blacksburg, VA (Table 6.8)	
Calculations:			
* Balance Point Temp	62.7	°F	$T_{bal} = T_i - q_{int}/UA_{ST}$
* HDD @ T_{bal}	4546	°F-d/yr	HDDTb = HDD65 - (0.021 * HDD65 + 114)(65 - T_{bal})
* Q_{del}	44.8	Million Btu/yr	Q_{del} = 24(UA)HDD
* Q_{fuel}	74.7	Million Btu/yr	$Q_{fuel} = Q_{del}$/(furn eff × dist eff)
* Annual fuel bill	$ 897	per year	$/yr = Q_{fuel} × fuel price
* **House without solar**	**1,108**	per year using all 250 ft² of windows	

* Rows are calculated values. All other information is data entry.

ordinary lightweight house without extra thermal mass is shown in Figure 7.11. With a south window area equal to 7% of the floor area, the sun warms the house to a reasonable 70°F in the afternoon. If we doubled the window area to 14%, the temperature would rise above 90°F, which is way too hot, which means we need additional thermal mass. With 14% glazing and enough additional thermal mass the house remains comfortable day and night without an auxiliary heat source.

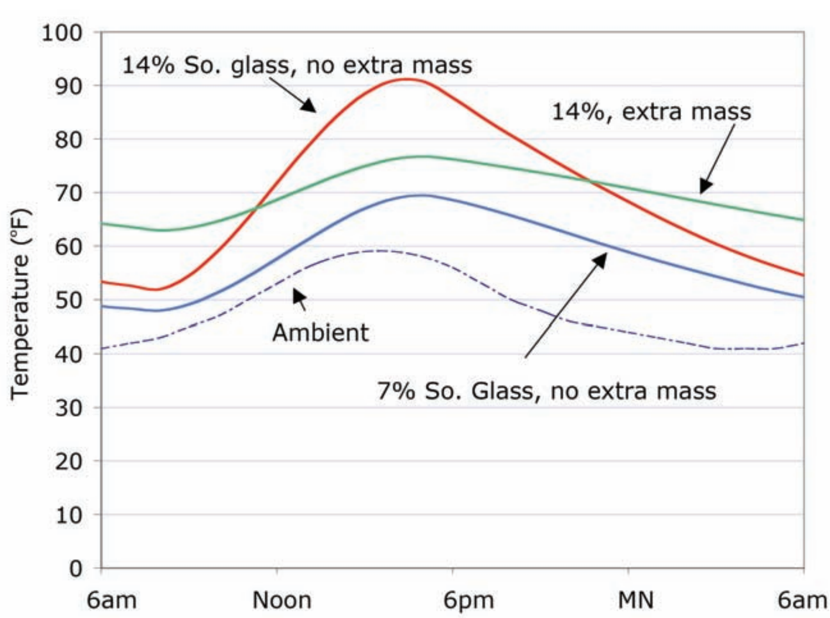
In most passive solar houses, heat storage in extra thermal mass is achieved by letting the sun warm up concrete, tile, or some other dense masonry material, or occasionally, water. A useful measure of the ability of a material to store heat is called *volumetric capacitance,* which is the product of the material's density ρ (lb/ft^3) times its specific heat c (Btu/lb-°F). Let's compare concrete and water for volumetric capacitance:

Concrete: $140\ lb/ft^3 \times 0.2\ Btu/lb\text{-}°F = 28\ Btu/°F\text{-}ft^3$

Water: $62.4\ lb/ft^3 \times 1.0\ Btu/lb\text{-}°F = 62.4\ Btu/°F\text{-}ft^3$

That means you can store more than twice as much heat by raising a cubic foot of water by 1°F than by raising a cubic foot of concrete by that same amount. In spite of that advantage, very few passive solar houses attempt to use water for thermal mass. Solution Box 7.3 demonstrates a useful guideline for sizing thermal mass.

figure 7.11



A computer simulation of a small, lightweight house showing the impact of having too much south-facing solar gain area and not enough mass. With enough mass, 14% of the floor area in south-facing glass remains comfortable with no external heat source.

SOLUTION

SOLUTION BOX 7.3

Sizing Thermal Mass

How much thermal mass do we need for a passive solar house?

Solution:

One recommendation for the amount of thermal mass needed in a passive solar house is to provide at least 30 Btu/°F of storage capacity per square foot of solar gain area. For a house with 200 ft^2 of solar aperture, that would suggest needing a thermal capacitance of

$$C = 30\ \text{Btu/°F-ft}^2 \times 200\ \text{ft}^2 = 6000\ \text{Btu/°F}$$

If we use concrete with a volumetric capacitance of 28 Btu/ft^3-°F, that says we need about

$$V = \frac{6000\ \text{Btu/°F}}{28\ \text{Btu/ft}^3\text{-°F}} = 214\ \text{ft}^3 \text{ of concrete}$$

If we use a concrete slab for mass, and estimate it is just the top 4 inches that is effective, that suggests a floor area of about

$$\text{Area of concrete} = \frac{214\ \text{ft}^3}{4/12\ \text{ft}} = 640\ \text{ft}^2$$

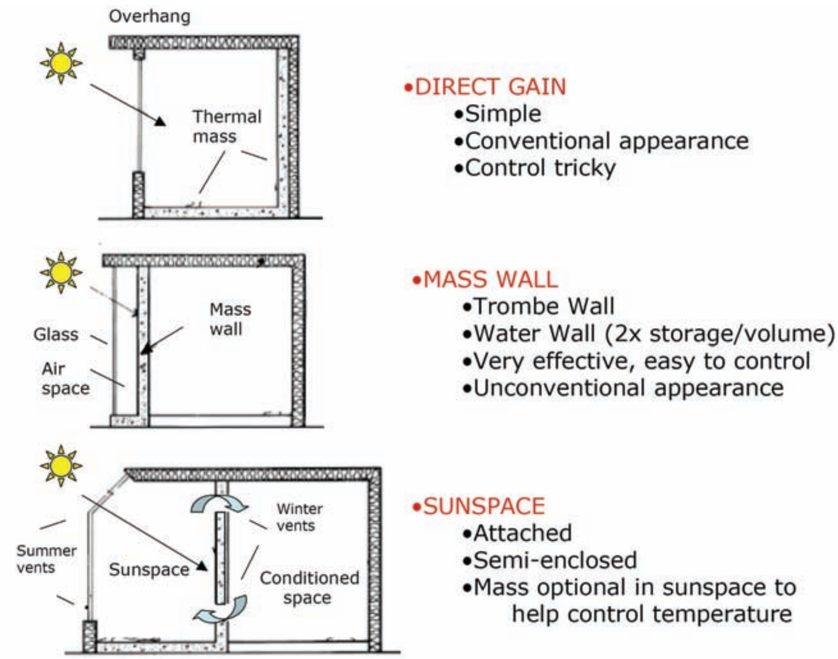
Another way to state this result is that you should have about 3 ft^2 of surface area of concrete thermal mass in the vicinity of the windows per square foot of solar glazing.

There is another approach to thermal mass that is quite promising. Rather than storing heat by changing the temperature of a substance, you instead change its state from solid to liquid when it absorbs heat, and transform it back to liquid to give back that heat. One such *phase change material* is made with hydrated calcium chloride, which absorbs 82 Btu/lb when it melts at 81°F. With a density of 97 lb/ft^3, that means it can store about 8000 Btu/ft^3 when it changes phase. That's about 14 times better than a 20°F temperature swing in a cubic foot of concrete.

7.2.5 Types of Passive Solar Heating Systems

There are three "generic" types of passive solar heating systems: *direct gain*, *mass wall*, and *sunspace*. These are illustrated in Figure 7.12. The essence of a direct gain system is just

figure 7.12



Three "generic" types of passive solar systems.

south-facing glass, an overhang to shade the glass in the summer, and enough thermal mass to adequately back up the solar gains. These systems are simple and result in a conventional appearance to the house. The trick is to provide enough mass to keep the temperature swings under control.

A second approach is based on putting the thermal mass directly behind the glazing, with an air gap to help keep the heat from dissipating to the ambient at night. The mass is usually a dark-colored concrete wall, in which case it is often called a *Trombe wall* named after a French engineer, Felix Trombe, who popularized the idea in the 1960s. The concept is simple and very effective. The mass not only absorbs solar energy, but it also provides a helpful delay between the time the sun hits the wall during the day and the time that the heat works its way through the mass so that it can radiate into the interior space in the evening. Their main disadvantage is aesthetic. We like to look out those windows. To mitigate that, many installations have a combination of direct gain and mass wall to let daylight in and provide views to the outside.

The third category of passive heating is based on an attached sunspace, or greenhouse. While there are many variations on sunspaces, the common denominator is that the range of temperatures allowed within the sunspace is much greater than would be tolerated in the rest of the house. Sunspaces are meant to get pretty warm during the daytime to provide heat that can be directed into the adjacent conditioned space, and then they are usually allowed to cool off quite a bit at night. The range of temperatures through which the sunspace swings can be controlled by the amount of mass used. The flip side is that more mass means more of the heat stays in the sunspace and therefore doesn't provide as much heat to the conditioned space inside the house.

7.2.6 Estimating Solar Performance

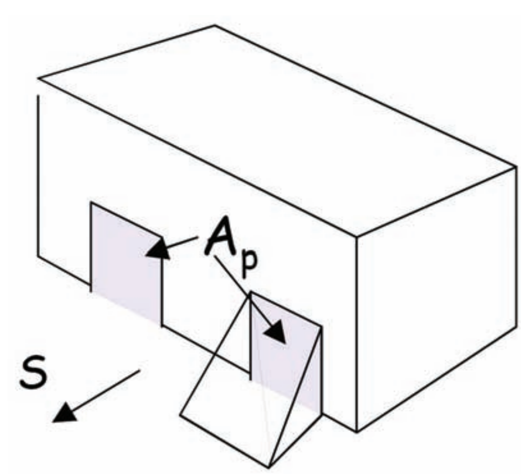
A careful analysis of passive solar performance is complicated and challenging, but we can make reasonable estimates based on work done in the 1970s by a team at the Los Alamos National Laboratory in New Mexico.[2] We'll use their simplest procedure, called the *Load-Collector Ratio* method, which results in a very rough estimate of the annual heat load for a south-facing, passive solar house. We begin by identifying the solar aperture area, A_p, which for direct-gain and mass-wall systems is just the south-facing glazing area. For a sunspace, A_p is the projected area of the glass onto the south wall as shown in Figure 7.13.

In this procedure, the solar aperture area is treated as if it is thermally neutral (in essence infinite R-value). That makes the UA-value the same as the one we used for a sun-tempered house, $(UA)_{ST}$. The key parameter that describes a passive solar house is called the load-collector ratio (LCR). The numerator of LCR is a heat loss term whereas the denominator is a solar gain term. Therefore, a low LCR is indicative of better solar performance.

Eq. 7.4

$$LCR = \frac{24(UA)_{ST}}{A_p}$$

figure 7.13



Identifying the solar aperture area, A_p.

[2] Balcomb, D., R. Jones, C. Kosiewicz, G. Lazarus, R. McFarland, and W. Wray, *Passive Solar Design Handbook, Vol. 3.* (New York: American Solar Energy Society, 1983).

The full LCR procedure is based on finding the closest match between your house design and a number of "standard" passive solar designs defined in the passive solar design handbook. You then pore over huge tables of numbers that use your LCR to find the *solar savings fraction* (SSF) for your particular house in your particular location (see, for example, Stein and Reynolds, 1992, for an extensive set of LCR tables). The energy that needs to be delivered by your heating system is then

Eq. 7.5

$$Q_{del}\ (\text{Btu/yr}) = 24(UA)_{ST}\ \text{HDD65}\ (1 - \text{SSF})$$

where HDD65 = degree-days at a 65°F base temperature

For illustrative purposes, we have simplified their procedure and their tables considerably. Table 7.4 allows you to pick a generic passive solar design (direct gain, sunspace, Trombe wall) for a particular city. For that design, find values for LCR2 and LCR5, then plug them into the following empirically derived relationship to find SSF:

Eq. 7.6

$$\text{SSF} = 0.18 + 0.3\ \frac{\log_{10}(\text{LCR2}/\text{LCR})}{\log_{10}(\text{LCR2}/\text{LCR5})}$$

Our simplified LCR method gives a quick estimate of the annual heating demand. The analogous month-by-month analysis is called the *solar load ratio* (SLR) method. There are several software packages built around the SLR method, including *BGW20004* from Solaequis and *BuilderGuide*.

Do these passive solar ideas really work? One very early study that carefully monitored forty actual houses produced the following persuasive answer to that question. In Figure 7.14 the normalized heating requirements (like our thermal index in Equation 6.20) broken down into the amount supplied by solar gains, internal gains, and back-up furnace are shown. For most of these houses, the furnace is required to supply less than 2 Btu/ft^2 per degree-day; most new houses today require something like 6–8 Btu/ft^2-°F day.

7.3 Cooling Loads

For a number of reasons, cooling calculations are more difficult to make than those for heating. Not only are there UA heat gains through the building envelope, there are also unwanted solar gains through windows, roofing that absorbs sunlight, infiltration and ventilation air that needs to be dehumidified as well as cooled, and finally, those internal gains that help heat a building in the winter but work against us when we need cooling (Figure 7.15).

7.3.1 Avoiding Cooling Loads

The best way to reduce air-conditioning load, of course, is to focus on avoiding the need for cooling in the first place. A good starting point is building orientation. We have already seen

table 7.4 Simplified Parameters for the LCR Method

		Trombe Wall (TWB1)		Direct Gain (DGB1)		Sunspace (SSB1)		HDD65	T_{avg}
		LCR2	LCR5	LCR2	LCR5	LCR2	LCR5	°F-d/yr	°F
Birmingham	AL	101	20	80	20	125	28	2844	62
Phoenix	AZ	308	68	274	92	353	87	1552	70
Tucson	AZ	281	63	248	85	331	84	1752	68
Los Angeles	CA	351	76	314	102	457	110	1819	62
Mount Shasta	CA	74	13	54	3	99	19	5890	50
Oakland	CA	213	46	192	58	289	66	2909	57
Red Bluff	CA	141	27	116	30	165	34	2688	63
Sacramento	CA	145	28	122	31	179	37	2843	60
San Diego	CA	391	86	350	117	500	123	1507	63
Santa Maria	CA	212	49	191	64	298	77	3053	57
Denver	CO	86	18	68	18	106	25	6016	50
Pueblo	CO	92	19	73	20	111	26	5394	53
Washington	DC	42	7	22	1	57	11	5010	54
Jacksonville	FL	248	54	213	71	294	73	1327	68
Atlanta	GA	92	18	72	17	116	26	3095	61
Boise	ID	69	10	50	1	85	14	5833	51
Chicago	IL	27	1	15	1	39	4	6127	51
Des Moines	IA	34	4	20	1	45	7	6710	49
Wichita	KS	58	10	38	1	73	14	4687	57
New Orleans	LA	212	44	182	57	257	61	1465	68
Boston	MA	32	4	20	1	44	7	5621	51
Kansas City	MO	50	8	30	1	64	12	5357	54
Omaha	NB	40	6	17	1	51	9	6601	49
Las Vegas	NV	207	45	180	58	233	56	2601	66
Reno	NV	104	22	84	23	133	30	6022	49
Albuquerque	NM	117	26	97	30	141	35	4292	57
Los Alamos	NM	79	17	60	16	105	25	6359	48
Charlotte	NC	97	19	77	19	119	27	3218	61
Raleigh-Durham	NC	84	17	65	15	104	23	3517	59
Tulsa	OK	80	16	60	13	97	22	3680	60
Medford	OR	61	7	40	1	81	12	4930	53
North Bend	OR	98	21	83	21	135	31	4688	52
Portland	OR	55	1	31	1	73	8	4792	53
Charleston	SC	142	29	120	34	172	40	2146	65
Nashville	TN	57	9	36	1	74	15	3696	59
Austin	TX	180	38	153	47	219	52	1737	68
Dallas	TX	136	29	113	34	164	39	2290	66
Houston	TX	183	38	153	47	221	53	1434	69
Salt Lake City	UT	73	13	55	1	92	18	5983	51
Roanoke	VA	65	12	47	1	83	18	4307	56
Seattle	WA	51	1	25	1	69	1	5185	51
Cheyenne	WY	69	14	51	11	87	20	7255	46

The full table is available in the *Passive Solar Design Handbook, Vol. 3.* Also given are base 65°F degree days and annual average temperature. Notes: LCR2 = LCR @SSF = 0.20; LCR5 = LCR @SSF = 0.50. DGB1 is double glazed, 3:1 mass-to-glazing ratio, 6" mass, no night insulation; TWB1 is 6", vented, double glazed; SSB1 is attached, 90/30, masonry common wall, opaque end walls.

SOLUTION BOX 7.4

SOLUTION

Applying the Simplified LCR Method to a Direct-Gain House

A house in Denver with a total UA-value of 400 Btu/hr-°F has 200 ft^2 of U-0.50 direct gain windows (with suitable mass). If the furnace and ducts are each 90% efficient and the fuel is natural gas at \$1.20/therm, estimate the fuel bill. Denver has HDD65 = 6016 °F-day/yr.

Solution:

The sun-tempered UA-value subtracts those solar windows

$$(UA)_{ST} = 400 \text{ Btu/hr-°F} - 200 \text{ ft}^2 \times 0.50 \text{ Btu/hr-ft}^2\text{-°F} = 300 \text{ Btu/hr-°F}$$

$$\text{The load collector ratio is LCR} = \frac{24(UA)_{ST}}{A_p} = \frac{24 \times 300}{200} = 36$$

From Table 7.4, LCR2 = 68 and LCR5 = 18, so using Equation 7.6 we get

$$SSF = 0.18 + 0.3\frac{\log_{10}(68/36)}{\log_{10}(68/18)} = 0.324$$

Using Equation 7.5 gives

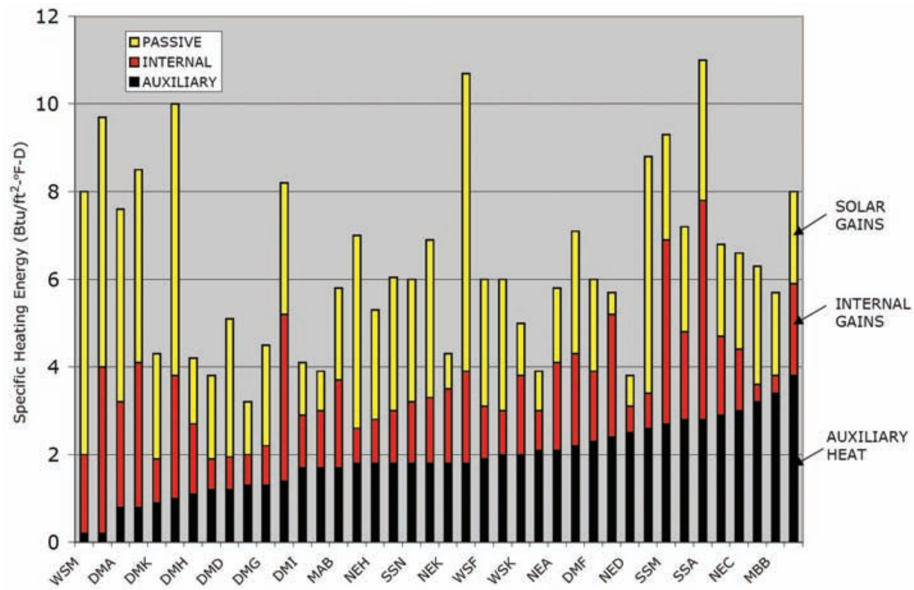
$$Q_{del} = 24 \text{ hr/day} \times 300 \text{ Btu/hr-°F} \times 6016 \text{ °F-day/yr} \times (1 - 0.324) = 29 \times 10^6 \text{ Btu/yr}$$

Accounting for furnace and duct losses, the final fuel bill will be about

$$\text{Fuel} = \frac{29 \times 10^6 \text{ Btu/yr}}{0.90 \times 0.90} \times \frac{\$1.20}{10^5 \text{ Btu}} = \$430/\text{yr}$$

the importance of east-west orientations to reduce wall and window areas exposed to the sun. Buildings can also be oriented to take advantage of prevailing winds that can help provide natural ventilation. As suggested in Figure 7.16, if breezes approach at a bit of an angle, rather than head on, ventilation efficiency is improved. Locating rooms that produce heat and humidity, such as kitchens and laundry rooms, on the leeward side of the house helps keep their heat and humidity from affecting other areas of the house. If there is an attached garage, it too should be placed on the leeward side of the house to keep it from blocking needed airflow in the rest of the building.

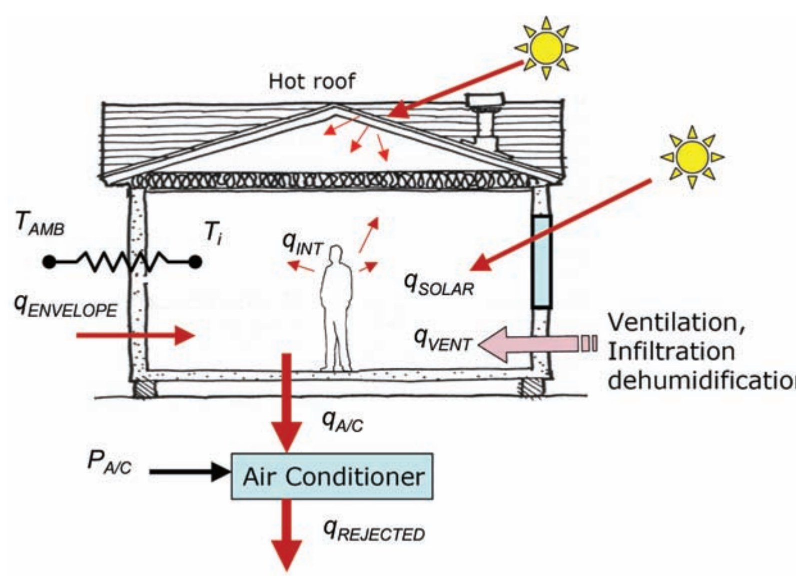
figure 7.14



Measured specific heating energy for forty passive solar homes showing most requiring less than 2 Btu/ft² per degree-day of auxiliary heating.

Source: Swisher (1985)

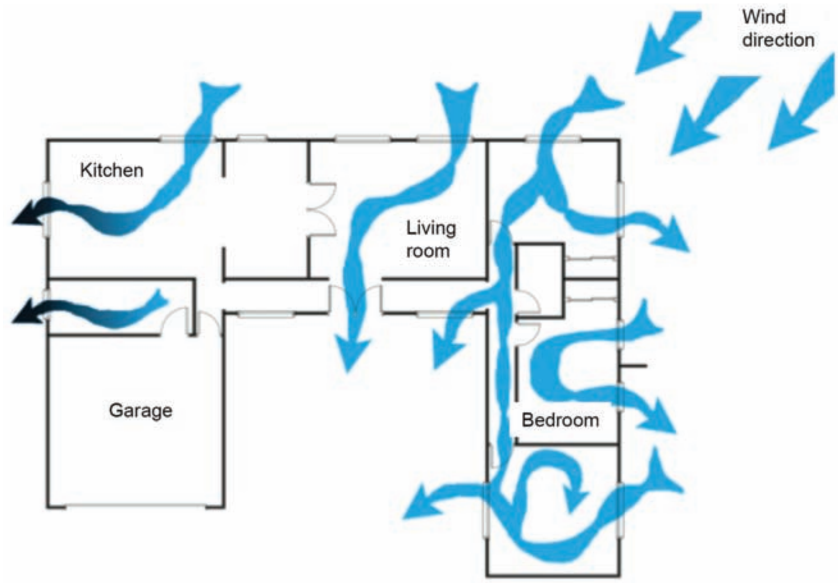
figure 7.15



Cooling loads are trickier to analyze.

A major cause of overheating in a building is the sun beating down all day long onto rooftops. As Figure 7.17 indicates, light-colored roofs may be as much as 70°F cooler than dark ones. Dark roofs not only increase the cooling load of a building, they also help increase

figure 7.16



Designing for good cross ventilation.

Source: DBEDT, 2001

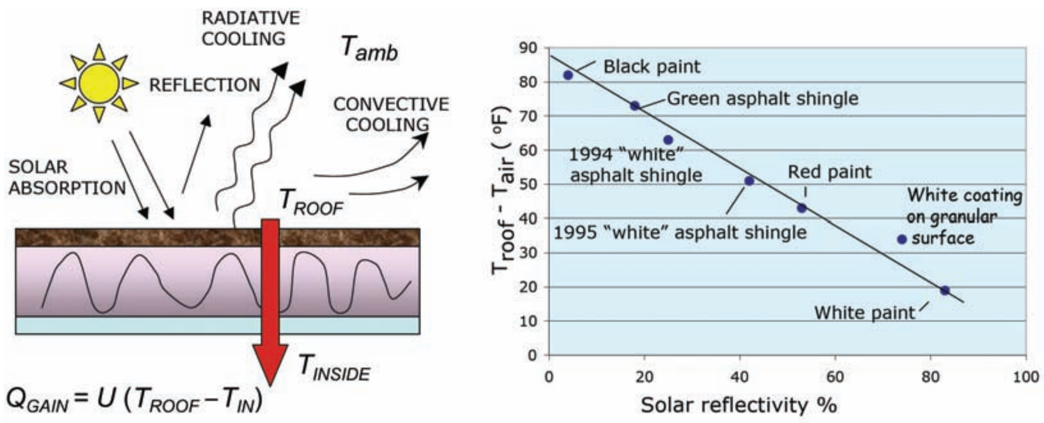
the ambient temperature of the whole neighborhood, a phenomenon called the *heat island effect*. Researchers at Lawrence Berkeley National Labs and at the Florida Solar Energy Center have monitored buildings with lightly colored, more reflective roofs and concluded that those buildings used up to 40% less energy for cooling than buildings with darker roofs. Extrapolating their results across the United States suggests savings on the order of $750 million per year could be realized if cool roofing materials were to be used.

Newly developed roofing materials that enable color retention while increasing the overall solar reflectivity suggest we don't really have to have white roofs to capture these savings. Recall that roughly half of incoming solar energy is in the infrared region and about half in visible wavelengths. These new materials attempt to reflect as much of that IR as possible, and then reflect just enough in the visible range to provide the desired color. Figure 7.18 shows this concept along with a comparison of the reflectivity and colors for cool roofing tiles versus standard tiles.

In addition to more reflective roofing materials, attic temperatures can be dramatically reduced by using continuous ridge and soffit vents augmented with shiny, foil radiant barriers under the roof rafters or on top of ceiling joists (Figure 7.19).

In commercial buildings, proper east-west axis orientation, choosing glass that reduces solar gains while letting in natural daylight, careful design of fins and overhangs, and thoughtful placement of vegetation to shade windows and roofs all have a significant effect. Reducing internal gains by using energy-efficient lighting, office machines, and appliances, is especially important in commercial buildings where such gains are a major driver of air-conditioning loads. In areas with hot days and cool nights, additional thermal mass to absorb "coolth" at

figure 7.17



Heat gain can be greatly increased due to the elevated temperature of roofing materials.

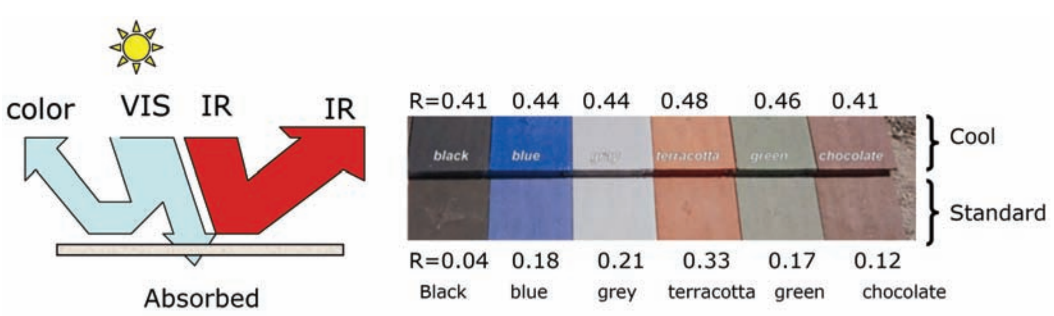
SOURCE: based on LBNL http://eetd.lbl.gov/HeatIsland/CoolRoofs/

night can help carry the building through the next day using a sort of thermal flywheel effect. Another approach to cool roofing takes advantage of the insulating and shading ability of plants growing on the roof itself. These *green roofs* are becoming especially popular in areas where stormwater runoff is a problem. When designed properly, green roofs help avoid storm surges by absorbing and temporarily storing rainwater.

7.3.2 The Building Envelope and Cooling Degree-Days

Having briefly explored ways to reduce cooling loads, we will now spend a little time trying to quantify some of the ways cooling loads can be calculated. For the building envelope, we

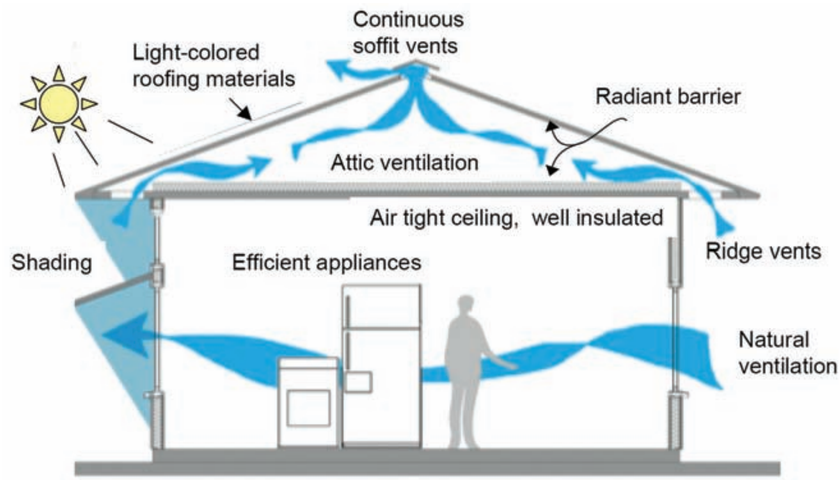
figure 7.18



Cool roofing reflects as much infrared as possible and enough visible to provide color. The cool roofing tile samples shown increase reflectance by about 0.3.

SOURCE: American Rooftile Coatings

figure 7.19



A combination of construction techniques can dramatically reduce the need for cooling.

Source: DBEDT, 2001

can use the same UA-value analysis developed in Chapter 6 to find heat gains due to ambient-to-indoor temperature differences. Notice, however, that the temperature differences driving heat gains (maybe 20°F–30°F) are often considerably smaller than those for heat loss calculations (often 40°F–60°F).

We can also use the same sort of degree-day analysis for annual cooling loads as we did for heating loads. The procedure for determining cooling degree-days is analogous to that used for heating degree-days. For every day that the average temperature is above the base temperature (T_b), cooling degree-days (CDD) are accrued; for every day they are below the base temperature, heating degree-days (HDD) are accrued.

The relationship between annual HDD and CDD is as follows:

Eq. 7.7
$$CDD_{Tb} = HDD_{Tb} - 365(T_b - T_{AVG})$$

where T_{AVG} = annual average temperature (e.g., Table 7.4)

We can use CDD for annual loads in just the same way that we used HDD:

Eq. 7.8
$$Q_{Envelope}\ (\text{Btu/yr}) = 24\ \text{hr/day} \times (UA)\ (\text{Btu/hr-°F}) \times CDD\ (\text{°F-day/yr})$$

To figure out the annual cost of cooling, we need to account for the efficiency of the air conditioner (AC) and the inefficiencies of the ducts. The efficiency of air conditioners is given by a quantity called the seasonal energy efficiency ratio (SEER), which is the cooling output (Btu/yr) divided by the electrical energy input (Wh/yr) for a hypothetical average U.S. climate.

Eq. 7.9

$$\text{SEER (Btu/Wh)} = \frac{\text{Annual cooling (Btu/yr)}}{\text{Electrical input (Wh/yr)}}$$

The first federal efficiency standard for central ACs in 1992 required a minimum SEER of 10. New standards raised the SEER requirement to 13 in 2006. Many older ACs have a SEER of only 6 or 7. Including duct efficiency, the electric energy input for an AC is given by

Eq. 7.10

$$\text{Annual Envelope Cooling Electricity (Wh/yr)} = \frac{24(UA)CDD}{SEER \cdot \eta_{Ducts}}$$

Solution Box 7.5 demonstrates the use of CDD and SEER.

7.3.3 Controlling Solar Gains with Better Windows

We already know the importance of orienting a building to minimize east- and west-facing windows, and we know something about using overhangs to shade south-facing windows. Even after exhausting the advantages of these simple design guidelines, there will almost always be windows that will be hit with solar radiation in those hot months of the year. Especially in large buildings, some of that radiation is useful in that it brings in daylight that helps reduce the need for artificial lighting. Table 7.5 presents some month-by-month clear-sky numbers for insolation striking windows with various orientations.

Recall from Figure 6.3 that the critical loads for commercial buildings are lighting and air-conditioning (AC). As Figure 7.7 suggests, to avoid solar gains, window orientation is of paramount importance. Compared to south-facing windows (easy to shade), east- and west-facing windows are typically exposed to twice the solar radiation in the summer, and that factor increases to 4 or 5 for horizontal skylight glazing. East- and west-facing glass can drive up air-conditioning loads; horizontal glazing is even worse.

The traditional approach to controlling solar gains for commercial buildings has been to choose windows that are either tinted (e.g., bronze) or reflective. The downside to tinted windows is that they block solar radiation by absorbing it in the glazing itself. The resulting hot glass can be extremely uncomfortable to sit next to as it radiates its heat into the interior space. Shiny, reflective windows avoid the heated-glass problem, but by indiscriminately blocking all wavelengths they provide very little natural daylight, which increases the need for artificial lights.

The more modern approach to controlling solar gains is with *spectrally selective* glass. Recall the solar spectrum introduced in Chapter 4 and redrawn here as Figure 7.20. About 2% of the insolation is in the ultraviolet (UV) portion of the spectrum (gives us skin cancer and fades materials), about 47% is in the visible range (helps us see things), and 49% is in the near infrared (provides heat but no light). The far infrared region shown corresponds to wavelengths emitted by objects at ordinary room temperatures.

SOLUTION BOX 7.5

Cooling Load in Houston Due to Envelope Gains

What would the cost of cooling be (envelope portion only) for a UA = 500 Btu/hr-°F house in Houston with 70% efficient ducts, an AC with SEER = 10, and electricity that costs $0.10/kWh? From Table 7.4, Houston has HDD65 = 1434 °F-day/yr and annual average temperature of 69°F.

Solution:

First find CDD65 from Equation 7.7.

$$\mathbf{CDD65 = HDD65 - 365\left(T_b - T_{AVG}\right) = 1434 - 365(65 - 69) = 2894\ °F\text{-}day/yr}$$

From Equation 7.10 the electricity needed by the air conditioner will be

$$\frac{24(UA)CDD}{SEER \cdot \eta_{Ducts}} = \frac{24\ \text{hr/day} \times 500\ \text{Btu/hr °F} \cdot 2894\ \text{°day/yr}}{10\ \text{Btu/Wh} \cdot 0.70} \times \frac{1\ \text{kW}}{1000\ \text{W}} = 4961\ \text{kWh/yr}$$

At $0.10/kWh, the cooling load due to the building envelope would be about $496/yr.

SOLUTION

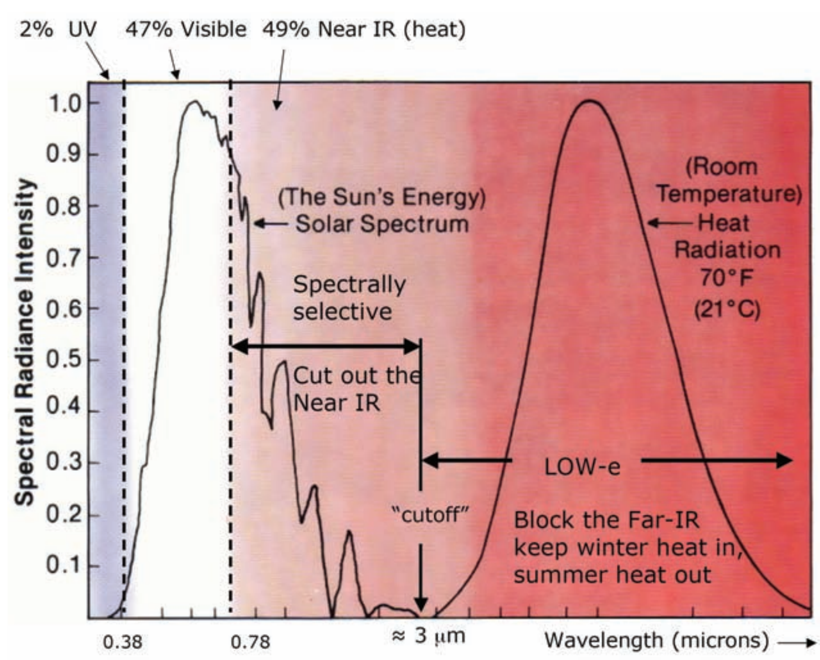
table 7.5 Daily Clear-sky Insolation (Btu/ft[2]) on Vertical Surfaces (e.g., Windows)

	LATITUDE 30 N			LATITUDE 35 N			LATITUDE 40 N			LATITUDE 45 N		
	S	SE/SW	E/W	S	SE/SW	E/W	S	SE/SW	E/W	S	SE/SW	E/W
JAN	1786	1336	654	1784	1315	599	1733	1268	536	1604	1164	445
FEB	1624	1339	834	1687	1349	777	1715	1333	707	1704	1293	631
MAR	1225	1200	946	1363	1257	925	1481	1312	900	1575	1351	868
APR	706	1001	1036	872	1097	1049	1031	1184	1058	1186	1262	1061
MAY	404	840	1064	554	928	1085	717	1027	1101	880	1120	1112
JUN	318	769	1051	457	857	1075	603	948	1092	763	1044	1104
JLY	402	825	1044	549	911	1066	706	1007	1082	864	1098	1093
AUG	698	971	1002	855	1061	1013	1006	1144	1021	1152	1217	1023
SEP	1179	1153	913	1307	1203	892	1414	1252	865	1498	1285	832
OCT	1570	1285	792	1619	1285	732	1632	1262	663	1611	1219	592
NOV	1739	1300	635	1730	1277	581	1667	1221	515	1526	1108	421
DEC	1808	1329	601	1769	1291	541	1652	1197	456	1445	1038	344
Annual	408,418	405,541	321,581	441,456	420,321	314,477	466,229	430,233	304,182	479,978	431,592	290,024

Conventional low-e windows focus on ordinary building and ambient temperature radiation. These low-e windows are designed to keep far infrared (thermal) radiation inside the building in the winter and outside in the summer. On the other hand, spectrally selective glazings have window coatings that are designed to block as much of the solar near-IR sunlight as possible, while allowing a controllable amount of visible solar wavelengths into the building. These spectrally selective windows, combined with automatic dimming systems to modulate the artificial lighting to account for the availability of natural daylight, can dramatically reduce lighting loads in commercial buildings.[3] Figure 7.21 presents the idea.

As shown in Figure 7.10, window labels now contain information on the fraction of visible energy transmitted as well as U-value, and solar heat gain coefficient (SHGC). Table 7.6 presents a number of window types with representative values of these important characteristics. All the double-pane, low-e windows have comparable R-values, but a good choice for passive solar heating might be the low-e 178 with #3 surface coating (SHGC = 0.63). For daylighting and reduced cooling loads you might choose the low-e 128, which has a low SHGC of 0.24. Figure 7.22

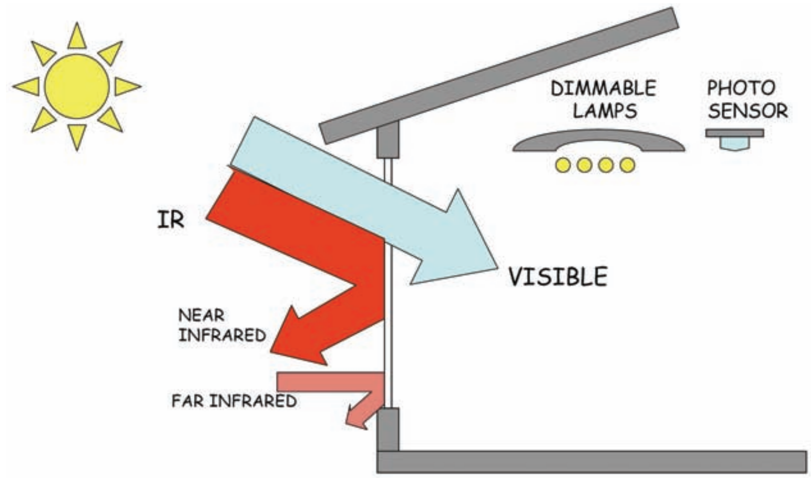
figure 7.20



The solar spectrum and the spectrum for objects near room temperature (the near-IR). Low-e windows reflect the far infrared, whereas spectrally selective, low-e coatings try to block both the near and far infrared.

[3] Two excellent sources of information on daylighting systems are the International Energy Agency's 2000 report *Daylight in Buildings: A Source Book on Daylighting Systems and Components,* and LBNL's *Tips for Daylighting with Windows*.

figure 7.21



Spectrally selective, low-e windows coupled with automatically dimming interior lighting systems take advantage of available natural daylight to reduce both lighting and cooling loads.

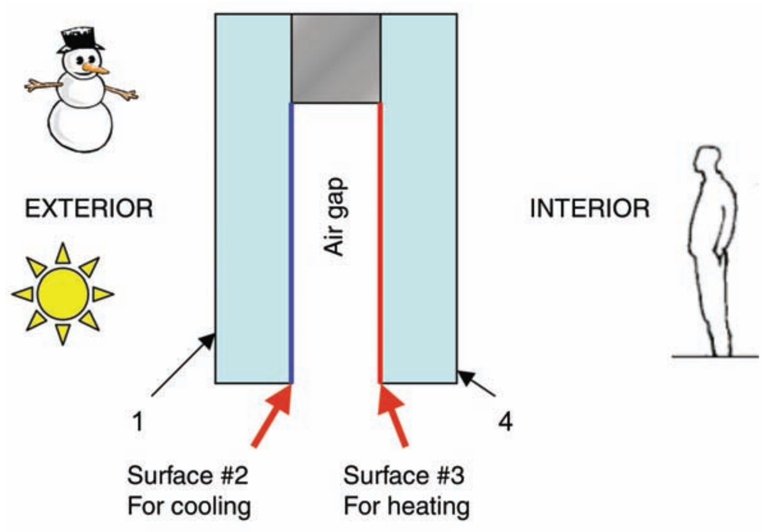
table 7.6 **Examples of Center-of-Glass Visible Transmittance, Solar-Heat-Gain Coefficients, U- and R-Values**

Type	Glass Coating	Visible Light Transmittance	SHGC	U-factor Air	R-Value Air	U-factor Argon	R-Value Argon
1-pane	Clear	0.90	0.86	1.04	0.96		
1-pane	Bronze Tinted	0.68	0.73	1.04	0.96		
2-pane	Clear	0.81	0.76	0.48	2.08		
2-pane	Bronze Tinted	0.61	0.63	0.48	2.08		
2-pane	Lo e 178 #3 Surface	0.78	0.63	0.31	3.23	0.27	3.70
2-pane	Lo e 172 #2 Surface	0.72	0.41	0.30	3.33	0.25	4.00
2-pane	Lo e 170 #2 Surface	0.70	0.37	0.30	3.33	0.25	4.00
2-pane	Lo e 140 #2 Surface	0.40	0.25	0.30	3.33	0.26	3.85
2-pane	Lo e 128 #2 Surface	0.38	0.24	0.30	3.33	0.25	4.00
2-pane	Lo E 172 #2 Surface	0.66	0.38	0.22	4.55	0.19	5.26
3-pane	Lo e 172 #2 & #3 Surfaces	0.58	0.35	0.16	6.25	0.13	7.69

shows the surfaces on which low-e coatings should be placed depending on whether controlling the cooling load or encouraging heating is the more important goal.

7.3.4 Dehumidification

A major part of the cooling load in many parts of the country is the energy required to dehumidify infiltration or ventilation air. It takes about 1060 Btu to evaporate one pound of figure 7.22 **The Glazing Number System**



Windows designed to emphasize cooling reduction have the low-e coating on surface #2, whereas those primarily controlling winter heat loss coat surface #3.

water, converting it from liquid water to water vapor. That means to dehumidify moist air, we have to remove 1060 Btu of *latent heat* for every pound of water removed.

To understand this dehumidification process, we need to become familiar with the simplified psychrometric chart shown in Figure 7.23. A "psych chart" is a plot of the moisture content of air (called the absolute humidity) versus dry bulb temperature (what you measure with a thermometer). The parameter is relative humidity (rH), which is the fraction of the maximum moisture that air can hold at a given dry bulb temperature.

The example in Figure 7.23 shows the process taken to cool air from an outside temperature of 80°F with 40% rH (point A) to a desired temperature of 65°F at 40% rH (point D). Imagine the air conditioner beginning to lower the temperature along the A-to-B path on the psych chart. The line is horizontal because the amount of moisture in the air hasn't changed yet (the absolute humidity is constant). When the air reaches 53°F (point B), it is fully saturated and any further decrease in temperature will cause moisture to condense out of the air. Dropping the temperature to 40°F moves the operating point from B to C and in the process enough moisture condenses to lower the absolute humidity from about 0.009 to 0.0055 lb H_2O/lb air. As the 40°F air at point C absorbs heat, it moves horizontally on the chart to the desired temperature and humidity (point D). Solution Box 7.7 demonstrates this process.

The examples in Solution Boxes 7.5 through 7.7 illustrate three primary sources of cooling load for buildings: heat transfer through the building envelope, solar gains through windows exposed to the sun, and dehumidification. Although they were illustrated for residential buildings, they apply equally well to larger, commercial buildings.

SOLUTION BOX 7.6

Cooling Load in Houston from West-Facing Windows

Suppose a house in Houston (latitude 29° N) has 100 ft² of unprotected, clear double-pane, west-facing windows. Estimate the cost of summertime cooling due to those windows if the AC has an SEER of 10, the ducts are 70% efficient, and electricity costs \$0.10/kWh.

Solution:

From Table 7.5 the daily insolation on east- or west-facing windows during the summer is about 1000 Btu/ft²-day. Let's imagine 100 such days. From Table 7.6, clear double-pane windows have an SHGC of 0.76. A reasonable estimate for summer solar gains would be

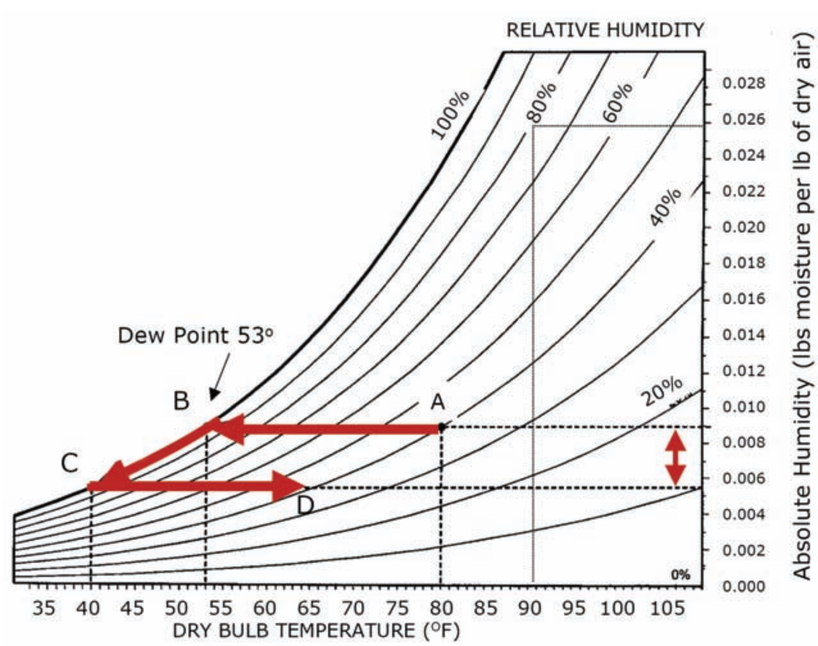
$$\text{Gain} = 100\ \text{ft}^2 \times 1000\ \text{Btu/ft}^2\text{-day} \times 100\ \text{days} \times 0.76 = 7.6 \times 10^6\ \text{Btu}$$

That heat has to be removed by the SEER 10 AC through 70% efficient ducts.

$$\text{Cost} = \frac{7.6 \times 10^6\ \text{Btu}}{10\ \text{Btu/Wh}} \times \frac{1}{0.70} \times \frac{1\ \text{kW}}{1000\ \text{W}} \times \$0.10/\text{kWh} = \$108$$

SOLUTION

figure 7.23



A simplified psych chart showing the path taken to cool air at 80°F, 40% rH down to 65°F and 40% rH. Each pound of water condensed liberates about 1060 Btu.

SOLUTION

SOLUTION BOX 7.7

Cooling Load Due to Latent Heat

Suppose a 2000 ft^2 house with 8-foot ceilings has an infiltration rate of 0.5 ach. Find the cooling load associated with dehumidifying infiltration air from ambient 90°F, 80% rH to a nice AC supply at 65°F, 40% rH. Assume air density is 0.075 lb/ft^3.

Solution:

The rate at which infiltration air entering the building must be cooled and dehumidified is

$$0.5 \text{ air changes/hr} \times (2000 \times 8) \text{ ft}^3\text{/air change} \times 0.075 \text{ lb/ft}^3 = 600 \text{ lb/hr}$$

From Figure 7.22, to drop the absolute humidity of outside air at 90°F, 80% rH to the desired 65°F, 40% rH requires the removal of about

$$(0.026 - 0.005) \text{ lb H}_2\text{O/lb air} \times 600 \text{ lb air/hr} \times 1060 \text{ Btu/lb} = 13{,}038 \text{ Btu/hr}$$

If we imagine an SEER = 10, 70% ducts, \$0.10/kWh, AC handling the dehumidification of infiltration for 100 days of summer, it would cost

$$\text{Cost} = \frac{13{,}038 \text{ Btu/hr} \cdot 24 \text{ hr/d} \cdot 100 \text{ d/yr}}{10 \text{ Btu/Wh} \cdot 0.70} \times \frac{1 \text{ kW}}{1000 \text{ W}} \times \frac{\$0.10}{\text{kWh}} = \$447\text{/yr}$$

7.4 Domestic Water Heating

Figure 6.3 showed the importance of residential water heating. As a single category, only residential space heating and commercial lighting account for more primary energy. We are all familiar with the conventional storage-tank versions of water heaters, but there are a number of other approaches that can provide hot water with greater energy efficiency, but perhaps at a higher first cost. Options include demand (also known as tankless or instantaneous) water heaters, solar water heaters, and heat-pump water heaters (Figure 7.24).

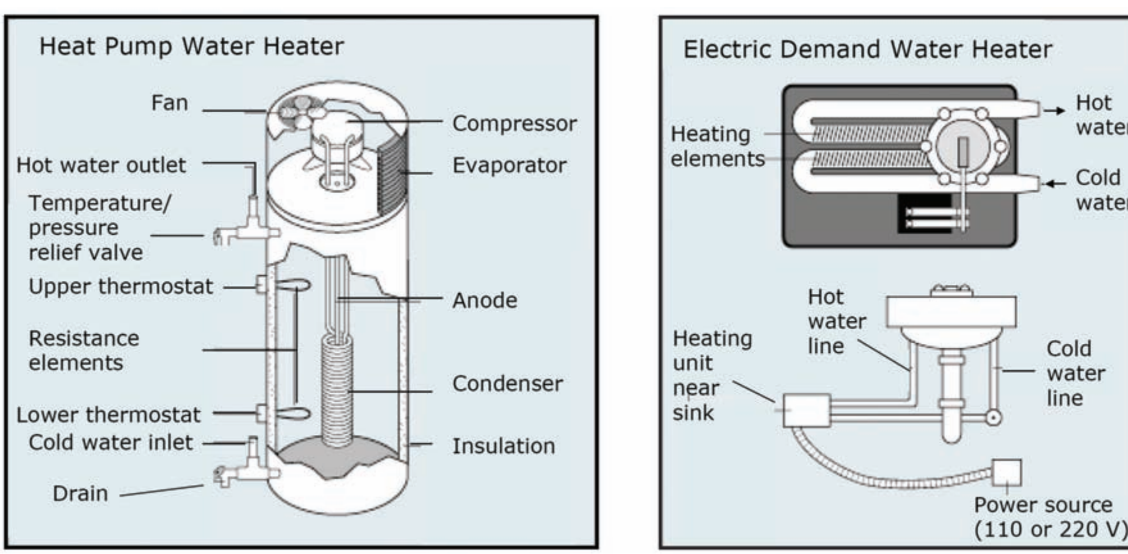
Conventional household storage water heaters typically range in size from about 20 gallons to 80 gallons and are fueled with natural gas, electricity, propane, or fuel oil. Their efficiency is indicated by an energy factor (EF), which includes the energy required to heat the water in the first place under an assumed 64-gallon/day use rate, plus standby and nearby piping losses. The most efficient conventional natural gas–fired storage water heaters have an EF of 0.60 to 0.65, which corresponds to an annual gas demand of around 230 therms. Condensing water heaters, which capture some of the latent heat in the exhaust gases, have energy factors as high as 0.86. Solution Box 7.8 shows how to use these EFs to help estimate the cost of water heating.

Electric water heaters have much higher energy factors, about 0.93 to 0.95, which is a reflection of the fact that the conversion of electricity to heat in resistive elements immersed in the water is nearly 100%. At that EF, and 64 gallons/day, their (expensive!) electricity demand is around 4500 kWh/yr. Heat pump water heaters using less than half as much electricity as conventional electric resistance water heaters are finally becoming commercially available. They are expensive, but their extra first cost pays for itself by way of reduced electricity bills.

Demand water heaters avoid the standby losses associated with conventional storage water heaters. In these units, water is heated instantaneously as hot water is drawn from the tap. For gas-fired units, pilotless demand heaters have longer lifetimes and higher EF ratings than conventional storage water heaters, which gives them a sizable life-cycle cost advantage.

Table 7.7 presents levelized annual cost estimates for various types of water heaters. As would be expected, natural gas–fired storage water heaters have much lower life-cycle costs than those fired by expensive electricity. However, when electricity is used in a heat pump water heater or as a backup for a solar water heater, annualized costs are comparable.

figure 7.24



Heat pump water heaters and demand water heaters are two variations on conventional hot water systems.

Source: www.eere.energy.gov/consumer/your_home/water_heating, 2006

SOLUTION

SOLUTION BOX 7.8

Cost of Water Heating

Estimate the annual fuel cost to heat 64 gallons per day from 55°F to 130°F in an EF 0.57 storage water heater fueled by $1/therm natural gas.

Solution:

Begin by figuring out the energy that would be required if the system were to be 100% efficient:

$$Q = 64 \text{ gal/day} \times 365 \text{ day/yr} \times (130 - 55)°\text{F} \times 1 \text{ Btu/lb-°F} \times 8.34 \text{ lb/gal}$$
$$= 14.6 \times 10^6 \text{ Btu/yr}$$

Dividing by the system efficiency and converting to therms gives an annual cost of

$$\text{Cost} = \frac{14.6 \times 10^6 \text{ Btu/yr}}{0.57} \times \frac{1 \text{ therm}}{100{,}000 \text{ Btu}} \times \frac{\$1.00}{\text{therm}} = \$256/\text{yr}$$

7.5 Solar Collectors for Hot Water

We have all felt the hot water that comes out of a dark hose that has been sitting in the sun. Solar water heating systems take advantage of that same concept to provide a portion of the hot water demand for the buildings they serve. The history of solar water heating systems is somewhat spotty. They were quite popular 100 years ago, before cheap fossil fuels came along and virtually wiped out the industry. They enjoyed somewhat of a resurgence in the 1970s and early 1980s after the oil shocks of that era focused our attention on reducing energy demand. By the late 1980s, however, with the elimination of tax credits, coupled with unreliable freeze protection systems and some really ugly installations, the industry pretty much died once again. Better technology and a renewed focus on our energy future are finally bringing these important systems back into play.

7.5.1 Flat-Plate Solar Collectors

At the heart of most solar water heating systems is the simple, flat-plate collector, consisting of a black absorber plate in an insulated box with a glass top to let in the sun (Figure 7.25).

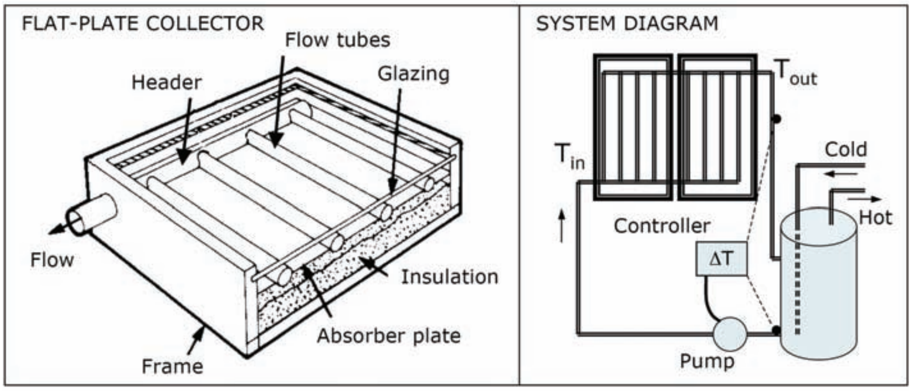
table 7.7 Levelized Costs for Various Types of Water Heaters

Water Heater Type	Energy Factor	Installed Cost	Annual Energy	1st yr Energy Cost	Life (years)	Levelized Cost $/yr
GAS FIRED			**Therms**			
Conventional storage	0.57	$380	256	$256	13	$351
High-efficiency storage	0.65	$525	225	$225	13	$329
Instantaneous demand	0.70	$650	209	$209	20	$243
High-efficiency pilotless demand	0.84	$1,200	174	$174	20	$255
Solar (SF = 0.7) with gas back-up	0.57	$2,500	77	$77	20	$271
ELECTRICITY			**kWh**			
Conventional storage	0.90	$350	4758	$428	13	$557
High-efficiency storage	0.95	$440	4508	$406	13	$539
Instantaneous demand	0.95	$600	4508	$406	13	$556
Electric heat pump	2.20	$1,200	1947	$175	13	$340
Solar (SF = 0.7) with electric back-up	0.90	$2,500	1427	$128	20	$318

Assumptions: 64 gpd demand, 75°F delta T, natural gas @ $1/therm, electricity @ 9¢/kWh, 3% fuel escalation, 5% discount rate, solar savings fraction 70%.

A pump, or sometimes just natural buoyancy, causes water to circulate from a storage tank to the collector. If it is pumped, the system needs a controller with sensors on the tank outlet and the collector outlet. If the collector is warmer than the tank, the controller turns on the pump. Each pass through the collector raises the water temperature by about 5°F or 10°F so that by the end of a sunny day you have a tank of hot water.

figure 7.25



Typical hydronic flat-plate collector and system diagram for a solar water heater.

A fairly straightforward thermal analysis of flat-plate collectors begins with an energy balance as shown in Figure 7.26. We have insolation I striking the collector area A, some fraction of that, $(\tau\alpha)$, is transmitted through the glazing system and absorbed by the plate. Some of the absorbed heat is then lost, mostly through the glazing, and some is taken away in the form of heat delivered to the storage tank. Using lowercase q to represent a heat rate, we can write

Eq. 7.11 $$q_{del} = q_{ABS} - q_{loss}$$

Eq. 7.12 $$q_{del} = IA(\tau\alpha) - U_L A\,(T_P - T_{amb})$$

where the quantity U_L = an overall heat loss factor Btu/hr-°F per ft^2 of collector area

If we divide the delivered energy by the incident radiation, we get the following equation for the efficiency of the collector:

Eq. 7.13 $$\eta = \frac{q_{del}}{q_{incident}} = \frac{IA(\tau\alpha) - U_L A(T_P - T_{amb})}{IA} = (\tau\alpha) - U_L\left(\frac{T_P - T_{amb}}{I}\right)$$

This awkward looking equation turns out to be remarkably straightforward when we plot efficiency versus $(T_P - T_{amb})/I$, as has been done in Figure 7.27a. It is just a straight line with y-axis intercept = $(\tau\alpha)$ and slope U_L. The x-axis is a normalized measure of how hot the collector is, how cold the environment is, and how much sunlight is hitting the panel. With just those three quantities we can find the collector efficiency.

Figure 7.27b shows a plot of collector efficiency that is almost exactly the same as 7.27a, but notice the x-axis parameter uses the inlet temperature of the collector T_{in} instead of the average plate temperature T_p. The collector inlet temperature is much easier to measure than the average plate temperature, so this little adjustment makes for far easier collector analysis. To legitimatize this switch, a little fudge factor, labeled F_R is shown in Figure 7.27b. Manufacturer descriptions of collector efficiency are specified by simply providing the "y-axis intercept" $F_R(\tau\alpha)$ and "slope factor" $F_R U_L$.

figure 7.26 **Energy Analysis of a Flat-Plate Collector**

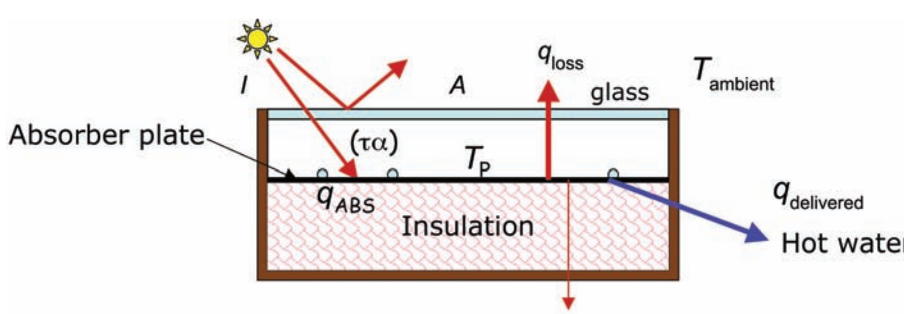
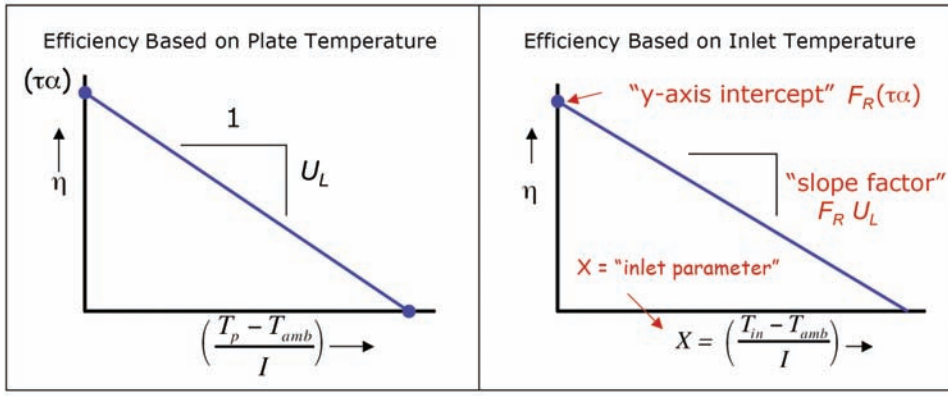


figure 7.27



Collector efficiency is specified by the "y-axis intercept" and "slope factor" with the x-axis assumed to use T_{in} rather than T_p.

Flat-plate collectors come with many options. They may have no glazing, or single-glazing, or double; they may have a *selective surface* with high absorptivity to solar wavelengths and low emissivity for the longer wavelengths radiated by the hot absorber. To gain some intuition into these options consider Figure 7.28, which shows efficiency curves for three versions of glazing under representative midday insolation and ambient temperature. With added glazing the y-axis intercept drops as less and less insolation reaches the absorber; on the other hand, with more glazing the heat loss represented by the slope decreases. The graph suggests that for low temperature applications, such as swimming pool heating, no glazing at all is probably most efficient; for average temperatures, such as water heating, single-glazing is probably best; and for solar space heating, double-glazing is usually the best choice.

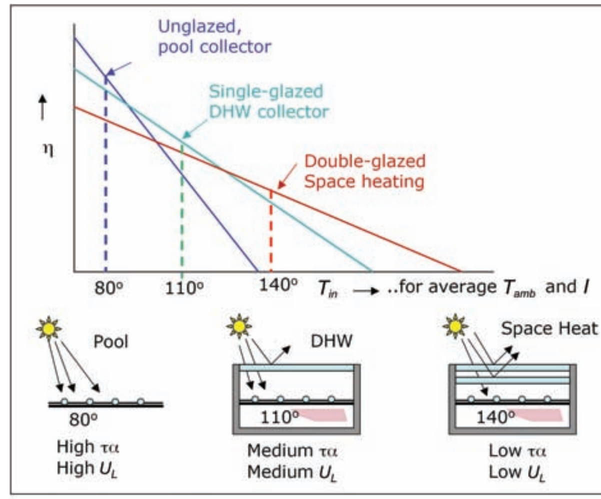
7.5.2 Solar Water Heater System Sizing

When collectors are tested, insolation is normal to the glazing. In real life, of course, the sun moves around all day long and the incidence angle changes with time and seasons. The more the sun's rays hit the collector at an off-axis angle, the greater the reflection off the glass, which reduces ($\tau\alpha$). To account for that reduction, an incidence angle modifier, called $K_{\tau\alpha}$, is used, which shifts the average y-axis intercept down a bit in the standard efficiency curve. A reasonable default value for single-glazed collectors is a $K_{\tau\alpha}$ of 0.93.

In sizing solar water heater systems, we need to include such factors as location, energy demand, insolation, collector tilt, collector parameters, ambient temperature, and system losses. Solution Box 7.9 demonstrates how these factors can be integrated into a collector sizing exercise.

The spreadsheet in Table 7.8 continues this example to show how an overall annual solar savings fraction (SF) for a solar water heater could be found. Although the above procedure is

figure 7.28



Unglazed collectors in mild weather may be best for pools; single-glazing makes sense for domestic hot water (DHW); double-glazing is needed for space heating.

adequate for hand or spreadsheet calculations, there are computer programs available on the Internet that may be worth purchasing if you want greater confidence in the results or if you are going to do this sort of sizing over and over again. One such program is called f-chart and it is downloadable from http://www.fchart.com.

7.5.3 Evacuated-Tube Solar Collectors

A relatively new, and quite exciting, product has been recently introduced that puts the absorber plate in a vacuum inside long cylindrical tubes. The vacuum eliminates convective losses from plate to glass, greatly improving efficiency especially at high plate temperatures and/or low ambient temperatures.

Besides the basic vacuum technology, these collectors use a clever technique to transfer heat from the absorber, within the evacuated tube, to the header above. They use very efficient heat pipes to do this. As shown in Figure 7.29, heat from the absorber plate vaporizes a working fluid in the heat pipe. That working fluid travels by convection to a heat-exchange bulb at the top of the tube, where it condenses and transfers its heat to the water circulating through the header. The evacuated tubes with their heat-exchange bulbs are installed by inserting them, one by one, into the copper header that runs along the top of the collector (Figure 7.30).

As can be seen from Figure 7.30, there is a considerable gap between tubes, which means on a per-unit-of-overall area, they have relatively low efficiency. But the tubes themselves have efficiencies that remain high and relatively constant over a wide range of temperatures, which means these can be used not only for mid-temperature water heating but also for higher-temperature space heating, and even higher temperature absorption cooling systems.

SOLUTION BOX 7.9

A Simple Solar Water Heater Sizing Estimate for Atlanta

SOLUTION

Size a solar collector to heat 64 gallons/day of water from 60°F to 140°F in Atlanta in June using a flat-plate collector with x-axis intercept $F_R(\tau\alpha) = 0.75$, a slope factor $F_R U_L = 1.18$ Btu/hr-°F-ft^2, and an incidence angle modifier $K_{\tau\alpha} = 0.93$.

Solution:

First we'll work on estimating the average collector efficiency using

$$\bar{\eta} = F_R(\tau\alpha)K_{\tau\alpha} - F_R U_L \left(\frac{\bar{T}_{in} - \bar{T}_{amb}}{\bar{I}} \right)$$

Let's use a LAT –15° tilt angle, which for latitude-34° Atlanta is 19°, fairly close to that of a typical roof surface so it should look pretty nice. From Table 7.2 (or from NREL's Web site http://rredc.nrel.gov/solar/pubs/redbook/), average June insolation is 1997 Btu/ft^2, which we will imagine is spread out over roughly a 12-hour period giving us an average hourly rate of about 1997/12 = 166 Btu/ft^2-hr. That same NREL source tells us the average daily maximum temperature in June is 86°F. So let's guess the average daytime temperature is about 80°F. The inlet temperature climbs from 60° in the morning to 140° by the end of the day, so we will use an average inlet temperature of 100°F. The average efficiency of the collectors will therefore be about

$$\bar{\eta} = 0.75 \cdot 0.93 - 1.18 \text{ Btu/hr-°F-ft}^2 \left(\frac{100° - 80°\text{F}}{166 \text{ Btu/hr-ft}^2} \right) = 0.55 = 55\%$$

To estimate the daily energy collected, we should probably account for dirt accumulation on the glazing plus piping losses and so forth. Let us say losses are 15%.

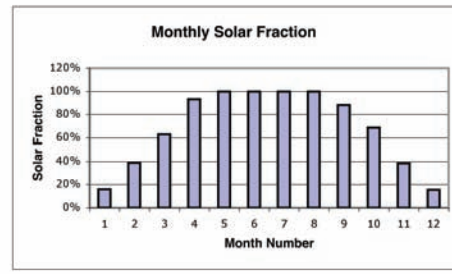
The collector area should therefore be

$$A = \frac{64 \text{ gal/day} \times 8.34 \text{ lb/gal} \times 1 \text{ Btu/lb°F} \times (140 - 60)°\text{F}}{1997 \text{ Btu/ft}^2\text{-day} \times 55\% \times (1 - 0.15)} = 46 \text{ ft}^2$$

That is, a collector area of around 50 square feet would be in the right ballpark.

table 7.8 Solar Water Heating Spreadsheet for the Atlanta Example in Solution Box 7.9

Location	Atlanta		Solar Water Heater Analysis
$F_{R(\tau\alpha)}$	0.75		
$F_R U_L$	1.18	Btu/ft²-hr-°F	
$K_{\tau\alpha}$	0.93		
T_h	140	°F	
T_c	60	°F	
Load	64	gal/day	
Losses	15%		
Load*	42,701	Btu/day	
Area	50	ft²	



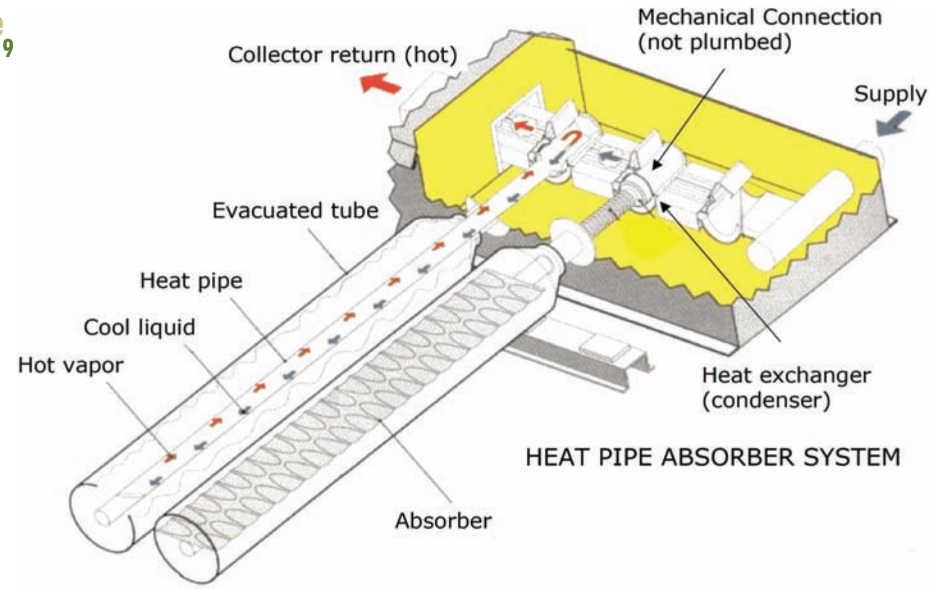
Month	Insolation Btu/ft²day	T_{amb} °F	Day Length hr/day	Efficiency* %	Delivered* Btu/day	Usable* Btu/day	% Solar*
Jan	1,078	44	9	15%	6,837	6,837	16%
Feb	1,331	49	9	29%	16,467	16,467	39%
Mar	1,617	58	10	39%	26,972	26,972	63%
Apr	1,902	67	10	49%	39,672	39,672	93%
May	1,965	74	11	52%	43,654	42,701	100%
Jun	1,997	80	12	55%	47,057	42,701	100%
Jly	1,934	82	11	58%	47,381	42,701	100%
Aug	1,870	81	11	57%	45,005	42,701	100%
Sep	1,680	76	10	53%	37,698	37,698	88%
Oct	1,553	67	10	44%	29,336	29,336	69%
Nov	1,205	57	9	32%	16,445	16,445	39%
Dec	1,014	48	9	15%	6,582	6,582	15%

* items are calculated; all else is data entry.
Annual Solar Fraction = 68%

7.5.4 Integral Collector-Storage Panels

In relatively mild climates, very simple collectors that combine collector and storage into a single unit have some significant advantages over conventional pumped systems. These integral-collector-storage (ICS) systems (also known as "batch" systems) are, in essence, just big, fat black hoses sitting up on the roof. The only time water moves through them is when someone turns on a hot-water tap in the house, at which time cold city water goes up to the ICS and pushes solar heated water down into the regular cold-water inlet to your conventional water heater where it is topped up in temperature if necessary (Figure 7.31). They have no moving parts, no pumps, no controllers, and no sensors to break down, which means they are inexpensive and extremely reliable. On the down side, water that heats up in the daytime unfortunately cools down at night because it is still sitting up on the roof exposed to the cold

figure 7.29



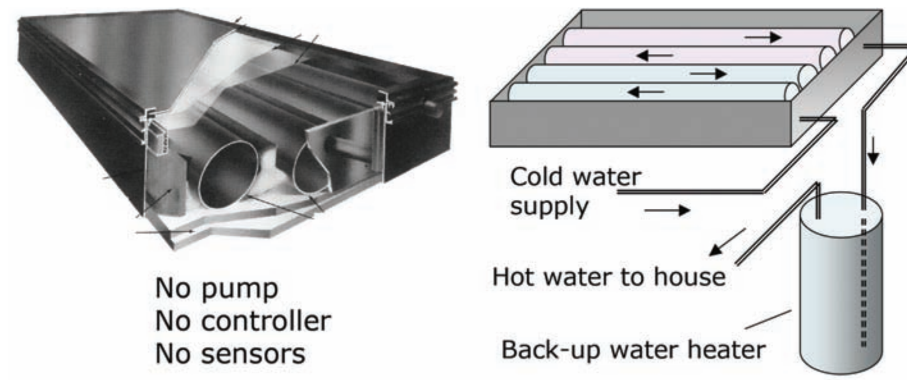
An evacuated-tube solar collector showing how heat pipes deliver heat to the header.

Source: Courtesy of Sunda

figure 7.30

Inserting tubes into the header into the of an evacuated tube collector.

figure 7.31



An integral-collector-storage system needs no pumps, controllers, or sensors. Whenever someone turns on a hot-water tap, cold water pushes heated ICS water into the regular backup water heater.

night sky (though you could imagine putting some night insulation over the glass cover to help keep heat in). With these systems it is better to take your shower at night than in the morning.

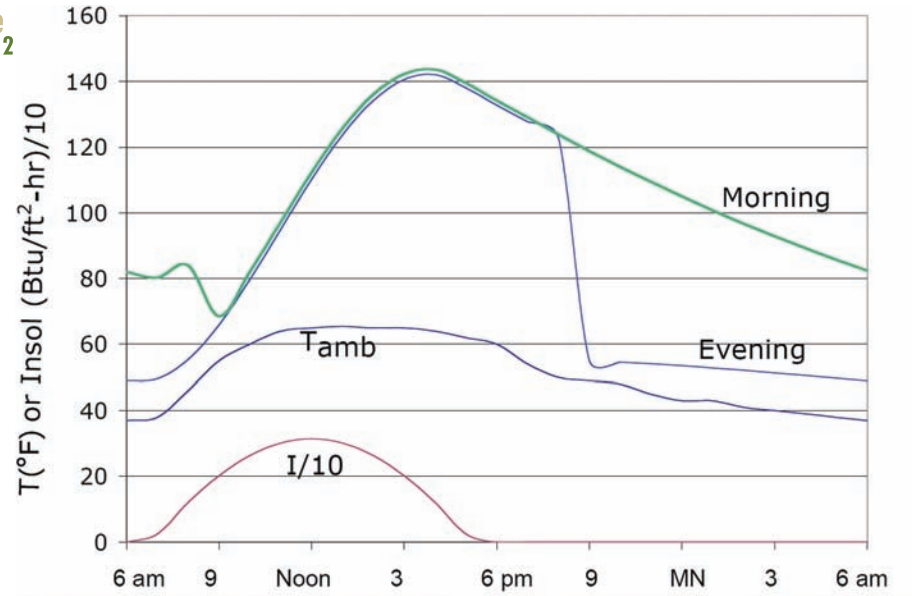
A computer simulation of an ICS system showing the impact of evening hot water use, before the collector has had a chance to cool down, versus morning use, is shown in Figure 7.32. For this example a 40-gallon demand taken from a 40-gallon ICS at 8:00 a.m. is compared with the same demand taken at 8:00 p.m. The ICS provides more than enough heat to satisfy the entire demand for the evening load but only 40% if the demand is postponed until the morning.

7.5.5 Solar System Variations

A number of system variations for solar water heaters are available. Many of the differences have to do with how the collectors are protected from freezing on cold nights.

- **Thermosiphoning systems** avoid the use of pumps and controllers by placing the storage tank above the collectors (Figure 7.33). When hot water in the collectors becomes more buoyant than the colder water at the bottom of the tank, the warm water rises and the colder water sinks creating a convective circulation loop.
- **Closed system with antifreeze:** Even if temperatures only occasionally dip below freezing, solar collectors need to be protected from the possibility of freezing. When water freezes it expands and can easily break open a flat plate collector with potentially disastrous consequences. Many systems have a closed loop containing a nontoxic antifreeze, such as propylene glycol, with a heat exchanger to transfer heat to the potable hot water system (Figure 7.34).

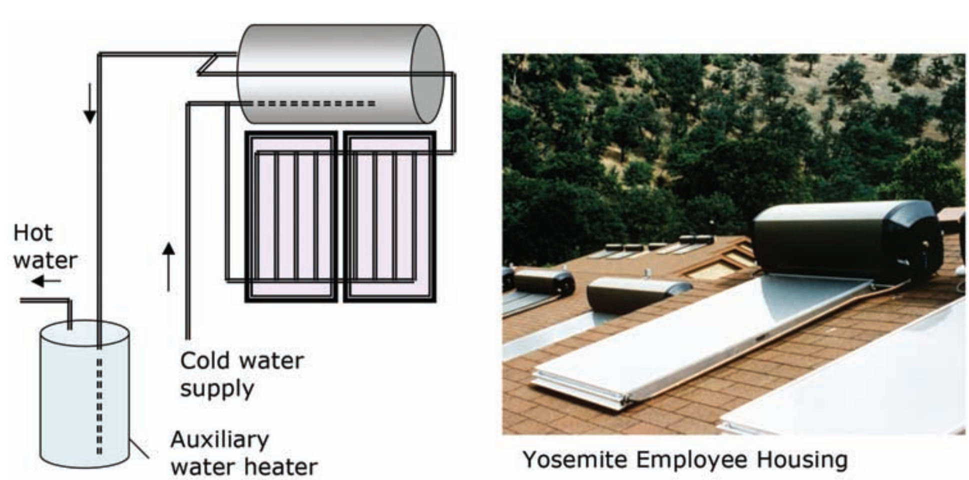
figure 7.32



Load Pattern	Hot Water Supplied	Btu/day Delivered	ICS Efficiency	% of Load 40 gal @120°F
Evening load	40 g @123°F	20,904	42%	104%
Morning load	40 g @ 84°F	8,015	16%	40%

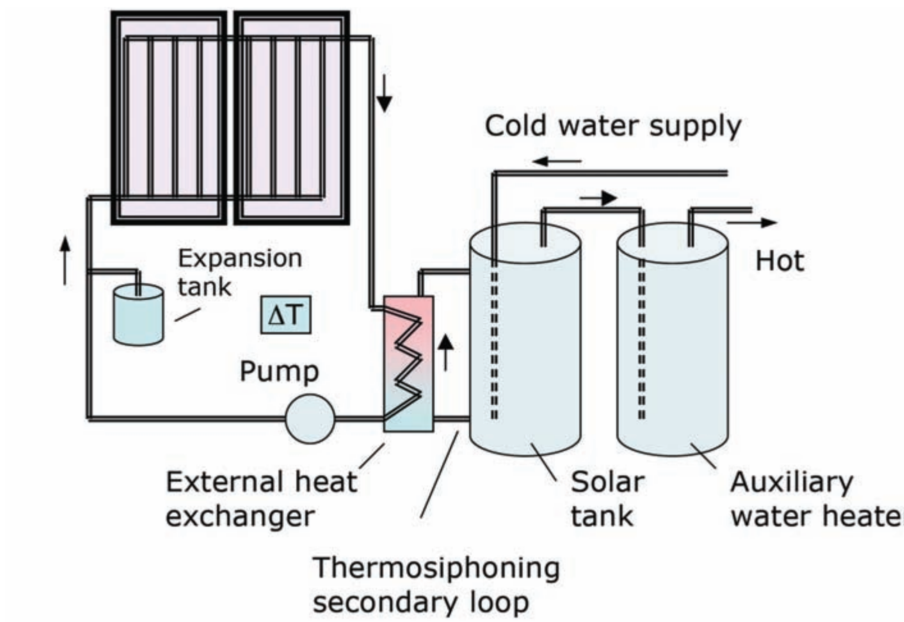
Computer simulation of a 40-gallon ICS serving a 40-gallon, 120°F load taken at 8:00 a.m. versus 8:00 p.m.

figure 7.33 **Thermosiphon Water Heater System**



With the tank placed above the collector, thermosiphoning systems don't need pumps or controls.

figure 7.34 **Antifreeze System with External Heat Exchanger**



A closed-loop, antifreeze-protected solar water heater system.

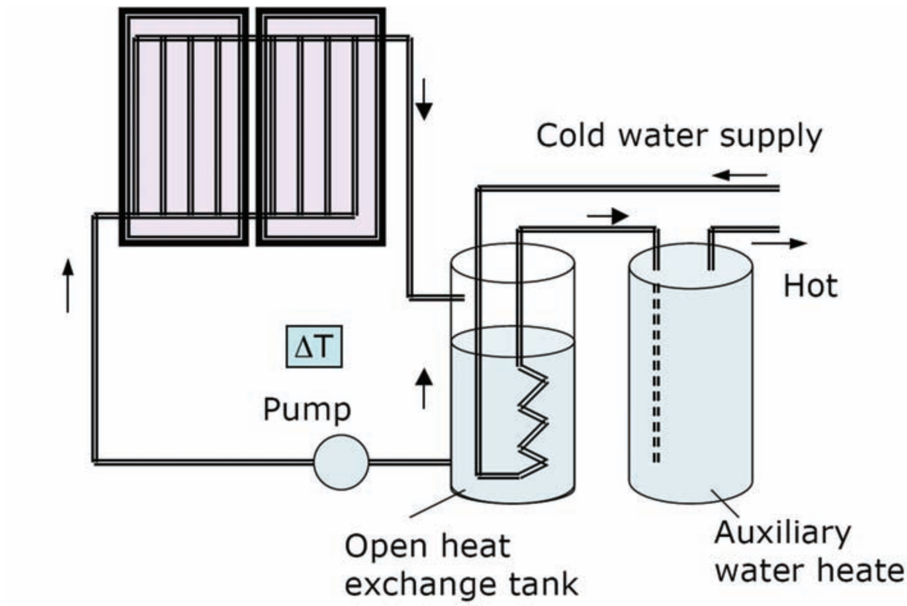
- **Drainback systems** have an unpressurized tank containing water or an antifreeze solution that is pumped around the collector loop (Figure 7.35). When the pump stops, water in the collector simply drains back into the tank. When a user draws hot water from a tap, it first passes through a heat exchanger in the open loop to preheat the water before it goes to the auxiliary water heater. These are relatively simple, reliable systems, but the pump must be strong enough to pump water against gravity up to the collector, which reduces the net energy provided by the system.

There are many choices of system type and method of freeze protection for solar water heating systems. Choosing the right one for a given household can be a challenge.

7.6 Summary

In this and the previous chapter, we have explored an array of design ideas that can significantly reduce the thermal energy demand in the buildings sector. With an aggressive effort to provide more insulation, better windows, tighter ducts, and more efficient heating and cooling systems, the heating demand can be reduced well below current building codes. And, in many locations, passive solar heating can nearly drive that heating demand toward zero.

figure 7.35 **Drainback System**



Drainback systems are freeze-protected by having an open loop that allows the collectors to drain whenever the pump is turned off.

With care in building orientation, use of overhangs, natural ventilation, spectrally selective windows, and new cool roofing materials, cooling loads can be kept under control even in quite challenging climate zones. Finally, solar energy can effectively cut the demand in the very important water heating sector as well.

In the next chapter, we will shift our attention to the electricity demands in buildings for lighting and appliances. At that point, we will take on the concept of a Whole Building Life-Cycle assessment, including the embodied energy required to construct the building in the first place. That will lead us toward Green Building rating systems and the ultimate goal of zero-energy, zero-carbon buildings for the future.