CHAPTER 3

BASIC PRINCIPLES

Solar architecture is not about fashion, it is about survival.
Sir Norman Foster

If we are anything, we must be a democracy of the intellect. We must not perish by the distance between people and government, between people and power. . . . And that distance can only be conflated, can only be closed, if knowledge sits in the homes and heads of people with no ambition to control others, and not up in the isolated seats of power.
J. Bronowski
The Ascent of Man*, 1973*

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3.1 INTRODUCTION

The heating, cooling, and lighting of buildings are accomplished by adding or removing energy. A good basic understanding of the physics of energy and its related principles is a prerequisite for much of the material in the following chapters. Consequently, this chapter is devoted to both a review of some rather well-known concepts and an introduction to some less familiar ideas such as mean radiant temperature, time lag, the insulating effect of mass, and embodied energy.

3.2 HEAT

Energy comes in many forms, and most of these are used in buildings. Much of this book, however, is concerned with energy in the form of heat, which exists in three different forms:

1. Sensible heat—can be measured with a thermometer
2. Latent heat—the change of state or phase change of a material
3. Radiant heat—a form of electromagnetic radiation

3.3 SENSIBLE HEAT

The random motion of molecules is a form of energy called sensible heat. An object whose molecules have a larger random motion is said to be hotter and to contain more heat (see Fig. 3.3a). Because this type of heat can be measured by a thermometer and felt by our skin, it is called sensible heat. If the two objects in Fig. 3.3a are brought into contact, some of the more intense random motion of the object on the left will be transferred to the object on the right by the heat-flow mechanism called conduction. Since the molecules must be close to each other in order to collide, and since in air the molecules are far apart, air is not a good conductor of heat. A vacuum allows no conduction at all.

Temperature is a measure of the intensity of the random motion of molecules. We cannot determine the heat content of an object just by knowing its temperature. For example, in Figure 3.3b (top), we see two blocks of a certain material that are both at the same temperature. Yet the block on the right will contain twice the heat because it has twice the mass.

The mass alone cannot determine the heat content either. In Figure 3.3b (bottom), we see two blocks of the same size, yet one block has more heat content because it has a higher temperature. Thus, sensible heat content is a function of both mass and temperature. Heat content is also a function of heat capacity, which is discussed in Section 3.15.

In the United States, we still use the Fahrenheit (°F) scale for temperature and the British thermal unit (Btu) as our unit of heat. The rest of the world, including Great Britain, uses the international system of units (SI), where temperature is measured in Celsius (°C) and heat in the joule or calorie. (See Table 3.3.)

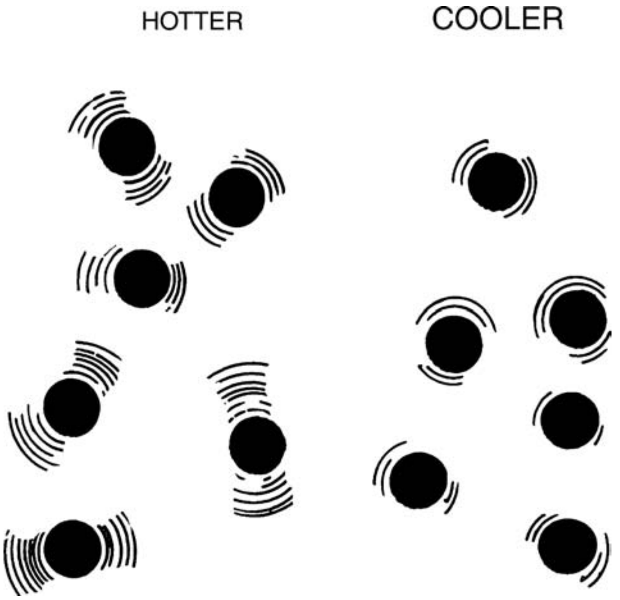

Figure 3.3a Sensible heat is the random motion of molecules, and temperature is a measure of the intensity of that motion.

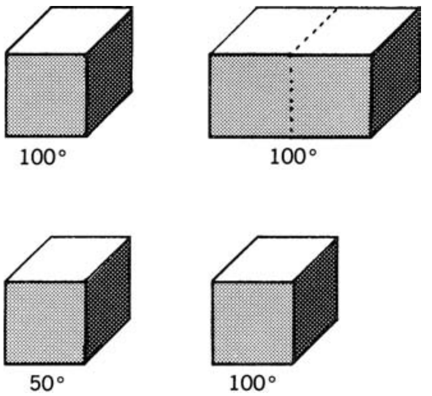

Figure 3.3b The amount of sensible heat is a function of both temperature and mass. In each case, the blocks on the right contain more sensible heat than the blocks on the left.

Table 3.3 Units of Heat and Temperature

	I–P System*	SI System
Heat	British thermal unit (Btu)	joule (J) or calorie (cal)
Heat flow	Btu/hour (Btu/h)	watt (W) or joule/second (J/s)
Temperature	Fahrenheit (°F)	Celsius (°C) or Kelvin (K)**

*I-P = inch-pound.
**A degree Celsius and a degree Kelvin have the same magnitude and are, therefore, interchangeable in many cases. They differ only in what they call zero (i.e., 0 degrees K = −273°C).

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3.4 LATENT HEAT

By adding 1 Btu of heat to 1 pound of water, its temperature is raised 1°F (4.2 joules added to a gram of water will raise its temperature 1°C). It takes, however, 144 Btu to change a pound of ice into a pound of water and about 1000 Btu to change a pound of water into a pound of steam (Fig. 3.4). It takes very large amounts of energy to break the bonds between the molecules when a change of state occurs. "Heat of fusion" is required to melt a solid and "heat of vaporization" is required to change a liquid into a gas. Notice also that the water is no hotter than the ice and the steam is no hotter than the water, even though a large amount of heat is added. This heat energy, which is very real but cannot be measured by a thermometer, is called latent heat. In melting ice or boiling water, sensible heat is changed into latent heat, and when steam condenses and water freezes, the latent heat is turned back into sensible heat.

Latent heat is a compact and convenient form for storing and transferring heat. However, since the melting and boiling points of water are not always suitable, other materials called refrigerants are used because they have the melting and boiling temperatures necessary for refrigeration machines.

A change of state is also known as a phase change. Materials that melt at a useful temperature can be used to store heat or be used as a heat sink to cool a building. Such materials are called **phase change materials (PCM)**.

3.5 EVAPORATIVE COOLING

When sweat evaporates from the skin, a large amount of heat is required. This heat of vaporization is drawn from the skin, which is cooled in the process. The sensible heat in the skin is turned into the latent heat of the water vapor.

As water evaporates, the air next to the skin becomes humid and eventually even saturated. The moisture in the air will then inhibit further evaporation. Thus, either air motion to remove this moist air or very dry air is required to make evaporative cooling efficient (Fig. 3.5).

Buildings can also be cooled by evaporation. Water sprayed on the roof can dramatically reduce its temperature. In dry climates, air entering buildings can be cooled with

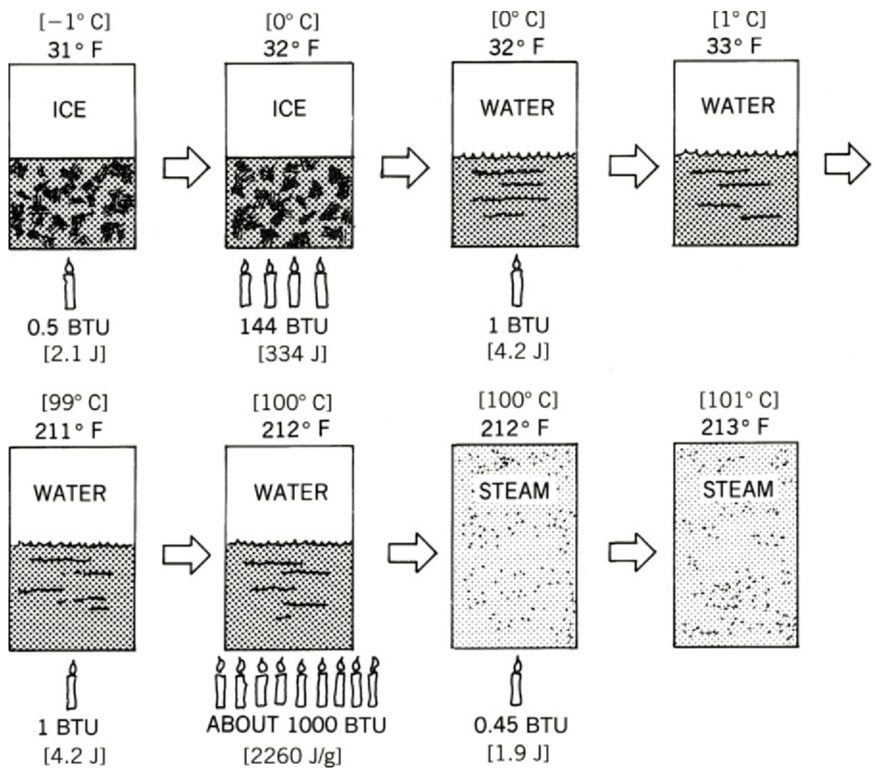

Figure 3.4 Latent heat is the large amount of energy required to change the state of a material (phase change), and it cannot be measured by a thermometer. The values given here are for 1 lb or 1 g of water, ice, or steam.

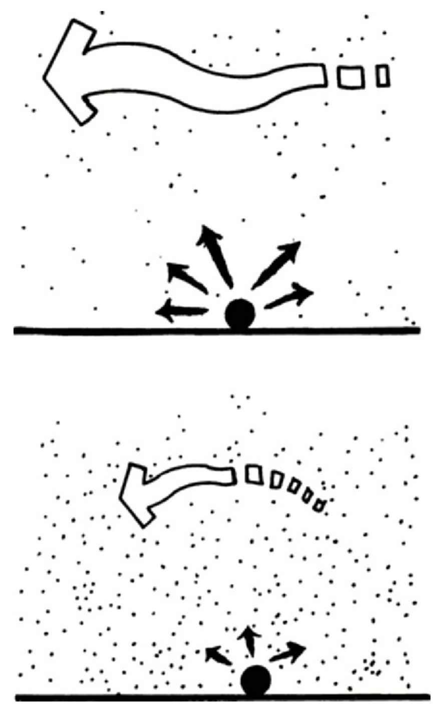

Figure 3.5 The rate of evaporative cooling is a function of both humidity and air movement. Evaporation is rapid when the humidity is low and air movement is high. Evaporation is slow when the humidity is high and air movement is low.

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water sprays. Such techniques will be described in Chapter 10.

3.6 CONVECTION

As a gas or liquid acquires heat by conduction, the fluid expands and becomes less dense. It will then rise by floating on top of denser and cooler fluid, as seen in Figure 3.6a. The resulting currents transfer heat by the mechanism called natural convection. This heat-transfer mechanism is very much dependent on gravity and, therefore, heat never convects down. Since we are surrounded by air, natural convection in air is a very important heat-transfer mechanism in our goal of being comfortable.

When there is no air motion due to the wind or a fan, natural convection currents tend to create layers that are at different temperatures. In rooms, hot air collects near the ceiling and cold air near the floor (Fig. 3.6b). This **stratification** can be an asset in the summer and a liability in the winter. Strategies to deal with this phenomenon will be discussed throughout this book. A similar situation occurs in still lakes where surface water is much warmer than deep water (Fig. 3.6b).

A different type of convection occurs when the air is moved by a fan or by the wind, or when water is moved by a pump (Fig. 3.6c). When a fluid (gas or liquid) is circulated between hotter and cooler areas, heat will be transferred by the mechanism known as forced convection.

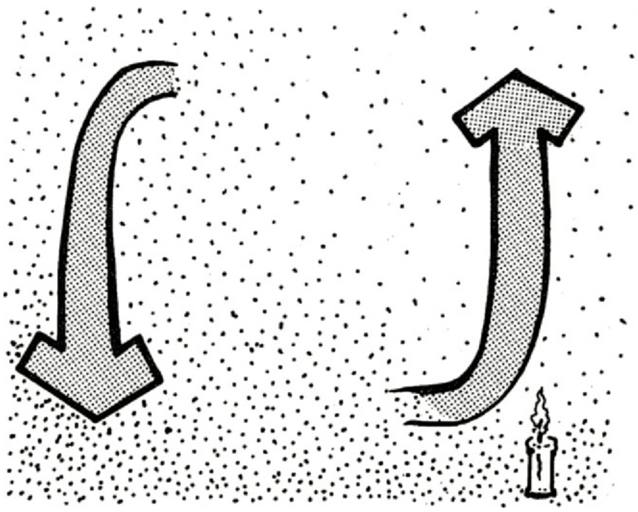

Figure 3.6a Natural convection currents result from differences in temperature.

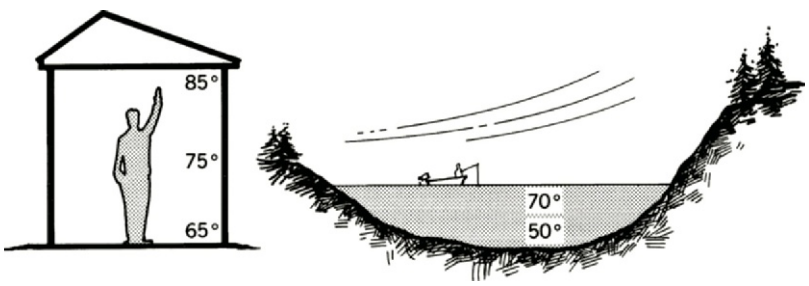

Figure 3.6b Stratification results from natural convection unless other forces are present to mix the air or water. (See also Colorplates 3 and 4.)

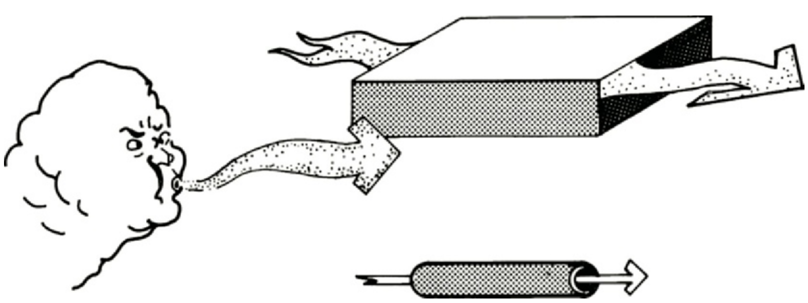

Figure 3.6c Forced convection is caused by wind, fans, or pumps.

3.7 TRANSPORT

In the eighteenth and nineteenth centuries, it was common to use warming pans to preheat beds. The typical warming pan, as shown in Figure 3.7, was about 12 in. (30 cm) in diameter and about 4 in. (10 cm) deep, and it had a long wooden handle. It was filled with hot embers from the fireplace, carried to the bedrooms, and passed between the sheets to remove the chill. In the early twentieth century,

Figure 3.7 Warming pans and hot-water bottles were popular in the past to transport heat from the fireplace or stove to cold beds.

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it was common to use hot-water bottles for the same purpose. This transfer of heat by moving material is called transport. Because of its convenience, forced convection is much more popular today for moving heat around a building than is transport.

3.8 ENERGY-TRANSFER MEDIUMS

In both the heating and cooling of buildings, a major design decision is the choice of the energy-transfer medium. The most common alternatives are air and water. It is, therefore, very valuable to understand the relative heat-transfer capacity of these two materials. Because air has both much lower density and much less specific heat than water, much more of it is required to store or transfer heat. To store or transfer equal amounts of heat, a volume of air about 3000 times greater than that of water is needed (Fig. 3.8).

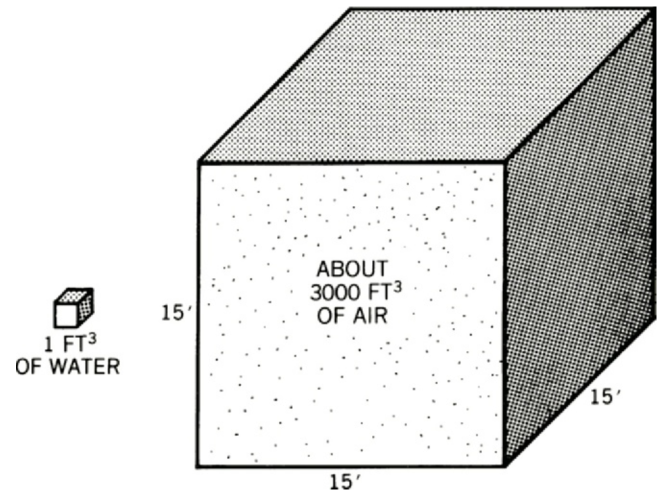

Figure 3.8 One cubic foot or 1 liter of water can store or transfer the same amount of heat as over 3000 ft^3 or 3000 liters of air.

3.9 RADIATION

The third form of heat is radiant heat. All parts of the electromagnetic spectrum transfer radiant energy. All bodies facing an air space or a vacuum emit and absorb radiant energy continuously. Hot bodies lose heat by radiation because they emit more energy than they absorb (Fig. 3.9a). Objects at room temperature radiate in the longwave infrared region of the electromagnetic spectrum, while objects hot enough to glow radiate in the visible part of the spectrum. Thus, the wavelength or frequency of the radiation emitted is a function of the temperature of the object.

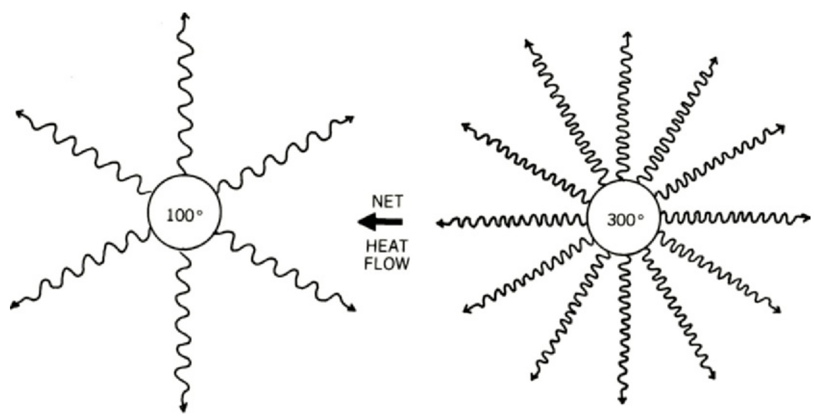

Figure 3.9a Although all objects absorb and emit radiant energy, there will be a net radiant flow from warmer to cooler objects.

Since radiation is not affected by gravity, a body will radiate down as much as up. Radiation is, however, affected by the nature of the material with which it interacts and especially the surface of the material. The four possible interactions, as illustrated in Figure 3.9b, are as follows:

1. Transmittance—the situation in which radiation passes through the material.
2. Absorptance—the situation in which radiation is converted into sensible heat within the material.
3. Reflectance—the situation in which radiation is reflected off the surface.
4. Emittance—the situation in which radiation is given off by the surface, thereby reducing the sensible heat content of the object. Polished metal surfaces have low emittance, while most other materials have high emittance.

For opaque materials the absorptance and reflectance both tell the same story. A high reflectance surface will be a low absorptance surface and vice versa (Fig. 3.9c).

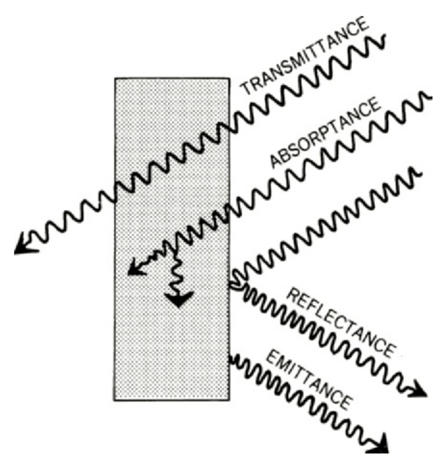

Figure 3.9b Four different types of interaction are possible between radiant energy and matter.

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The type of interaction that will occur is a function not only of the material but also of the wavelength of the radiation. For example, glass interacts very differently with solar radiation (short-wave) than with thermal

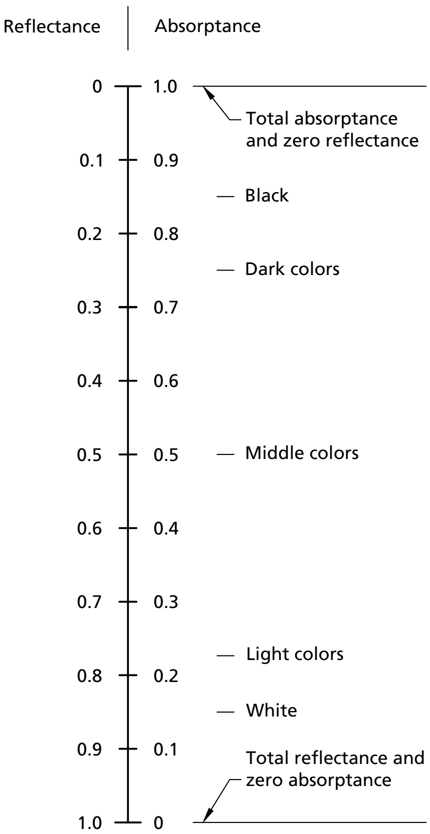

Figure 3.9c The type of interaction depends not only on the nature of the material but also on the wavelength of the radiation.

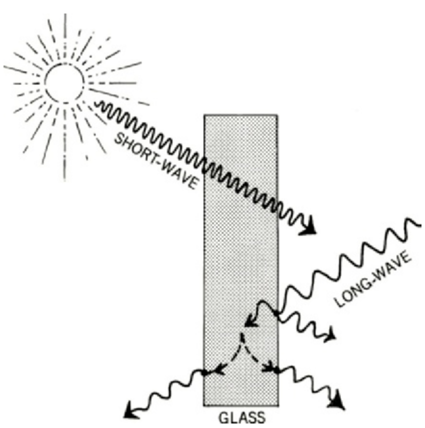

Figure 3.9d Glass has high transmittance to short-wave radiation (e.g., solar radiation), but it absorbs and reflects long-wave infrared radiation (ie.g., heat radiation). The interaction depends on the wavelength, or frequency, of the radiation.

radiation (long-wave infrared), as shown in Figure 3.9d. Glass is mostly transparent to short-wave radiation and opaque to long-wave radiation. The long-wave radiation is mostly absorbed, thereby heating up the glass. Much of the absorbed radiation is then reradiated from the glass inward and outward. The net effect is that some of the long-wave radiation is blocked by the glass. The greenhouse effect, explained below, is partly due to this property of glass and most plastics used for glazing. Polyethelene is the major exception, since it is transparent to infrared radiation.

3.10 GREENHOUSE EFFECT

The concept of the greenhouse effect is vital for understanding both solar energy and climate change. The greenhouse effect is due to the fact that the type of interaction that occurs between a material and radiant energy depends on the wavelength of that radiation.

Figure 3.10a illustrates the basic concept of the greenhouse effect. The short-wave solar radiation is able to pass easily through the glass, whereupon it is absorbed by indoor objects. As these objects warm up, they increase their emission of radiation in the long-wave portion of the electromagnetic spectrum. Since glass

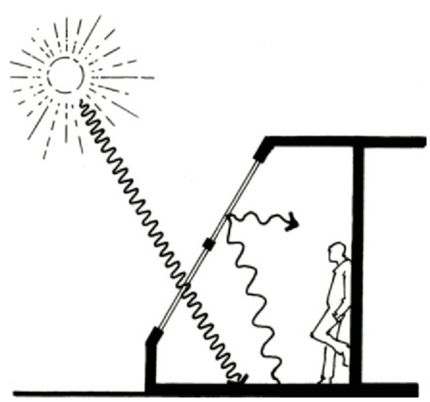

Figure 3.10a The greenhouse effect is a consequence of the fact that glazing transmits short-wave but blocks long-wave radiation.

is opaque to this radiation, much of the energy is trapped. The glass has created, in effect, a heat trap, and the indoor temperature begins to rise.

To better understand this very important concept, let us look at the vertically aligned graphs in Figure 3.10b. First, look at the top graph, which describes the behavior of glass with respect to radiation. The percentage transmission is given as a function of the wavelength of the radiation. Notice that glass has a very high transmission for radiation between 0.3 and 3 μm (millionth of a meter) and zero transmission for radiation above and below that "window."

The bottom graph of Figure 3.10b shows the wavelengths of the solar radiation reaching the earth. It consists of about 5 percent ultraviolet (UV), about 45 percent visible light, and about 50 percent solar infrared (IR). The bottom graph also shows the wavelengths of radiation emitted by objects at room temperature, which are also part of the infrared spectrum. To distinguish these from the solar infrared, they are called long-wave infrared and, consequently, the solar infrared is also called short-wave infrared.

The graphs together show that the part of the electromagnetic spectrum for which glass is transparent corresponds to solar radiation, and the part for which glass is opaque corresponds to the long-wave infrared heat radiation given off by objects at room temperature. The solar radiation enters through the glass and is absorbed by objects in the room. These objects heat up and then increase their reradiation in the long-wave infrared part of the spectrum. Since glass is opaque to this radiation, much of the energy is trapped and the room heats up. This is one of the mechanisms that causes a greenhouse to warm up. The other mechanism of the greenhouse effect is the obvious fact that the glazing stops the convective loss of hot air. These mechanisms together form a very effective heat trap.

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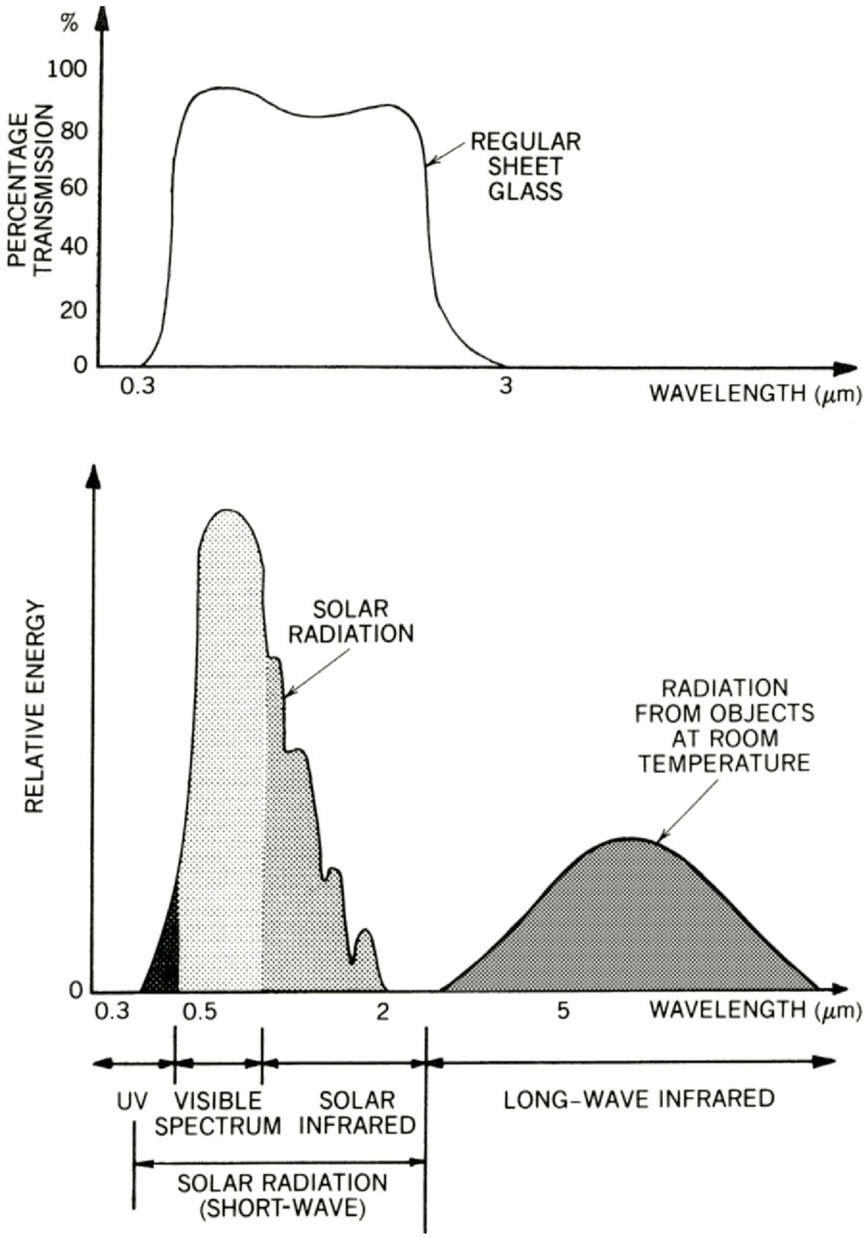

Figure 3.10b Note that these two graphs are aligned vertically. Thus, the top graph shows that glass transmits about 90 percent of both the visible and short-wave infrared portions of sunlight. It also shows that glass does not transmit any of the long-wave infrared radiation emitted by objects at room temperature.

Note that glass changes from 0 to about 80 percent transmission in the ultraviolet part of the spectrum. Thus, the longer wavelengths of UV pass through the glass, while the shorter UV, which cause sunburn, do not. The longer UV radiation contributes to both solar heating and the fading of colors.

3.11 EQUILIBRIUM TEMPERATURE OF A SURFACE

Understanding the heating, cooling, and lighting of buildings requires a fair amount of knowledge of the behavior of radiant energy. For example, what is the best color for a solar collector, and what is the best color for a roof to reject solar heat in the summer? Figure 3.11 illustrates how surfaces of different colors and finishes interact with radiant energy. To understand why a black metal plate will get much warmer in the sun than a white metal plate, we must remember that materials vary in the way they emit and absorb radiant energy. The balance between absorptance and emittance determines how hot the plate will get, the **equilibrium temperature**. Black has a much higher equilibrium temperature than white because it has a much higher absorptance factor. However, black is not the ideal collector of radiant energy because of its high emissivity. Its equilibrium temperature is suppressed because it reradiates much of the energy it has absorbed.

To increase efficiency in solar collectors, a type of **selective surface** was developed. These finishes have the same high absorptance as black but are stingier in emitting radiation. Thus, their equilibrium temperature is very high.

White is the best color to minimize heat gain in the summer because it is not only a poor absorber but also a good emitter of any energy that is absorbed. Thus, white neither likes to collect nor keep heat, and a very low equilibrium temperature results. This low surface temperature minimizes the heat gain to the material below the surface.

Polished-metal surfaces, such as shiny aluminum, can be used as radiant barriers because they neither absorb nor emit radiation readily. For this reason, aluminum foil is sometimes used in buildings as a radiant barrier. However, the equilibrium temperature of a polished-metal surface is higher than that of a white surface because the metal does not emit whatever it has absorbed. Although both white and polished metals absorb about the same small percentage of sunlight, white is a much better emitter of heat radiation and so will be cooler in the sun than a polished-metal surface.

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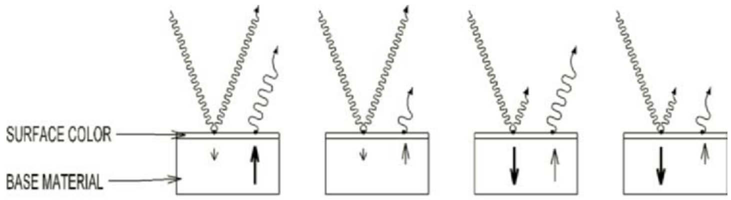

SURFACE COLOR	WHITE	SHINY METAL	BLACK	SELECTIVE COATING
SHORT-WAVE (SOLAR ABSORBTANCE)	LOW	LOW	HIGH	HIGH
LONG-WAVE EMITTANCE	HIGH	LOW	HIGH	LOW
EQUILIBRIUM TEMPERATURE	COOL	WARM	HOT	VERY HOT

Figure 3.11 The equilibrium temperature is a consequence of both the absorptance and the emittance characteristics of a material. If these colors were the finishes of automobiles, it would be easy to predict which would be hotter and which cooler.

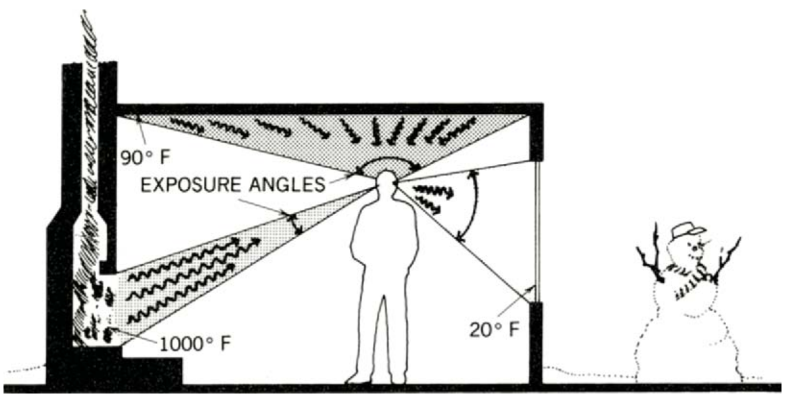

Figure 3.12 The mean radiant temperature (MRT) at any point is the combined effect of the temperature and angle of exposure of all surfaces in view.

SIDEBOX 3.12

Mean Radiant Temperature

MRT is the weighted average radiant temperature of a point in space, and it varies from point to point. The most precise calculation would use solid angles, but for simplicity, the following two-dimensional version in plan or section is often used:

$$\mathrm{MRT_A} = \frac{\sum T \cdot \Theta}{360} = \frac{T_1 \cdot \Theta_1 + T_2 \cdot \Theta_2 + T_3 \cdot \Theta_3 + \cdots}{360^{\circ}}$$

where

$\mathrm{MRT_A}$ = mean radiant temperature for point A
T = temperature of a surface
Θ = exposure angle of a surface from the point being considered

3.12 MEAN RADIANT TEMPERATURE

To determine if a certain body will be a net gainer or loser of radiant energy, we must consider both the temperature and the exposure angle of all objects that are in view of the body in question. The mean radiant temperature (MRT) describes the radiant environment for a point in space (see Sidebox 3.12). For example, the radiant effect on one's face by a fireplace (Fig. 3.12) is quite high because the fire's temperature at about 1000°F (540°C) more than compensates for the small angle of its exposure. A radiant ceiling can have just as much of a warming effect but with a much lower temperature (90°F) (32°C) because its large area creates a large exposure angle. The radiant effect can also be negative, as in the case of a person standing in front of a cold window.

Walking toward the fire (Fig. 3.12) would increase the MRT, while walking toward the cold window would reduce it because the relative size of the exposure angles would change. Many a "cold draft" near large windows in winter is actually a misinterpretation of a low MRT. The significant effect MRT has on thermal comfort is further explained in the next chapter.

3.13 HEAT FLOW

Heat flows naturally from a higher temperature to a lower temperature but not necessarily from more heat to less heat. To better understand this, we can consider a water analogy. In this analogy, the height between different levels of water represents the temperature difference between two heat sources and the volume of water represents the amount of heat.

When both reservoirs are at the same level, as shown in Figure 3.13 (top), there is no flow. The fact that there is more water (heat) on one side than the other is of no consequence.

If, however, the levels of the reservoirs are not the same, then flow

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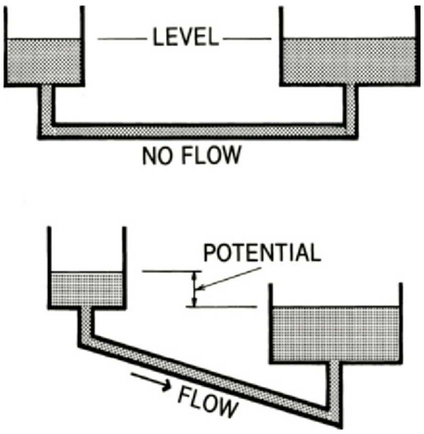

Figure 3.13 A water analogy shows how temperature, not heat content, determines heat flow.

occurs, as indicated in Figure 3.13 (bottom). Notice that this occurs even when the amount of water (heat) is less on the higher side. Just as water will flow only down, so heat will flow only from a higher temperature to a lower temperature.

To get the water to a higher level, some kind of pump is required. Heat, likewise, can be raised to a higher temperature only by some kind of "heat pump," which works against the natural flow. Refrigeration machines, the essential devices in air conditioners and refrigerators, pump heat from a lower to a higher temperature. They will be explained in some detail in Chapter 16.

In the I–P system, heat flow is measured in Btu per hour (Btu/h). For example, the heat loss from a building is measured in Btu/h, and the rating of a furnace, which describes the rate at which heat is delivered, is also given in Btu/h. In the SI system, heat flow is described by watts (W), which are equal to joules per second (J/s) (see again Table 3.3).

3.14 HEAT SINK

It is easy to see how transporting hot water to a room also supplies heat to the room. It is not so obvious, however, to see how supplying chilled water cools the room. Are we supplying "coolth"? This imaginary concept only confuses and should not be used. The correct and very useful concept is that of a heat sink. In Figure 3.14 (top) the room is cooled by the chilled water that is acting as a heat sink. The chilled water soaks up heat and gets warmer while the room gets cooler.

Often the massive structure of a building acts as a heat sink. Many massive buildings feel comfortably cool on hot summer days, as in Figure 3.14 (bottom). During the night, these buildings give up their heat by convection to the cool night air and by radiation to the cold sky—thus recharging their heat-sink capability for the next day. However, in very humid regions the high nighttime temperatures prevent effective recharging of the heat sink; consequently, massive buildings are not helpful as heat sinks in very humid climates.

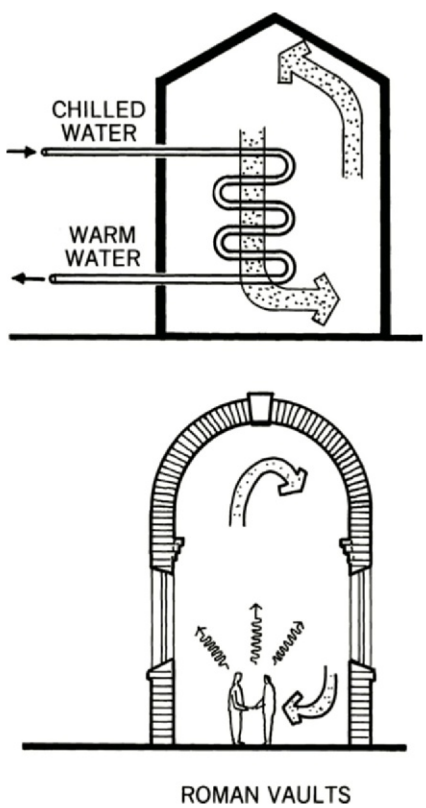

Figure 3.14 The cooling effect of a heat sink can result from a cold fluid or from the mass of the building itself.

3.15 HEAT CAPACITY

The amount of heat required to raise the temperature of a material 1°F (1°C) is called the heat capacity of that material. The heat capacity of different materials varies widely, but in general, heavier materials have a higher heat capacity. Water is an exception in that it has the highest heat capacity even though it is a middleweight material (Fig. 3.15). In architecture we are usually more interested in the heat capacity per volume than in the heat capacity per weight, which is more commonly known as specific heat.

Also note again the dramatic difference in heat capacity between air and water, as shown in Figure 3.8. This clearly indicates the reason water is used so often to store or move heat. See Figure 7.17a for the heat capacity of various common materials.

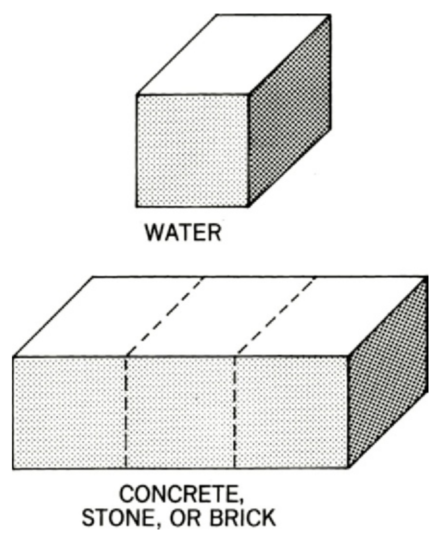

Figure 3.15 If the container of water and the concrete block are at the same temperature, they will contain the same amount of sensible heat. Because it takes only one-third as much water to hold the same amount of heat as concrete, water has three times the volumetric heat capacity of concrete.

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3.16 THERMAL RESISTANCE

The opposition of materials and air spaces to the flow of heat by conduction, convection, and radiation is called thermal resistance. By knowing the resistance of a material, we can predict how much heat will flow through it and can compare materials with each other. The thermal resistance of building materials is largely a function of the number and size of air spaces that they contain. For example, 1 in. or 1 cm of wood has the same thermal resistance as 12 in. or 12 cm of concrete mainly because of the air spaces created by the cells in the wood (Fig. 3.16). However, this is true only under steady-state conditions, where the temperatures across a material remains constant for a long period of time. Under certain dynamic temperature conditions, 12 in. or 12 cm of concrete can appear to have more resistance to heat flow than 1 in. or 1 cm of wood. To understand this, we must consider the concept of time lag, explained in Section 3.18. Because the units of thermal resistance are complex and hard to remember, technical literature frequently gives the thermal resistance in terms of R-value (see Sidebox 3.16).

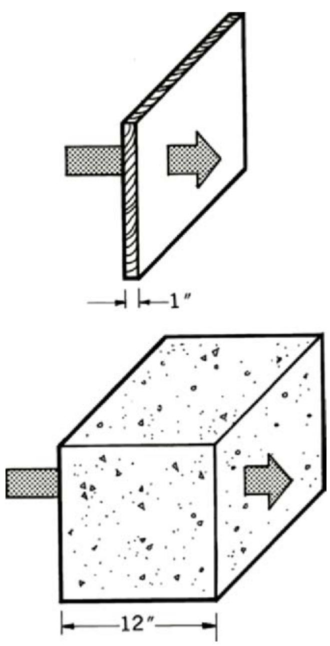

Figure 3.16 The heat flow is equal through the two materials because the thermal resistance of wood is twelve times as great as that of concrete.

SIDEBOX 3.16

In I-P units, thermal resistance in R-value $= \dfrac{ft^2 \times °F}{Btu/h}$

where Btu/h = heat flow per hour
or in SI

$$\text{RSI-value} = \frac{m^2 \times °C}{W}$$

where
m = meter
°C = degrees Celsius
W = watts

Ordinary building materials and their air spaces resist heat that is flowing by the mechanisms of conductance and convection, while **radiant barriers** resist the heat flowing by radiation through air or a vacuum. The most common radiant barriers are made of aluminum foil because of its relatively low cost and because it has both a high reflectance and low emittance (see Figure 15.6c).

3.17 HEAT-FLOW COEFFICIENT

Much of the technical literature describes the thermal characteristics of wall or roof systems in terms of the heat-flow coefficient U rather than the total thermal resistance R. Because the heat-flow coefficient is a measure of heat flow, it is the reciprocal of thermal resistance (see Sidebox 3.17).

SIDEBOX 3.17

$$U = \frac{1}{R_T}$$

where
U = U-coefficient
R_T = total resistance = $\sum R = R_1 + R_2 + R_3 + \cdots$

3.18 TIME LAG

Consider what happens when two walls with equal thermal resistance but with a different mass are first exposed to a temperature difference. Although 12 in. or 12 cm of concrete and 1 in. or 1 cm of wood have the same thermal resistance, they do not have the same heat capacity. The 12 in. or 12 cm concrete wall will have twenty-four times the heat capacity of the 1 in. or 1 cm wood wall.

If the temperature difference across both walls is the same, equal amounts of heat will start flowing through both walls. However, the initial heat to enter will be used to raise the temperature of each material. Only after the walls have substantially warmed up can heat reach the indoors. This delay in heat transfer is very short for the 1 in. or 1 cm wooden wall because of its low heat capacity, while it is much longer for the concrete wall with its high heat capacity. This delay of heat-flow is a phenomenon known as **time lag**.

The concept of time lag can be understood more easily by means of a water analogy in which pipe friction represents thermal resistance and an in-line storage tank represents the thermal capacity of a material (Fig. 3.18). The small tank represents 1 in. (1 cm) of wood (small heat capacity) and the large tank represents 12 in. (12 cm) of concrete (large heat capacity). After four hours, water (heat) is

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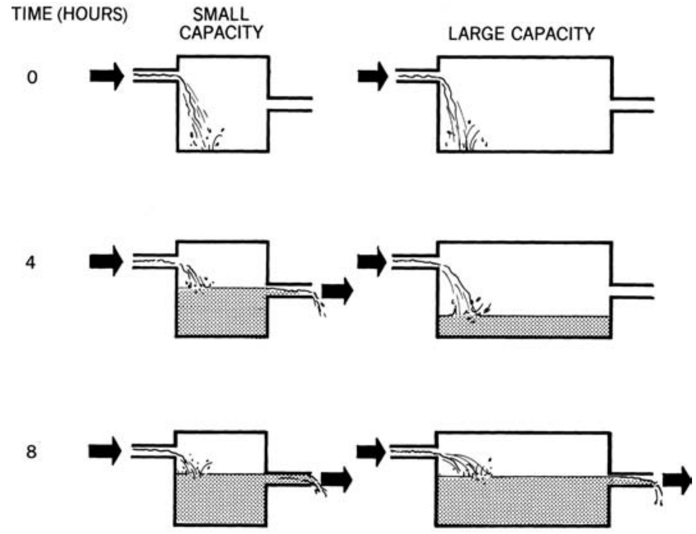

Figure 3.18 This water analogy of time lag illustrates how high storage capacity delays the passage of water under dynamic conditions. Similarly, high heat capacity delays the transmission of heat under dynamic conditions. This example is analogous to heat flowing through either 1 in. or 1 cm of wood (small capacity) and 12 in. or 12 cm of concrete (high capacity).

The diameter of the pipes determines the resistance to the flow of water just as thermal resistance determines the flow of heat. The high resistance of wood and the fairly high resistance of concrete are represented in this analogy by small pipe diameters. Although a 6 inch thick solid steel wall would have lots of thermal mass, the low thermal resistance of steel would practically eliminate any time lag just as large diameter pipes would quickly fill both the small and large containers of water.

flowing through the pipe with the low capacity but not through the system with the high capacity. Thus, high-capacity materials have a greater time lag than low-capacity materials. Also note that the time lag ends when the storage tanks are full. Under steady-state conditions there is no time lag.

3.19 INSULATING EFFECT OF MASS

If the temperature difference across a massive material fluctuates in certain specific ways, then the massive material will act as if it had high thermal resistance. Consider a massive concrete house in the desert on a hot summer day. A wall of this building is shown at three different times of day (Fig. 3.19). At 11 A.M. the indoor temperature is lower than the outdoor temperature and heat will flow inward. However, most of this heat is diverted to raising the temperature of the wall.

At 4 P.M. the outdoor temperature is very high. Although some heat is now reaching the indoors, much of the heat is still being used to further raise the temperature of the wall.

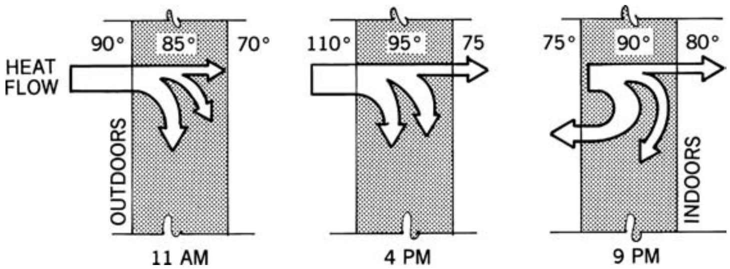

Figure 3.19 The "insulating" effect of mass is most pronounced in hot and dry climates in the summer. The same wall is shown at three different times of the day. Note that much of the heat entering the wall never makes it to the indoors.

However, at 9 P.M. the outside temperature has declined enough to be below the wall temperature. Now most of the heat that was stored in the wall is flowing outward without ever reaching the interior of the house. In this situation, the time lag of the massive material "insulated" the building from the high outdoor temperatures. It is important to note that the benefits of time lag occur only if the outdoor temperature fluctuates. Also, the larger the daily temperature swing, the greater the insulating effect of the mass. Thus, this insulating effect of mass is most beneficial in hot and dry climates during the summer. This effect is not very helpful in cold climates where the temperature remains consistently below the indoor temperature, and it is only slightly helpful in humid climates, where the daily temperature range is small. In very humid climates, the thermal mass can be a liability and should be avoided if the building is naturally ventilated.

3.20 ENERGY CONVERSION

The first law of thermodynamics states that energy can be neither created nor destroyed, only changed in form. But while energy is never lost, the second law of thermodynamics states that its ability to do work can decline. For example, high-temperature steam can generate electricity with a steam turbine, while the same amount of heat in the form of warm water cannot perform this task. Electricity is a very high-grade, valuable energy form, and to use it to purposely generate low-grade heat is a terrible waste. Sunlight is another high-grade energy source. It should be used to daylight a building before it turns into heat.

Whenever energy is converted into a different form, there will be a loss. Figure 3.20 shows the conversion of a fossil fuel into electricity. The low efficiency (approximately 30 percent) is a consequence of the large number of conversions required. Thus, electrical

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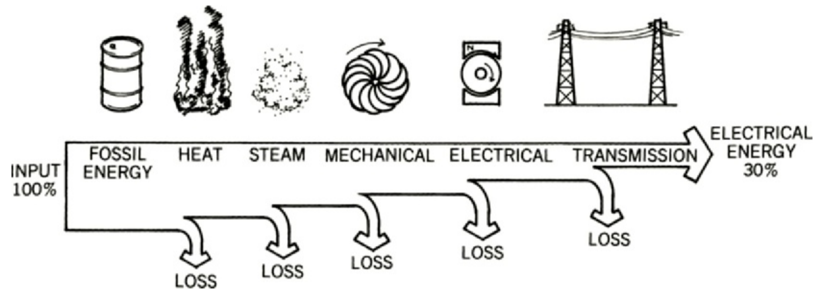

Figure 3.20 In the conversion of fossil fuel into electricity, about 70 percent of the original source energy is lost.

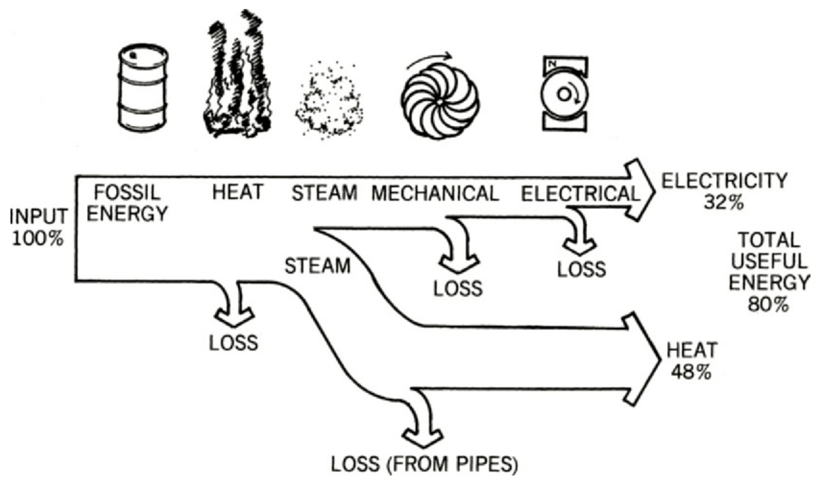

Figure 3.21a Because combined-heat-and-power (CHP) systems generate electricity at the building site, they are able to utilize much of the heat normally wasted at the power plant, and they eliminate the transmission losses.

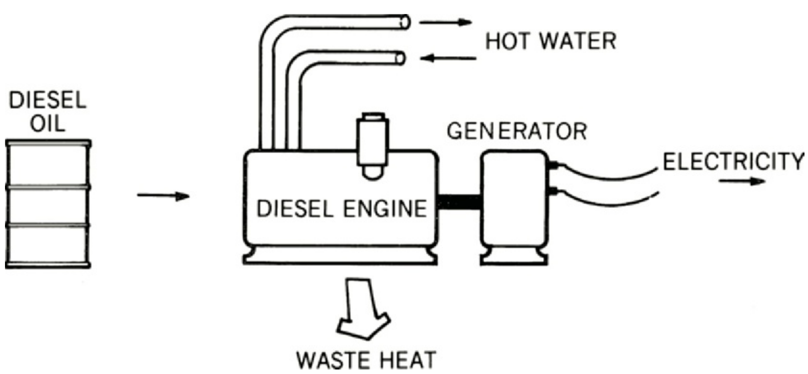

Figure 3.21b Packaged CHP units are self-contained and easily integrated into a building. The fuel could be natural gas, gasoline, diesel oil, or biodiesel oil.

energy should not be used when a better alternative is available. For example, heating directly with natural gas can be more than 90 percent efficient. It is important, however, to note that this example does not argue for the use of fossil fuels, either at the power plant or in the home. As the rest of the book explains, there are better ways to heat, cool, and light our buildings.

3.21 COMBINED HEAT AND POWER

Combined heat and power (CHP), also known as cogeneration, can greatly reduce the energy losses in producing electricity. Through the generation of electricity at the building site, efficiencies of up to 80 percent are possible. Heat, normally wasted at the central power plant, can be used for domestic hot-water or space heating (Fig. 3.21a). Also, overland electrical-transmission losses are almost completely eliminated. Compact and fairly maintenance-free packaged CHP units are commercially available for all sizes of buildings (Fig. 3.21b).

Even more efficient is **trigeneration**, where the waste heat is used not only for heating and hot water but also for cooling in the summer. An absorption refrigeration unit (see Section 16.9) can be powered by the waste heat given off by an engine/generator producing electricity.

3.22 FUEL CELLS

Combined Heat and Power (CHP) can be even more efficient if a fuel cell is used to generate the electricity. Because fuel cells are safe, clean, noiseless, low-maintenance, and compact, they can be placed in any building. Thus, as in CHP, there are no transmission losses, and the waste heat can be used (Fig. 3.22).

Fuel cells are powered with hydrogen that combines with oxygen in the air to form water, electricity, and heat. No emissions pollute the air or cause global warming. No flue is needed. A green high-rise building, 4 Times Square in New York City, uses two fuel cells, located on the fourth floor, to generate a significant portion of the electrical load. Because the building does not have access to a supply of hydrogen, natural gas is used and reformed into hydrogen and carbon dioxide. However, much less carbon dioxide is produced than in conventional natural gas systems because of the high efficiency of the fuel cells.

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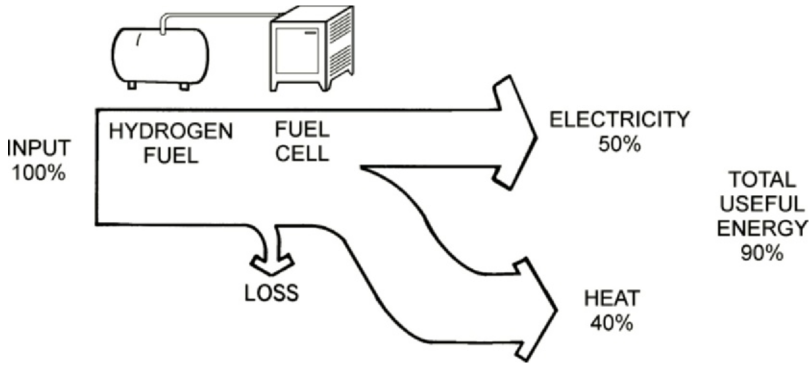

Figure 3.22 Because fuel cells use hydrogen to directly generate electricity and useful heat right inside buildings, about 90 percent of the original energy can be utilized. Fuel cells run off of nonpolluting hydrogen.

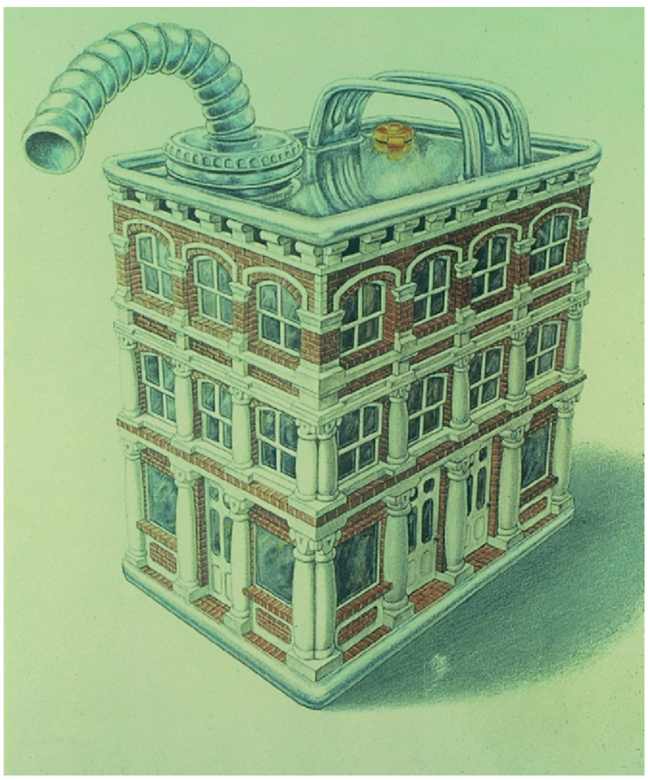

Figure 3.23 A large amount of embodied energy can be saved when existing buildings are reused. (From a poster, copyright 1980, by the National Trust for Historic Preservation.)

It is very important to again note that hydrogen is not a source of energy but rather a way to store energy. Hydrogen has to be made by means of energy-intensive processes such as electrolysis, in which electricity splits the water molecule into hydrogen and oxygen. Fuel cells have their greatest potential to create sustainable buildings when fueled with hydrogen made from renewable sources of energy, such as wind or photovaetics.

3.23 EMBODIED ENERGY

Most discussions of energy and buildings are concerned with the use and operation of a building. It is now recognized that it can take large quantities of energy to construct a building. This embodied energy is a result of both the construction machinery and the energy required to make and transport the materials. For example, aluminum embodies four times as much energy as steel and about twelve times as much as wood. The embodied energy in a modern office building is about the same as the amount of energy the building will consume in twenty years. However, if the new building is very energy efficient, the embodied energy might equal sixty years of operational energy.

Much of the embodied energy can be saved when we recycle old buildings. Thus, conservation of energy is a strong argument for adaptive reuse and historic preservation (Fig. 3.23).

The greenest building is the one that has already been built!
—Carl Elefante, architect

3.24 CONCLUSION

The basic principles described in this chapter will be applied throughout this book. Many of these ideas will make more sense when their applications are mentioned in later chapters. It will often prove useful to refer back to these explanations, although more detailed explanations will be given when appropriate. Special concepts, such as those related to lighting, will be explained when needed.

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KEY IDEAS OF CHAPTER 3

1. Sensible heat is the type of heat that can be measured with a thermometer. Dry air has only sensible heat.
2. Heat energy absorbed or given off as a material changes phase is called latent heat. It is also called heat of vaporization and heat of fusion, and it cannot be measured with a thermometer. Air has latent heat when it has water vapor.
3. Heat is transferred by conduction, convection, radiation, and transport.
4. Stratification of temperatures results from natural convection.
5. Water can hold about 3000 times as much heat as an equal volume of air. Therefore, we say that water has a much greater heat capacity than air.
6. Matter and energy interact in four ways:
   a. Transmittance
   b. Absorptance
   c. Reflectance
   d. Emittance
7. The greenhouse effect traps heat by allowing most short-wave radiation to be admitted while blocking most long-wave radiation from leaving.
8. The equilibrium temperature of an object sitting in the sun is a result of the relative absorptance and emittance characteristics of the exposed surface.
9. The mean radiant temperature (MRT) describes the radiant environment. An object will simultaneously gain radiation from hotter objects and lose radiation to cooler objects.
10. A cooler object is a potential heat sink. Chilled water or a massive building cooled overnight can act as a heat sink to cool the interior of a building.
11. Thermal resistance is a measure of a material's resistance to heat flow by the mechanisms of conduction, convection, and radiation.
12. Time lag is the phenomenon describing the delay of heat flow through a material. Massive materials have more time lag than light materials.
13. A radiant barrier (usually made of aluminum foil) can significantly reduce heat flow by radiation.
14. Under certain dynamic temperature conditions, the time lag of massive materials can resist heat flow.
15. The second law of thermodynamics tells us that usable energy is lost every time energy is converted from one form to another. As a consequence, heating a home directly with gas can be 90 percent efficient, while heating with resistance electricity, which was generated by gas, is only 30 percent efficient.
16. Combined heat and power (CHP), also called cogeneration systems, produce electricity where it is needed thereby eliminating transmission losses. Also, the waste heat can be used to heat the building and hot water.
17. Fuel cells have the potential to efficiently generate electricity and supply useful heat as a by-product inside buildings with little or no pollution. But hydrogen must be made, and, therefore, is not a source of energy. Hydrogen made from renewable sources of energy will be sustainable.
18. The energy needed to construct a building is the embodied energy of that building. When buildings are demolished, this embodied energy is lost. Some embodied energy can be saved if parts of the building are recycled and reused.

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