Chapter 1

Human Comfort and Health Requirements

Thermal and atmospheric conditions in an enclosed space are usually controlled in order to ensure (1) the health and comfort of the occupants or (2) the proper functioning of sensitive electronic equipment, such as computers, or certain manufacturing processes that have a limited range of temperature and humidity tolerance. The former is referred to as *comfort conditioning,* and the latter is called *process air conditioning.* The conditions required for optimum operation of machinery may or may not coincide with those conducive to human comfort.

Process air conditioning requirements are highly specific to the equipment or operation involved. Specifications are generally available from the producer or manufacturer, and the ASHRAE[a] *Handbook of Applications* provides a description of acceptable conditions for a number of generic industrial processes.

Once the necessary conditions for process or machinery operation are established, attention must be paid to providing acceptable comfort, or at least relief from discomfort or physiological stress, for any people also occupying the space.

Although human beings can be considered very versatile "machines" having the capacity to adapt to wide variations in their working environment while continuing to function, their productivity does vary according to the conditions in their immediate environment. Benefits associated with improvements in thermal environment and lighting quality include:

- Increased attentiveness and fewer errors
- Increased productivity and improved quality of products and services
- Lower rates of absenteeism and employee turnover
- Fewer accidents
- Reduced health hazards such as respiratory illnesses

Indeed, in many cases, air conditioning costs can be justified on the basis of increased profits. The widespread availability of air conditioning has also enabled many U.S. companies to expand into the Sun Belt, which was previously impractical.

Air conditioning and electric lights have eliminated the need for large windows, which provided light and ventilation in older commercial and institutional buildings. Although windows are still important for aesthetics, daylighting, and natural ventilation, windowless interior spaces may now be used to a much greater extent. Air conditioning allows for more compact designs with lower ceilings, fewer windows, less exterior wall areas, and less land space for a given enclosed area. Conditioned air, which is cleaner and humidity-controlled, contributes to reduced maintenance of the space. As a testament to the importance placed on air conditioning, over one-third of the entire U.S. population presently spends a substantial amount of time in air-conditioned environments. And all of this represents growth since the commercialization of refrigeration cooling in the early 1950s.

On the other hand, this improvement in comfort has come about at the expense of greater equipment installation, maintenance, and energy costs. A substantial portion of the energy consumed in buildings is related to the maintenance of comfortable environmental conditions. In fact, approximately 20 percent of the *total* U.S. energy consumption is directed toward this task.

But this doesn't have to continue to be the case. With an understanding of the factors that determine comfort in relation to climate conditions, designers may select design strategies that provide human comfort more economically. Thus, prior to investigating the energy-consuming mechanical systems in buildings, we will begin by discussing the concepts of human comfort.

Comfort Conditions

Besides being aesthetically pleasing, the human environment must provide light, air, and thermal comfort. In addition, proper acoustics and hygiene are important. Air requirements and thermal comfort are covered in this chapter, while illumination and acoustical considerations will be presented in later chapters.

Comfort is best defined as the absence of discomfort. People feel uncomfortable when they are too hot or too cold, or when the air is odorous and stale. Positive comfort conditions are those that do not distract by causing unpleasant sensations of temperature, drafts, humidity, or other aspects of the environment. Ideally, in a properly conditioned space, people should not be aware of equipment noise, heat, or air motion.

The feeling of comfort—or, more accurately, discomfort—is based on a network of sense organs: the eyes, ears, nose, tactile sensors, heat sensors, and brain. *Thermal comfort* is that state of mind that is satisfied with the thermal environment; it is thus the condition of minimal stimulation

[a] The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), a professional organization of engineers, conducts basic research of importance to the progress of the industry. Its handbooks are recognized references and data from them are widely used in this text. A major function of ASHRAE is to promulgate national voluntary consensus standards relating to the work of its members. Based on authoritative research and assembled with great care, ASHRAE standards are accepted throughout the industry and usually serve as the basis for state and local building codes.

of the skin's heat sensors and of the heat-sensing portion of the brain.

The environmental conditions conducive to thermal comfort are not absolute, but rather vary with the individual's metabolism, the nature of the activity engaged in, and the body's ability to adjust to a wider or narrower range of ambients.

For comfort and efficiency, the human body requires a fairly narrow range of environmental conditions compared with the full scope of those found in nature. The factors that affect humans pleasantly or adversely include:

1. Temperature of the surrounding air
2. Radiant temperatures of the surrounding surfaces
3. Humidity of the air
4. Air motion
5. Odors
6. Dust
7. Aesthetics
8. Acoustics
9. Lighting

Of these, the first four relate to thermal interactions between people and their immediate environment. In order to illustrate how thermal interactions affect human comfort, the explanation below describes the body temperature control mechanisms and how environmental conditions affect them.

HUMAN PHYSIOLOGY

Heat vs. Temperature

The sense of touch tells whether objects are hot or cold, but it can be misleading in telling just how hot or cold they are. The sense of touch is influenced more by the rapidity with which objects conduct heat to or from the body than by the actual temperature of the objects. Thus, steel feels colder than wood at the same temperature because heat is conducted away from the fingers more quickly by steel than by wood.

As another example, consider the act of removing a pan of biscuits from an oven. Our early childhood training would tell us to avoid touching the hot pan, but at the same time, we would have no trouble picking up the biscuits themselves. The pan and biscuits are at the same temperature, but the metal is a better conductor of heat and may burn us. As this example illustrates, the sensors on our skin are poor gauges of temperature, but rather are designed to sense the degree of heat flow.

Heat

By definition, *heat* is a form of energy that flows from a point at one temperature to another point at a lower temperature. There are two forms of heat of concern in planning for comfort: (1) sensible heat and (2) latent heat. The first is the one we usually have in mind when we speak of heat.

Sensible Heat. *Sensible heat* is an expression of the degree of molecular excitation of a given mass. Such excitation can be caused by a variety of sources, such as exposure to radiation, friction between two objects, chemical reaction, or contact with a hotter object.

When the temperature of a substance changes, it is the heat content of the object that is changing. Every material has a property called its *specific heat,* which identifies how much its temperature changes due to a given input of sensible heat.

The three means of transferring sensible heat are radiation, convection, and conduction. All bodies emit *thermal radiation.* The net exchange of radiant heat between two bodies is a function of the difference in temperature between the two bodies. When radiation encounters a mass, one of three things happens: (1) the radiation continues its journey unaffected (in which case it is said to be transmitted), (2) it is deflected from its course (in which case it is said to be reflected), or (3) its journey comes to an end (and it is said to be absorbed). Usually, the response of radiation to a material is some combination of transmission, reflection, and absorption. The radiation characteristics of a material are determined by its temperature, emissivity (emitting characteristics), absorptivity, reflectivity, and transmissivity.

Conduction is the process whereby molecular excitation spreads through a substance or from one substance to another by direct contact. *Convection* occurs in fluids and is the process of carrying heat stored in a particle of the fluid to another location where the heat can conduct away. The heat transfer mechanisms of radiation, conduction, and convection are elaborated on in Chapter 2.

Latent Heat. Heat that changes the state of matter from solid to liquid or liquid to gas is called *latent heat.* The *latent heat of fusion* is that which is needed to melt a solid object into a liquid. A property of the material, it is expressed per unit mass (per pound or per kilogram). The *latent heat of vaporization* is the heat required to change a liquid to a gas. When a gas liquefies (condenses) or when a liquid solidifies, it releases its latent heat.

Enthalpy. *Enthalpy* is the sum of the sensible and latent heat of a substance. For example, the air in our ambient environment is actually a mixture of air and water vapor. If the total heat content or enthalpy of air is known, and the enthalpy of the desired comfort condition is also known, the difference between them is the enthalpy or heat that must be added (by heating and humidification) or removed (by cooling and dehumidification).

Units. The common measure of quantity of heat energy in the English system of units is the *British thermal unit* (*Btu*). It is that heat energy required to raise 1 pound of water 1 degree Fahrenheit. The rate of flow of heat in these units is expressed in Btu per hour (Btuh).

In the International system of units (SI units), the corresponding measure is the *joule.* The rate of heat flow in SI units is joules per second, or *watts* (*W*).

Temperature

Temperature is a measure of the degree of heat intensity. The temperature of a body is an expression of its molecular excitation. The temperature difference between two points indicates a potential for heat to move from the warmer to the colder point.

The English system of units uses the Fahrenheit degree scale, while in SI units the Celsius degree scale is used. Note that temperature is a measure of heat *intensity,* whereas a Btu or joule is a measure of the *amount* of heat energy.

The *dry-bulb temperature* of a gas or mixture of gases is the temperature taken with an unwetted bulb that is shielded from radiant exchange. The familiar wall thermometer registers the dry-bulb temperature of the air.

If a thermometer bulb is moistened, any evaporation of water extracts sensible heat from the air surrounding the bulb. The sensible heat vaporizes the water and becomes latent heat. The exchange of sensible for latent heat in the air does not change the total heat content, but the air temperature is lowered. Thus, a thermometer with a wetted bulb (such as that shown in Figure 1.9) indicates a lower temperature than a dry-bulb thermometer. The drier the air, the greater the exchange of latent for sensible heat, making the wet-bulb temperature correspondingly lower.

The *wet-bulb temperature* is therefore a means of expressing the humidity of air. Dry- and wet-bulb temperatures that are the same indicate that the air has already absorbed all the water vapor it can hold, no evaporation can take place, and the percentage humidity is 100 percent. By comparing dry- and wet-bulb temperature readings, one can determine the level of humidity in the air. The larger the temperature difference, the lower the humidity.

The capability of air to hold moisture depends on the dry-bulb temperature. The higher the temperature, the more moisture the air can hold. Thus, as a mixture of air and water vapor is cooled, it becomes relatively more humid. At some temperature, the air becomes saturated with the given water content. In other words, the quantity of water vapor present is all that the air can hold at that temperature. Any further lowering of temperature will cause condensation of some of the water vapor. The temperature at which condensation begins is known as the *dew-point temperature.*

The temperatures of the surfaces surrounding an enclosed space in relation to the temperature of a body within the space determine the rate and direction of radiant heat flow between the body and the surrounding surfaces. The comfort of a person in a space is affected by this radiant exchange of heat. Therefore, it is useful to know the radiant surface temperatures or the average (mean) value of them. The equivalent uniform temperature of an enclosure causing the same radiant exchange as the given real conditions is known as the *mean radiant temperature* (*MRT*).

These concepts will be reviewed in Chapter 2 and are merely introduced here in order to provide an understanding of the following discussion of human physiology.

Body Temperature Control

Human beings are essentially constant-temperature animals with a normal internal body temperature of about 98.6°F (37.0°C). Heat is produced in the body as a result of metabolic activity, so its production can be controlled, to some extent, by controlling metabolism. Given a set metabolic rate, however, the body must reject heat at the proper rate in order to maintain thermal equilibrium.

If the internal temperature rises or falls beyond its normal range, mental and physical operation is curtailed, and if the temperature deviation is extreme, serious physiological disorders or even death can result. Sometimes the body's own immunological system initiates a body temperature rise in order to kill infections or viruses.

The importance of maintaining a fairly precise internal temperature is illustrated in Figure 1.1, which shows the consequences of deep-body temperature deviations. When body temperature falls, respiratory activity—particularly in muscle tissue—automatically increases and generates more heat. Shivering is the extreme manifestation of this form of body temperature control.

An extremely sensitive portion of the brain called the *hypothalmus* constantly registers the temperature of the blood and seems to be stimulated by minute changes in blood temperature originating anywhere in the body (this could result from drinking a hot beverage or a change in skin

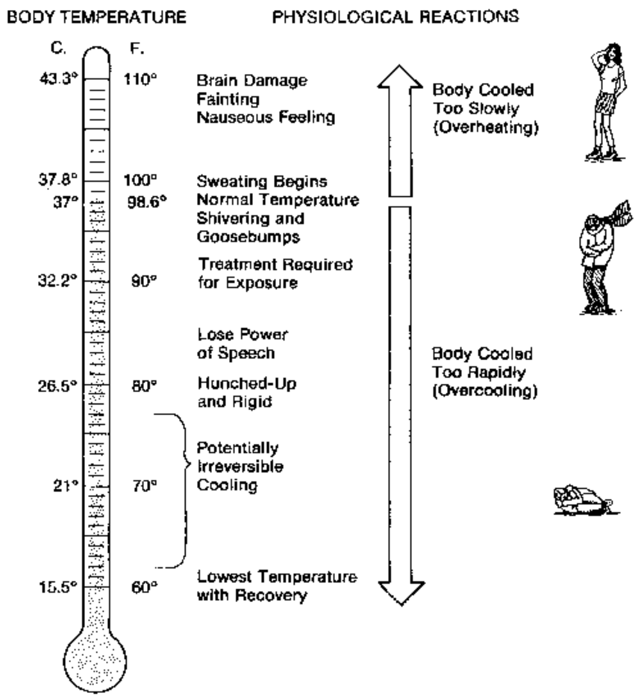

FIGURE 1.1. Physiological reactions to body temperature.

surface temperature). The skin also has sensors that signal to the brain the level of heat gain or loss at the skin.

It is the hypothalmus that appears to trigger the heat control mechanisms to either increase or decrease heat loss. This is accomplished by controlling the flow of blood to the skin by constricting or dilating the blood vessels within it. Since blood has high thermal conductivity, this is a very effective means of rapid thermal control of the body. By controlling peripheral blood flow, the body is able to (1) increase skin temperature to speed up elimination of body heat, (2) support sweating, or (3) reduce heat loss in the cold.

When body temperature rises above normal, the blood vessels in the skin dilate, bringing more heat-carrying blood to the surface. This results in a higher skin temperature and, consequently, increased heat loss. At the same time, sweat glands are stimulated, opening the pores of the skin to the passage of body fluids which evaporate on the surface of the skin and thereby cool the body. This evaporating perspiration is responsible for a great deal of heat loss. A minor amount of heat is also lost continuously by evaporation of water from the lungs and respiratory tracts.

When body heat loss is high, people experience a feeling of lassitude and mental dullness brought about by the fact that an increased amount of the blood pumped by the heart goes directly from the heart to the skin and back to the heart, bypassing the brain and other organs. A hot environment also increases strain on the heart, since it has to beat more rapidly to pump more blood to the periphery of the body.

When the body loses more heat to a cold environment than it produces, it decreases heat loss by constricting the outer blood vessels, thereby reducing blood flow to the outer surface of the skin. This converts the skin surface to a layer of insulation between the interior of the body and the environment. It has about the same effect as putting on a light sweater. If the body is still losing too much heat, the control device increases heat production by calling for involuntary muscular activity or shivering. When heat loss is too great, the body tends to hunch up and undergo muscular tension, resulting in a strained posture and physical exhaustion if the condition persists for any length of time.

Within limits, the body can acclimate itself to thermal environmental change. Such limits are not large, especially when the change is abrupt, such as when passing from indoors to outdoors. The slower seasonal changes are accommodated more easily. Changes in clothing assist the acclimatization. Whenever the body cannot adjust itself to the thermal environment, heat stroke or freezing to death is inevitable.

The physiological interpretation of comfort is the achievement of thermal equilibrium at our normal body temperature with the minimum amount of bodily regulation. We feel uncomfortable when our body has to work too hard to maintain thermal equilibrium. Under conditions of comfort, heat production equals heat loss without any action necessary by the heat control mechanisms. When the comfort condition exists, the mind is alert and the body operates at maximum efficiency.

It has been found that maximum productivity occurs under this condition and that industrial accidents increase at higher and lower temperatures. Postural awkwardness due to a cold feeling results in just as many accidents as does mental dullness caused by a too warm environment.

HEAT BALANCE

Like all mammals, humans "burn" food for energy and must discard the excess heat. This is accomplished by evaporation coupled with the three modes of sensible heat transfer: conduction, convection, and radiation. For a person to remain healthy, the heat must not be lost too fast or too slowly, and a very narrow range of body temperature must be maintained.

The body is in a state of thermal equilibrium with its environment when it loses heat at exactly the same rate as it gains heat. Mathematically, the relationship between the body's heat production and all its other heat gains and losses is:

$$\text{Heat production} = \text{heat loss} \tag{1.1}$$

or

$$M = E \pm R \pm C \pm S \tag{1.2}$$

where:

M = metabolic rate
E = rate of heat loss by evaporation, respiration, and elimination
R = radiation rate
C = conduction and convection rate
S = body heat storage rate

Equation 1.2 is illustrated in Figure 1.2.

The body always produces heat, so the metabolic rate (M) is always positive, varying with the degree of exertion. If environmental conditions are such that the combined heat loss from radiation, conduction, convection, and evaporation is less than the body's rate of heat production, the excess heat must be stored in body tissue. But body heat storage (S) is always small because the body has a limited thermal storage capacity. Therefore, as its interior becomes warmer, the body reacts to correct the situation by increasing blood flow to the skin surface and increasing perspiration. As a result, body heat loss is increased, thereby maintaining the desired body temperature and the balance expressed by Equation 1.2.

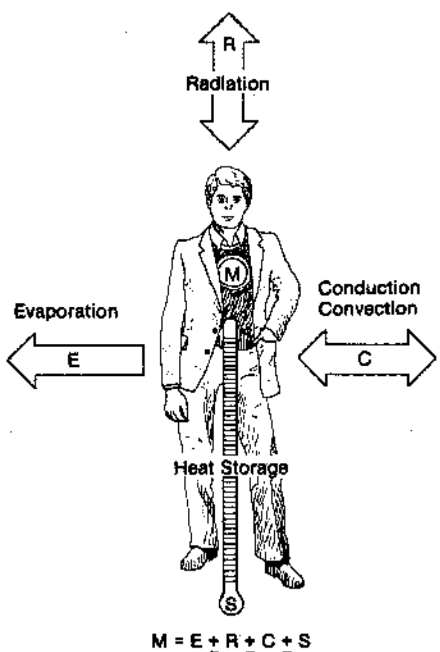

FIGURE 1.2. Heat balance of the human body interacting with its environment.

The converse condition—where heat loss is greater than body heat production—causes a reversal of the above process and, if necessary, shivering. This increased activity raises the metabolic rate.

Table 1.1 indicates the environmental and human factors that influence each of the major terms in Equation 1.2. Metabolism is discussed at greater length later in this chapter, while the other major factors—evaporation, radiation, conduction, and convection—are discussed below.

Evaporation

The body can either gain or lose heat by radiation (R) and conductive-convective heat transfer (C), depending on the temperature of the surrounding objects and ambient air. By contrast, evaporation (E) is exclusively a cooling mechanism.

Evaporative losses usually play an insignificant role in the body's heat balance at cool temperatures. They become the predominant factor, however, when ambient temperatures are so high that radiant or convective heat losses cannot occur.

At comfortable temperatures, there is a steady flow of sensible heat from the skin to the surrounding air. The amount of this sensible heat depends upon the temperature difference between the skin and air. Although the deep body temperature remains relatively constant, the skin temperature may vary from 40° to 105°F (4° to 41°C) according to the surrounding temperature, humidity, and air velocity. During the heating season, the average surface temperature of an adult indoors wearing comfortable clothing is approximately 80°F (27°C). At lower surrounding temperatures, the skin temperature is correspondingly lower.

When the surrounding environment is about 70°F (21°C), most people lose sensible heat at a rate that makes them feel comfortable. If the ambient temperature rises to the skin temperature, the sensible heat loss drops to zero. If the ambient temperature continues to rise, the body gains heat from the environment, and the only way it can lose heat is by increasing evaporation.

Evaporative heat losses also increase at high activity levels, when the metabolic heat production rises. A person engaged in strenuous physical work may sweat as much as a quart of fluid in an hour.

The rate of evaporation and evaporative heat loss is deter-

TABLE 1.1 FACTORS INFLUENCING THE HEAT BALANCE EQUATION

Factor	Environment	Human
Metabolism (M)	Little effect	Activity Weight Surface area Age Sex
Evaporation (E)	Wet-bulb temperature Dry-bulb temperature Velocity	Ability to produce sweat Surface area Clothing
Radiation (R)	Temperature difference between bodies Emissivity of surfaces	Surface area Clothing
Convection (C)	Dry-bulb temperature Velocity	Clothing Mean body surface temperature Surface area

Source: John Blankenbaker, "Ventilating Systems for Hot Industries," *Heating/Piping/Air Conditioning,* Vol. 54, No. 2, February 1982, p. 61. (Reproduced from the original: *Industrial Ventilation.* American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation, Lansing, Michigan, 1976, p. 3-2.) Used by permission of Reinhold Publishing, a Division of Penton/IPC.

mined by the evaporation potential of the air. It is dependent to a minor degree on the relative humidity of the surrounding air and, to a much greater extent, on the velocity of air motion. Moisture, which is evaporated from the skin surface, is carried away by the passing air stream.

Sufficient heat must be added to the perspiration to vaporize it, and this heat is drawn from the body. This heat loss equals the latent heat of vaporization of all the moisture evaporated. It is thus commonly known as the latent heat component of the total heat rejected by the body.

While the skin sweats only at moderate to high temperatures, evaporative losses of water from the respiratory passages and lungs occur continuously. The breath "seen" when exhaled in frosty weather is evidence that the air leaving the lungs has a high moisture content. We generally exhale air that is saturated (100 percent RH), and even at rest, the body requires about 100 Btuh (30 W) of heat to evaporate this moisture from the lungs into the inhaled air. Since it takes a considerable amount of heat to convert water into vapor, the evaporative heat loss from our lungs and skin plays an important role in disposing of body heat.

Radiation

Radiation is the net exchange of radiant energy between two bodies across an open space. The human body gains or loses radiant heat, for example, when exposed to an open fire, the sun, or a window on a cold winter day.

Each body—the earth, the sun, a human body, a wall, a window, or a piece of furniture—interacts with every other body in a direct line of sight with it. Radiation affects two bodies only when they are in sight of each other. This means that the energy cannot go around corners or be affected by air motion. For example, when we are uncomfortably hot in the direct light of the sun, we can cut off the radiant energy coming directly from the sun by stepping into the shade of a tree. Since air is a poor absorber of radiant heat, nearly all radiant exchanges are with solid surfaces to which we are exposed.

Radiant heat may travel toward or away from a human body, depending on whether the radiating temperatures of surrounding surfaces are higher or lower than the body's temperature. In a cold room, the warmer body or its clothing transmits radiant heat to all cooler surfaces such as walls, glass, and other construction within view. If there is a cold window in sight, it will typically have the largest impact in terms of draining heat away and making the body feel colder. By closing the drapes, a person can block the radiant transfer in the same way that a person can cut off the radiant energy from the sun by stepping into the shade of a tree.

The rate of radiant transfer depends on the temperature differential, the thermal absorptivity of the surfaces, and the distance between the surfaces. The body gains or loses heat by radiation according to the difference between the body surface (bare skin and clothing) temperature, and the MRT of the surrounding surfaces.

The MRT is a weighted average of the temperatures of all the surfaces in direct line of sight of the body (see Figure

1.3). Although the MRT tends to stabilize near the room air temperature, it is also affected by large glass areas, degree of insulation, hot lights, and so on. The inside surface temperature of an insulated wall will be much closer to the room air temperature than will that of an uninsulated wall.

If the MRT is below the body temperature, the radiant heat term, R, in Equation 1.2 is a positive number, and the body is losing radiant heat. If the MRT is above the body temperature, R is negative, and the body is gaining radiant heat. This could be a benefit if the room air temperature is cool, causing excess body heat loss, while it would be detrimental if the ambient conditions are hot and humid, and the body is already having trouble rejecting heat.

It should be kept in mind that the body loses radiant heat according to its surface temperature. For a comfortable, normally dressed adult, the weighted average temperature of the bare skin and clothed surfaces is about 80°F (27°C). In still air at a temperature near skin temperature, radiant exchange is the principal form of heat exchange between the body and its environment.

To illustrate the body's radiant interaction with surrounding surfaces, consider a person during the heating season working at a desk facing the center of an office with his or her back 5 feet (1.5 m) from an outside wall (see Figure 1.4a). The wall surface temperature is 59°F (15.0°C). If the room air temperature is 74°F (23.3°C) at the ceiling, 72°F (22.2°C) at the floor, and a uniform 73°F (22.8°C) in between, including the space between the person's back and the wall, will he or she be comfortable? Probably not, because the radiant heat loss to the cold wall is so high that the office worker will feel chilly. (As a rule of thumb, if the MRT is 10°F (5°C) hotter or colder than comfortable room air conditions, an occupant will feel uncomfortable.) What can be done to correct this situation?

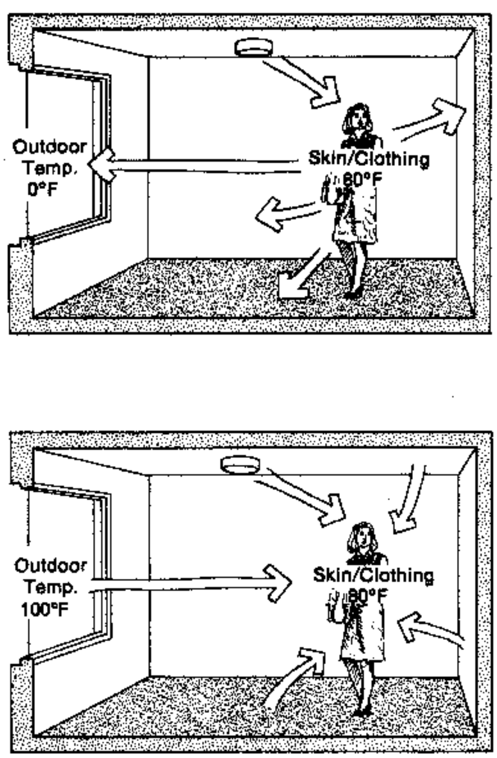

FIGURE 1.3. Radiant heat transfer with surrounding surfaces.

1. The wall surface temperature could be changed by adding insulation to the wall construction, or by hanging an insulative tapestry or wall hanging over the wall, as was done in medieval castles (Figure 1.4b).
2. The position of the desk might be changed, moving the person closer to an inside wall (Figure 1.4c). The radiant exchange would then be predominantly influenced by the surface temperature of the inside wall, which would be near the air temperature of 73°F (22.8°C). Thus, the radiant heat loss would be one-third of what it was: 80° − 73° = 7°F instead of 80° − 59° = 21°F (27° − 23° = 4°C instead of 27° − 15° = 14°C).
3. If the desk cannot be moved, the temperature of the air might be increased by turning up the thermostat. Increasing the air temperature would decrease the convective heat loss from the body. Suppose that setting the air temperature at 77°F (25°C) would decrease the convective heat loss by the same amount that the radiant heat loss would be decreased by moving the desk away from the outside wall. This would balance the heat loss from the body. The trouble is that everyone else in the room not sitting near an outside wall would be too warm.

Exactly the same thing might be true during the cooling season. A person might be too warm because of the radiant heat the body gains from a warm outside wall or window. In this case, the sensible heat loss from the body could be *increased* by *decreasing* the air temperature. This puts one person's body heat loss in balance, but everyone else in the room would be too cool.

Thus, not only is good, properly operated heating and cooling equipment important for maintaining comfort, but the building construction itself can also have a strong influence. Poorly insulated walls and windows should be flagged as comfort problems. Furthermore, the type of occupancy must be borne in mind when analyzing the intended comfort conditions.

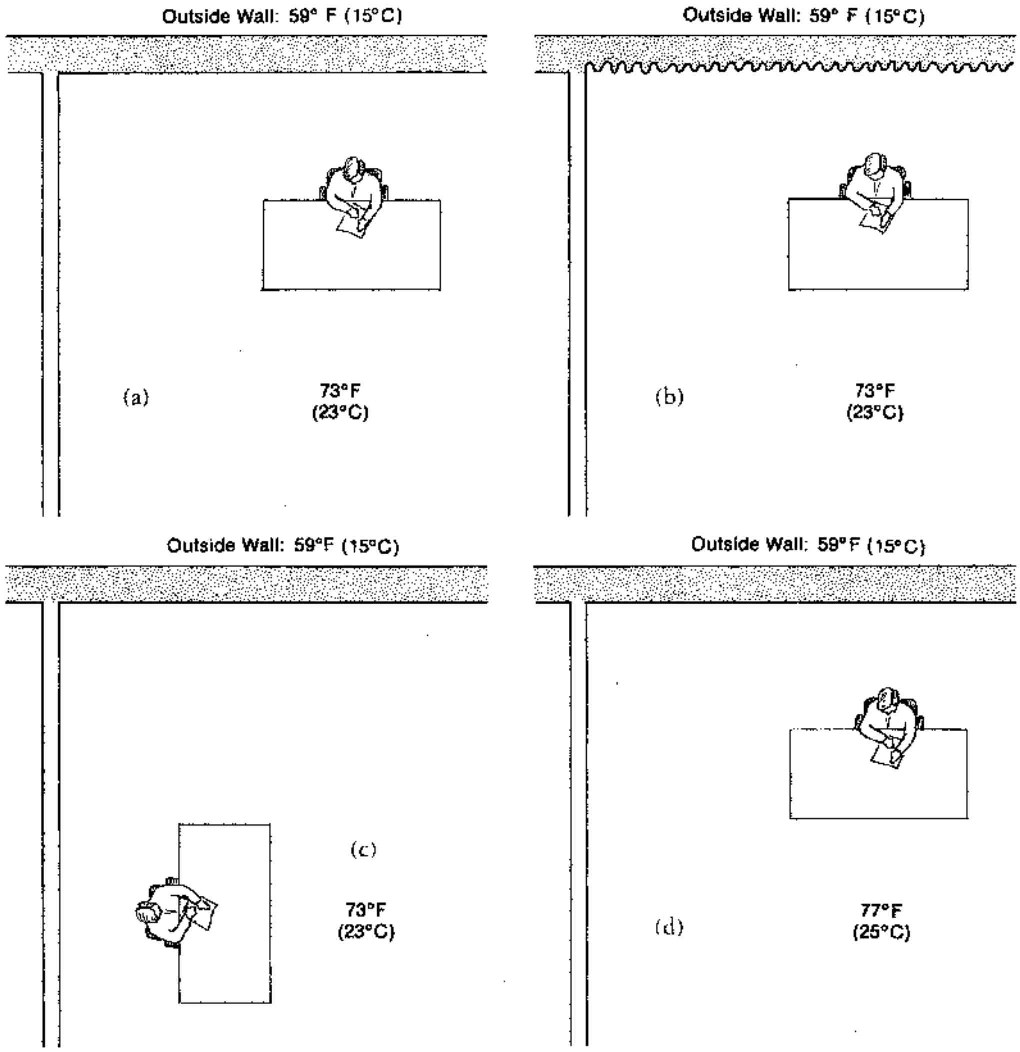

FIGURE 1.4. Alternative methods of achieving radiant comfort.

Convection-Conduction

Air passing over the skin surface is instrumental not only to the evaporation of moisture, but also to the transference of sensible heat to or from the body. The faster the rate of air movement, the larger the temperature difference between the body and surrounding air, and the larger the body surface area, the greater the rate of heat transfer.

When the air temperature is lower than the skin (and clothing) temperature, the convective heat term in equation 1.2 is "plus," and the body loses heat to the air. If the air is warmer than the skin temperature, the convective heat term is "minus," and the body gains heat from the air. Convection becomes increasingly effective at dissipating heat as air temperature decreases and air movement increases.

The conduction heat loss or gain occurs through contact of the body with physical objects such as the floor and chairs. If two chairs—one with a metal seat and the other with a fabric seat—have been in a 70°F (21°C) room for a period of time, they will both have a temperature of 70°F (21°C), but the metal one will feel colder than the one with the woven seat.

There are two reasons for this. First, metal is a good conductor, and it is the rate at which heat is conducted away—not the temperature—that we feel. Also, the metal chair has a smoother surface, which makes a good contact and thus facilitates better conduction. Clothing also plays an important role in conductive heat transfer, insulating us from the warm or cold surface, just as a pot holder protects us from a hot pot.

Combined Effects

The physiological basis of comfort was previously stated as the achievement of thermal equilibrium with a minimal amount of body regulation of M, E, R, and C. Figure 1.5 shows the relation between all these factors for lightly clothed and unclothed subjects at rest. Note that convective and radiant heat loss is greater for the lightly clothed subjects. Also, the heat loss by convection and radiation decreases with increasing air temperature, while evaporative heat loss increases with increasing air temperature.

Heat loss by evaporation is relatively constant below certain air temperatures—approximately 75°F (24°C) for the heavily clothed subject and 85°F (29°C) for the lightly clothed subject. The metabolic rate at a given activity level is stable when the temperature ranges from about 70° to 90°F (21° to 32°C).

To illustrate the various modes of heat loss operating in conjunction, consider a person outdoors in 100°F (38°C) air temperature. Referring to Equation 1.2, the convective heat loss is "minus" because the body is gaining heat from the air. The MRT is much higher than the body surface temperature—the sidewalk, street, building walls, sunny sky, and everything else in the range of view of the body is warmer than the body surface temperature. Thus, the radiant heat term is also "minus" because the body is gaining radiant heat.

But as the person walks down the sidewalk, the metabolism produces about 700 Btuh (200 W), and all that heat must be lost in addition to that gained by convection and radiation in order to maintain the heat balance. The total the body must lose may be over 1,000 Btuh (300 W), all by evaporation. The sweat glands automatically open, and the resultant moisture emitted onto the body surface then evaporates. The heat drawn from the body to evaporate the moisture keeps the skin cool as long as the surrounding air will carry away the water vapor so that more can be evaporated. This in turn keeps the deep-body temperature close to 98.6°F (37.0°C).

As the dry-bulb temperature of the surrounding air rises from the comfortable 70s to the 80s and 90s, less sensible heat (convective and radiative) is lost by the body, while the latent heat (evaporation) loss increases. Thus, if a body at rest produces 400 Btuh (117 W), it may lose 290 Btuh (85 W) of sensible heat and 110 Btuh (32 W) of latent heat at 70°F (21°C). At higher temperatures, the sensible component drops to nearly zero, and the latent heat must increase to almost the full 400 Btuh (117 W) in order to lose the same amount of heat.

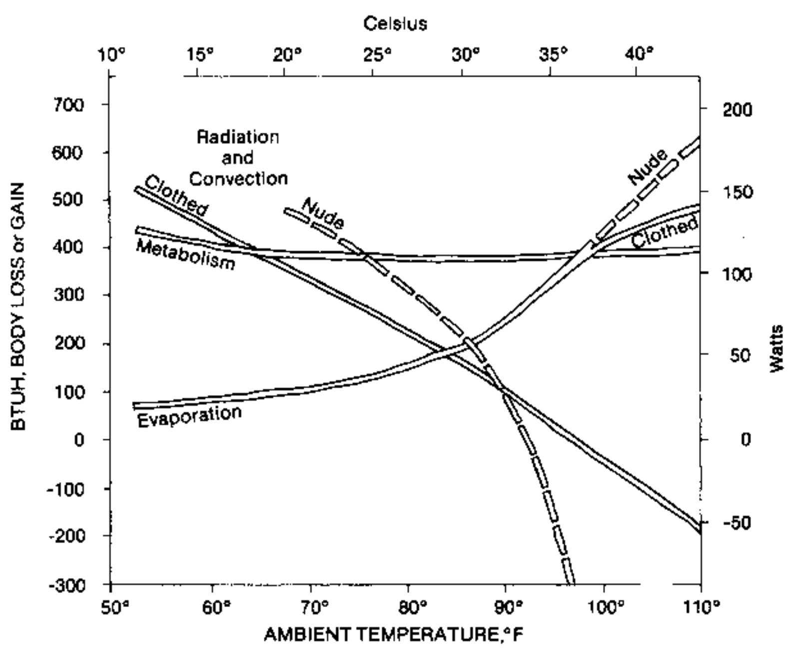

FIGURE 1.5. Relationship between metabolism, evaporation, radiation, convection, and temperature.

When people work under conditions of high temperature and extremely high humidity, both the sensible heat loss and the evaporation of moisture from their skins are reduced. Under these conditions, the rate of evaporation must be increased by blowing air rapidly over the body.

METABOLISM

As part of the process of being alive, people metabolize (oxidize) the food taken into the body, converting it into electrochemical energy. This energy is used for growth, regeneration, and operation of the body's organs, such as muscle contraction, blood circulation, and breathing. It enables us to carry out our normal bodily functions and to perform work upon objects around us.

As with all conversions from one form of energy to another, there is a certain conversion efficiency. Only about 20 percent of all the potential energy stored in the food is available for useful work. The other 80 percent takes the form of heat as a by-product of the conversion. This results in the continuous generation of heat within the body, which must be rejected by means of sensible heat flow (radiation, convection, or conduction) to the surrounding environment or by evaporating body fluids. If more food energy is ingested than is needed, it is stored as fat tissue for later use.

There is a continuous draw of energy for the operation of life-sustaining organs such as the heart. This is the idle level of bodily activity corresponding to the state of rest. It requires minimum energy conversion, and thus a minimum amount of heat is released as a by-product. When the body is engaged in additional mental or physical activity, metabolism increases to provide the necessary energy. At the same time, by-product heat generation also increases. The fuel for this is drawn from food currently being digested or, if necessary, from the fat stores.

When the body heat loss increases and the internal temperature begins to drop, metabolism increases in an effort to stabilize the temperature even though there is no additional mental or physical activity. In this case, all of the additional energy metabolized is converted into heat.

In general, the metabolic rate is proportional to body weight, and is also dependent upon the individual's activity level, body surface area, health, sex, age, amount of clothing, and surrounding thermal and atmospheric conditions. Metabolism rises to peak production at around 10 years of age and drops off to minimum values at old age. It increases due to a fever, continuous activity, or cold environmental conditions if the body is not thermally protected.

To determine the optimum environmental conditions for comfort and health, one must ascertain the metabolic level during the course of routine physical activities, since body heat production increases in proportion to the level of exercise. When the activity level shifts from sleeping to heavy work, the metabolism varies accordingly, as shown in Figure 1.6.

Table 1.2 presents average metabolic rates for a variety of steady activities in *met* units. One met is defined in terms of body surface area as

$$18.4 \text{ Btuh/ft}^2 = 58.2 \text{ W/m}^2 = 50 \text{ kcal/m}^2\cdot\text{hr}$$

For an average-size man, the met unit corresponds to approximately

$$360 \text{ Btuh} = 100 \text{ W} = 90 \text{ kcal/hr}$$

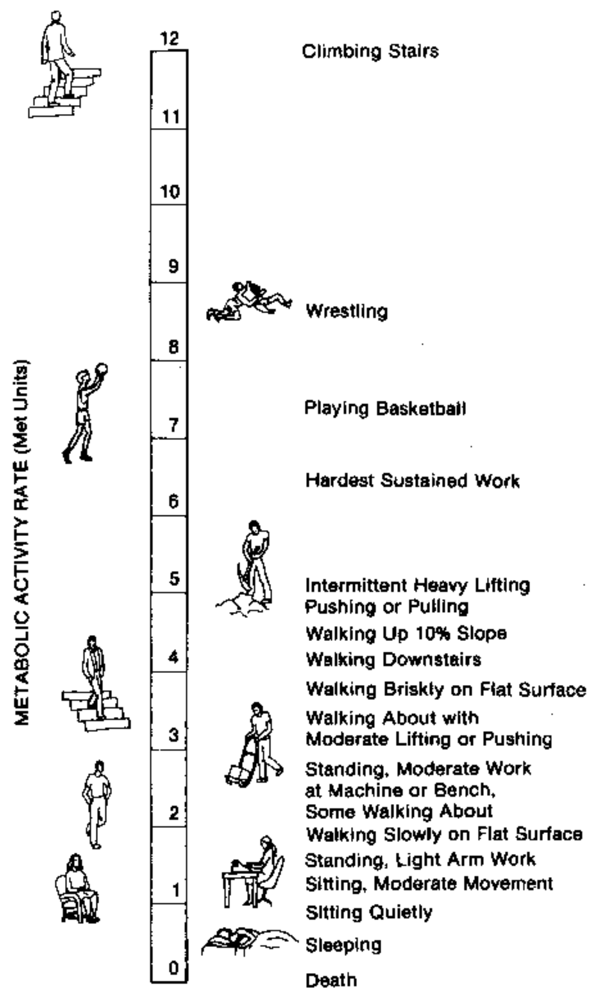

FIGURE 1.6. Scale of activity level variations (in met units).

TABLE 1.2 METABOLIC RATE AT DIFFERENT TYPICAL ACTIVITIES

Activity	Metabolic Rate in Met Units[a]	Activity	Metabolic Rate in Met Units[a]
Resting		**Miscellaneous Work**	
Sleeping	0.7	Watch-repairing, seated	1.1
Reclining	0.8	Lifting/packing	1.2 to 2.4
Seated, reading	0.9	Garage work (e.g., replacing tires, raising cars by jack)	2.2 to 3.0
Office Work		**Vehicle Driving**	
Seated, writing	1.0	Car	1.5
Seated, typing or talking	1.2 to 1.4	Motorcycle	2.0
Seated, filing	1.2	Heavy vehicle	3.2
Standing, talking	1.2	Aircraft flying, routine	1.4
Drafting	1.1 to 1.3	Instrument landing	1.8
Miscellaneous office work	1.1 to 1.3	Combat flying	2.4
Standing, filing	1.4	**Leisure Activities**	
Walking (on Level Ground)		Stream fishing	1.2 to 2.0
2 mph (0.89 m/s)	2.0	Golf, swinging and walking	1.4 to 2.6
3 mph (1.34 m/s)	2.6	Golf, swinging and with golf cart	1.4 to 1.8
4 mph (1.79 m/s)	3.8	Dancing	2.4 to 4.4
Domestic Work		Calisthenics exercise	3.0 to 4.0
Shopping	1.4 to 1.8	Tennis, singles	3.6 to 4.6
Cooking	1.6 to 2.0	Squash, singles	5.0 to 7.2
House cleaning	2.0 to 3.4	Basketball, half court	5.0 to 7.6
Washing by hand and ironing	2.0 to 3.6	Wrestling, competitive or intensive	7.0 to 8.7
Carpentry			
Machine sawing, table	1.8 to 2.2		
Sawing by hand	4.0 to 4.8		
Planing by hand	5.6 to 6.4		

[a] Ranges are for activities that may vary considerably from place to place and from person to person. 1 met = 18.4 Btuh/ft^2 = 58.2 W/m^2 = 50 kcal/hr·m^2. Some activities are difficult to evaluate because of differences in exercise intensity and body position among people.

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A met is the average amount of heat produced by a sedentary man, and any metabolic rate can be expressed in multiples of this standard unit.

For the more intense activities listed in Table 1.2, actual metabolic rates depend on the relation between the intensity of the given activity and the individual's peak capacity. Another factor affecting metabolic rate is the heavy, protective clothing worn in cold weather, which may add 10 to 15 percent to the rate. Pregnancy and lactation may increase values by 10 percent.

CLOTHING

Another determinant of thermal comfort is clothing. In the majority of cases, building occupants are sedentary or slightly active and wear typical indoor clothing. Clothing, through its insulation properties, is an important modifier of body heat loss and comfort.

The insulation properties of clothing are a result of the small air pockets separated from each other to prevent air from migrating through the material. Newspaper, for example, can serve as good insulation if several sheets are separated so that there are layers of air between the layers of paper; this can be used as a crude, but effective, emergency blanket to cover the body. Similarly, the fine, soft down of ducks is a poor conductor and traps air in small, confined spaces. In general, all clothing makes use of this principle of trapped air within the layers of cloth fabric.

Clothing insulation can be described in terms of its *clo* value. The clo value is a numerical representation of a clothing ensemble's thermal resistance. 1 clo = 0.88 ft^2·hr·°F/Btu

(0.155 $m^2 \cdot °C/W$). A heavy two-piece business suit and accessories have an insulation value of about 1 clo, while a pair of shorts is about 0.05 clo. Clo values for common articles of clothing are listed in Table 1.3. The total insulation value of a clothing ensemble can be estimated as the sum of the individual garment clo values.

The relationship between clothing insulation and room temperature necessary for a neutral thermal sensation is presented in Figure 1.7 for sedentary occupants, and specified air speed and humidity. Comfortable clothing levels are expressed as a function of *operative temperature,* which is based on both air and mean radiant temperatures. At air speeds of 8 fpm (0.4 m/s) or less and MRT less than 120°F (50°C), the operative temperature is approximately the average of the air and mean radiant temperatures and is equal to the adjusted dry-bulb temperature.

There is no combination of conditions that would satisfy all people all of the time. The *optimum operative temperature,* represented by the middle line in Figure 1.7, is the temperature that satisfies the greatest number of people with a given amount of clothing and specified activity level. The upper and lower *thermal acceptability limits* demarcate a room environment that at least 80 percent of the occupants would find thermally acceptable.

From the 1920s to the early 1970s, energy was abundant and inexpensive. During this period, the preferred amount of clothing worn by building occupants decreased, and correspondingly the preferred temperatures increased from about 68°F (20°C) for winter to the year-round range of 72° to 78°F (22° to 25.5°C). Present conditions, however, make it desirable to minimize energy consumption for providing thermal comfort.

TABLE 1.3 CLO VALUES FOR INDIVIDUAL ITEMS OF CLOTHING

Men		Women	
Clothing	**clo**	**Clothing**	**clo**
Underwear		Underwear	
Sleeveless	0.06	Girdle	0.04
T-shirt	0.09	Bra and panties	0.05
Briefs	0.05	Half slip	0.13
Long underwear, upper	0.10	Full slip	0.19
Long underwear, lower	0.10	Long underwear, upper	0.10
		Long underwear, lower	0.10
Shirt		Blouse	
Light, short sleeve	0.14	Light, long sleeve	0.20
long sleeve	0.22	Heavy, long sleeve	0.29
Heavy, short sleeve	0.25	Dress, light	0.22
long sleeve	0.29	Dress, heavy	0.70
(Plus 5% for tie or turtleneck)			
Vest, light	0.15	Skirt, light	0.10
Vest, heavy	0.29	Skirt, heavy	0.22
Trousers, light	0.26	Slacks, light	0.10
Trousers, heavy	0.32	Slacks, heavy	0.44
		Sweater	
Sweater, light	0.20	Light, sleeveless	0.17
Sweater, heavy	0.37	Heavy, long sleeve	0.37
Jacket, light	0.22	Jacket, light	0.17
Jacket, heavy	0.49	Jacket, heavy	0.37
Socks		Stockings	
Ankle length, thin	0.03	Any length	0.01
thick	0.04	Panty hose	0.01
Knee high	0.10		
Shoes		Shoes	
Sandals	0.02	Sandals	0.02
Oxfords	0.04	Pumps	0.04
Boots	0.08	Boots	0.08
Hat and overcoat	2.00	Hat and overcoat	2.00

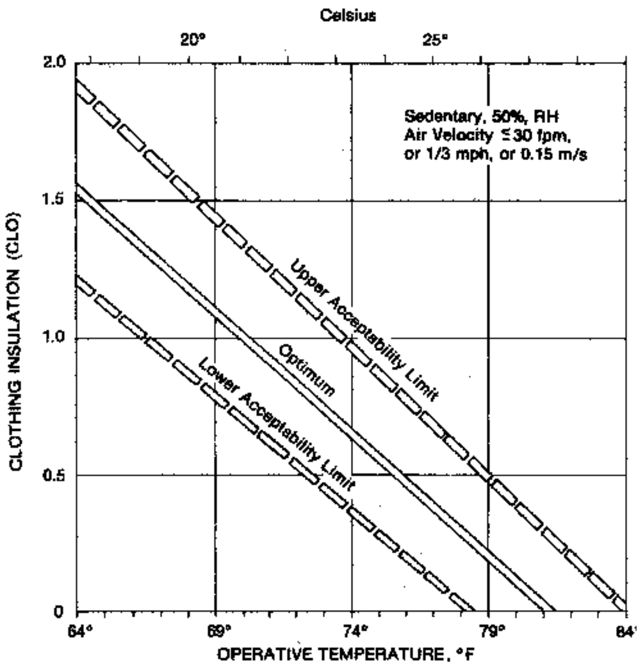

FIGURE 1.7. Clothing level (in clo units) necessary for comfort at different operative temperatures. (Reprinted from *Standard 55* by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.)

Conditions that are thermally acceptable to at least 80 percent of normally clothed occupants are presented in Figure 1.7. By adjusting clothing as desired, the remaining occupants can satisfy their own comfort requirements. Energy savings can be achieved if the insulation value of clothing worn by people indoors is appropriate to the season and outside weather conditions.

During the summer months, suitable clothing in commercial establishments consists of lightweight dresses, lightweight slacks, short-sleeved shirts or blouses, stockings, shoes, underwear, accessories, and sometimes a thin jacket. These ensembles have insulation values ranging from 0.35 to 0.6 clo.

The winter heating season brings a change to thicker, heavier clothing. A typical winter ensemble—including heavy slacks or skirt, long-sleeved shirt or blouse, warm sweater or jacket, and appropriately warm accessories—would have an insulation value ranging from 0.8 to 1.2 clo. During more temperate seasons, the clothing would likely consist of medium-weight slacks or skirt, long-sleeved shirt or blouse, and so on, having a combined insulation value of 0.6 to 0.8 clo. Figure 1.8 illustrates various clo values.

These seasonal clothing variations of building occupants allow indoor temperature ranges to be higher in the summer than in the winter and yet remain comfortable. In the wintertime, additional clothing lowers the ambient temperature necessary for comfort and for thermal neutrality. Adding 1 clo of insulation permits a reduction in air temperature of approximately 13°F (7.2°C) without changing the thermal sensation. At lower temperatures, however, comfort requires a fairly uniform level of clothing insulation over the entire body. For sedentary occupancy of more than an hour, the operative temperature should not be less than 65°F (18°C).

The insulation of a given clothing ensemble can be estimated by adding up the clo values of the individual items worn, as listed in Table 1.3, and multiplying the sum by 0.82. A rough approximation of the clo value may also be estimated by multiplying each pound of clothing by 0.15 clo (or each kilogram by 0.35 clo).

ENVIRONMENTAL FACTORS

Satisfaction with the thermal environment is a complex, subjective response to many interacting variables. Our perception of comfort is influenced by these variables, which include the characteristics of the physical environment, amount of clothing, activity level, and the demographic character of the subject (age, sex, health, etc.). Researchers have identified the seven major determinants of thermal comfort response:

1. Air (dry-bulb) temperature
2. Humidity
3. Mean radiant temperature
4. Air movement
5. Clothing
6. Activity level
7. Rate of change of any of the above

As any one of these variables changes, the others need to be adjusted to maintain the thermal equilibrium between heat gain and heat loss in order for a person to continue to feel comfortable. The important environmental parameters are temperature, humidity, radiation, and air movement, while the important personal parameters are clothing and activity. The personal parameters have already been covered, so the following discussion concentrates on the environmental parameters.

Dry-Bulb Temperature

Dry-bulb temperature affects the rate of convective and evaporative body heat loss. It is perhaps the most important determinant of comfort, since a narrow range of comfortable

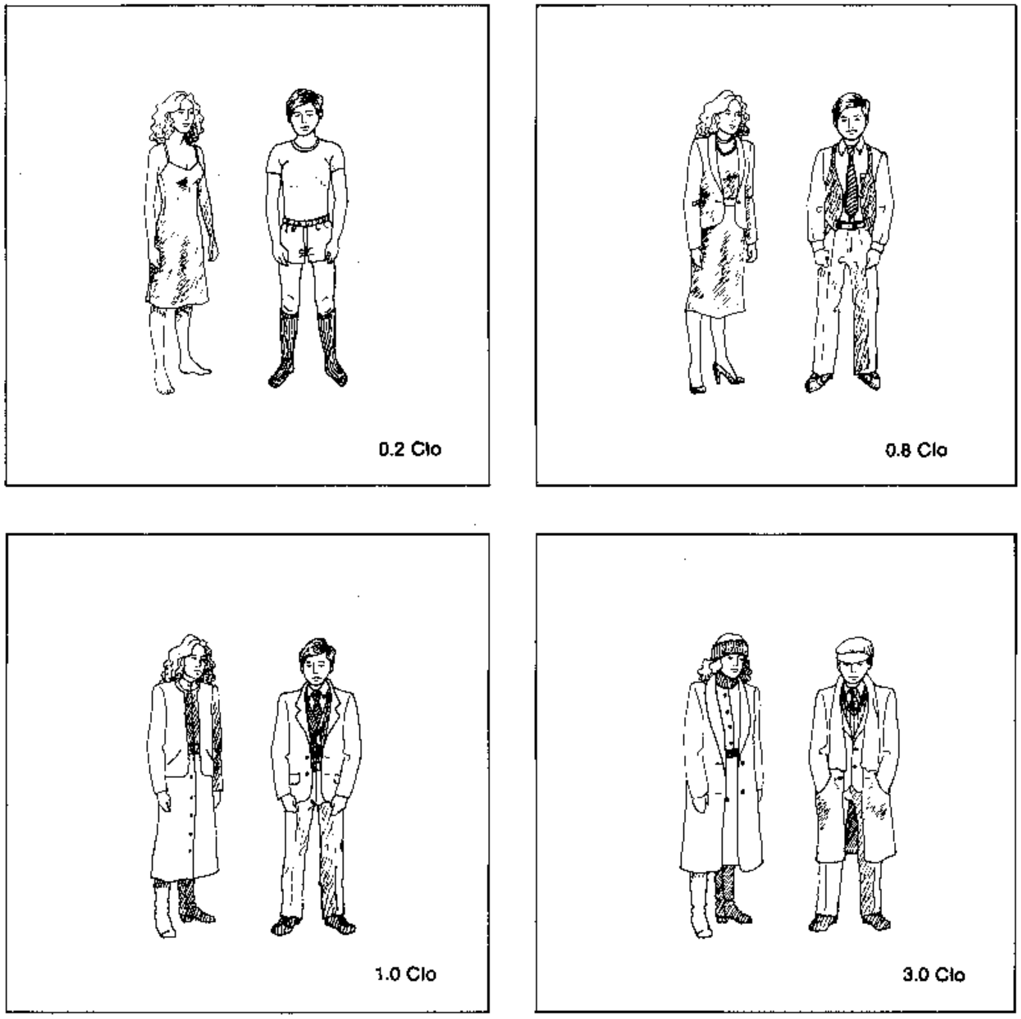

FIGURE 1.8. Illustration of a range of clo values.

temperatures can be established almost independently of the other variables. There is actually a fairly wide range of temperatures that can provide comfort when combined with the proper combination of relative humidity, MRT, and air flow. But as any one of these conditions varies, the dry-bulb temperature must be adjusted in order to maintain comfort conditions.

Temperature drifts or ramps are gradual temperature changes over time. *Drifts* refer to passive temperature changes, while *ramps* are actively controlled temperature changes. People may feel comfortable with temperatures that rise or fall like a ramp over the course of time, even though they would be uncomfortable if some of the temperatures were held constant. Ideal comfort standards call for a change of no more than 1°F/hr (0.6°C/hr) during occupancy, provided that the temperature excursion doesn't extend far beyond the specified comfort conditions and for very long.

Air temperature in an enclosed space generally increases from floor to ceiling. If this variation is sufficiently large, discomfort could result from the temperature being overly warm at the head and/or overly cold at the feet, even though the body as a whole is thermally neutral. Therefore, to prevent local discomfort, the vertical air temperature difference within the occupied zone should not exceed 5°F (3°C). The *occupied zone* within a space is the region normally occupied by people. It is generally considered to be the first 6 feet (1.8 m) above the floor and 2 feet (0.6 m) or more away from walls or fixed air conditioning equipment. The floor temperature should be between 65° and 84°F (18° and 29°C) to minimize discomfort for people wearing appropriate indoor footwear.

Humidity

Humidity is the amount of water vapor in a given space. The density of water vapor per unit volume of air is called *absolute humidity.* It is expressed in units of pounds (of water) per cubic foot (of dry air). The *humidity ratio* or *specific humidity* is the weight of water vapor per unit weight of dry air; it is given in either grains per pound or pound per pound (kg/kg).

The amount of moisture that air can hold is a function of the temperature. The warmer the air, the more moisture it can hold. The amount of water present in the air relative to the maximum amount it can hold at a given temperature without causing condensation (water present ÷ maximum water holding capability) is known as the *degree of saturation.* This ratio multiplied by 100 is the *percentage humidity.* This percentage is a measure of the dryness of air. Low percentages indicate relative dryness, and high percentages indicate high moisture.

Percentage humidity is often mistakenly called relative humidity. *Relative humidity* (*RH*) is the ratio of the actual vapor pressure of the air-vapor mixture to the pressure of saturated water vapor at the same dry-bulb temperature times 100. Percentage and relative humidity are numerically close to each other but are not identical. The concept of vapor pressure will be discussed later; the intent here is simply to point out the distinction between percentage humidity and RH.

Although human tolerance to humidity variations is much greater than tolerance to temperature variations, humidity control is also important. High humidity can cause condensation problems on cold surfaces and retards human heat loss by evaporative cooling (sweating and respiration). Air already laden with moisture cannot absorb much more from the skin.

The drier and warmer the air, the greater the rate of heat flow from the skin by evaporation of perspiration into the air. However, low humidity tends to dry throat and nasal passages. Low humidity can cause annoying static electric sparks, which can be hazardous in the presence of explosive gases. Carpeting is commercially available with a conductive material such as copper or stainless steel woven into the pile and backing to reduce voltage buildup and help alleviate static electricity problems.

The thermal effect of humidity on the comfort of sedentary persons is small, that is, comfort is maintained over a wide range of humidity conditions. In winter, the body feels no discomfort over a range of RH from 50 percent down to 20 percent. In summer, the tolerance range extends even higher, up to 60 percent RH when the temperature is 75°F; above that, the skin feels sweaty.

Nevertheless, some types of industrial applications, such as textile manufacturing, optical lens grinding, and food storage, maintain an RH above 60 percent because of equipment, manufacturing processes, or product storage requirements. At the other extreme, certain pharmaceutical products, plywood cold pressing, and some other processes require an RH below 20 percent. Hospitals also must carefully control humidity since the level of bacteria propagation is lowest between 50 and 55 percent RH.

Humidity can be expressed as dew point, RH, wet-bulb temperature, or vapor pressure. None of these, however, by itself defines the amount of moisture present without knowledge of one of the others or the coincident dry-bulb temperature. In general, any of these five parameters can be found by means of tables or a psychrometric chart (Figure 2.11) if any two of them are already known.

A common and simple instrument for determining humidity is the sling psychrometer shown in Figure 1.9. It consists of two mercury-filled glass thermometers mounted side by side on a frame fitted with a handle by which the device can be whirled through the air. One of the thermometers has a cloth sock that is wetted. As moisture from the wet sock evaporates into the moving air, the wet-bulb temperature drops.

The drier the air surrounding the sling psychrometer, the more moisture that can evaporate from the sock. This evaporation lowers the wet-bulb temperature accordingly. The greater the difference between the wet-bulb and dry-bulb temperatures (called the *wet-bulb depression*), the lower the RH. A table is normally provided with the device for correlating dry- and wet-bulb temperatures with RH.

Mean Radiant Temperature

As an illustration of the importance of radiant temperature, experiments have been conducted in rooms in which the surface temperatures were controlled. Subjects were surprised to find out that they were warm at air temperatures of 50°F (10°C) when the room surfaces were sufficiently heated and that they were cool at air temperatures of 120°F (49°C) when room surfaces were cooled.

The MRT affects the rate of radiant heat loss from the body. Since the surrounding surface temperatures may vary widely, the MRT is a weighted average of all radiating surface temperatures within line of sight. Two-dimensionally, it can be calculated as follows:

$$\text{MRT} = \frac{\Sigma T\theta}{360} = \frac{T_1\theta_1 + T_2\theta_2 + \cdots + T_n\theta_n}{360} \tag{1.3}$$

where

T = surface temperature
θ = surface exposure angle (relative to occupant) in degrees

Example

The office in Figure 1.10 has insulated walls and glass walls. Regarding the human occupants as cylinders, and ignoring the radiant contributions from the floor and ceiling:

1. What is the MRT for occupant A on a cold winter day when it is 0°F (−18°C) outside? The inside surface temperature of the exterior wall is 67°F (19°C), and the glass temperature is 48°F (9°C). Interior partitions are at 72°F (22°C).
2. What is the MRT for occupant B under the same conditions?
3. What is the MRT for occupant A on a warm summer day when it is 95°F (35°C) outside? The inside surface temperature of the exterior wall is 80°F (27°C), and the shaded glass temperature is 85°F (29°C). Interior partitions are at 77°F (25°C).

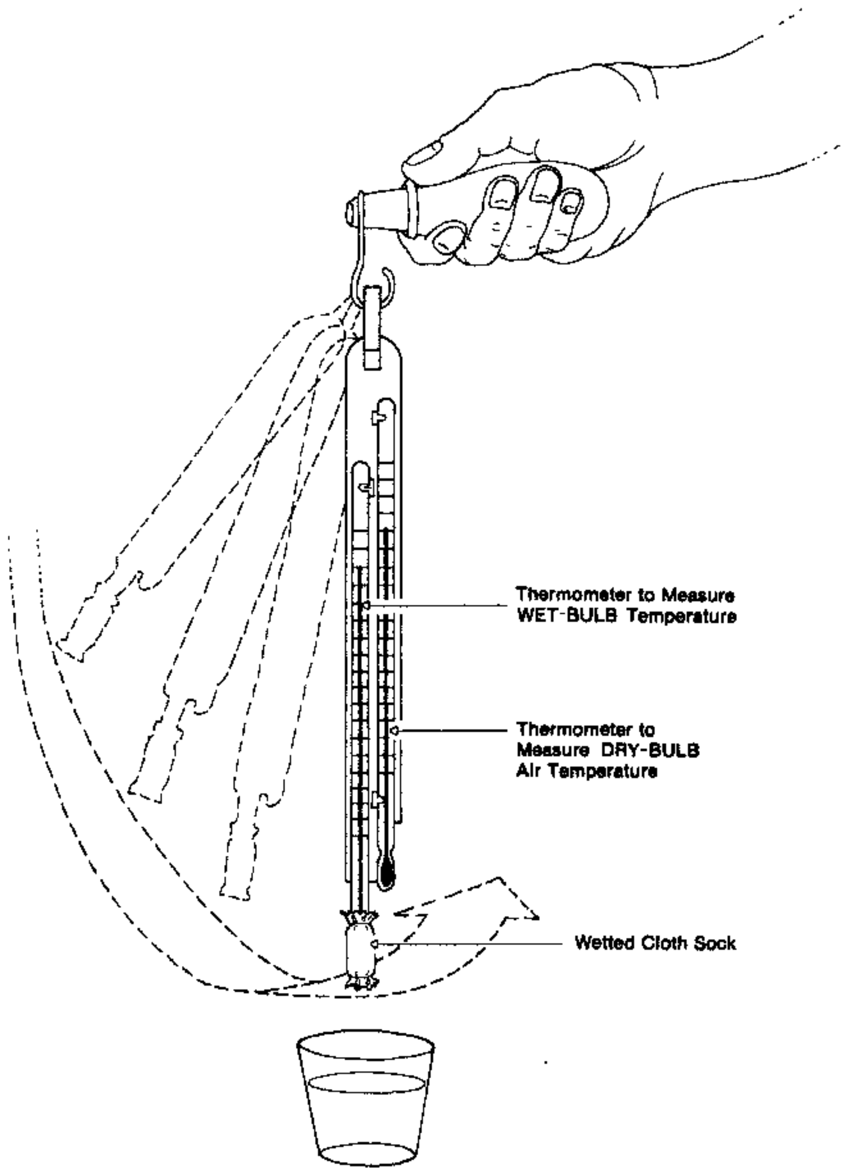

FIGURE 1.9. Sling psychrometer.

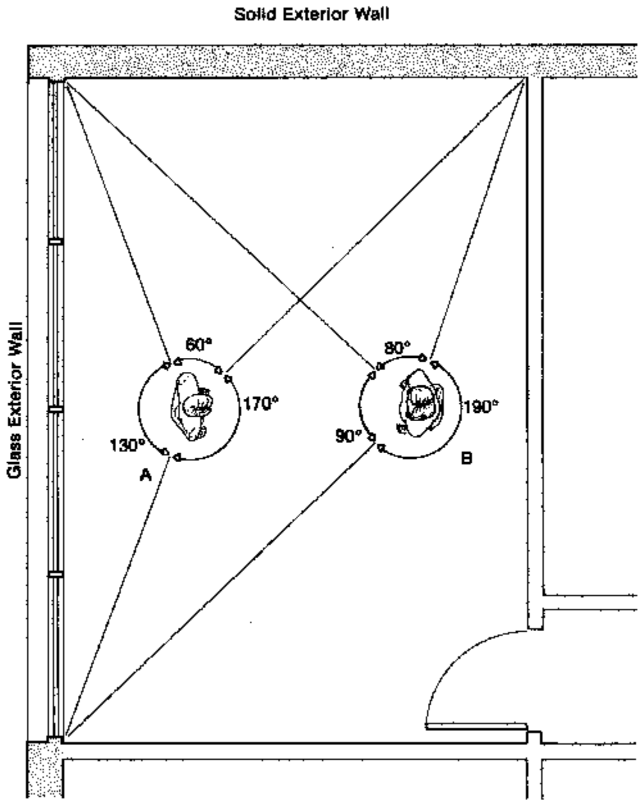

FIGURE 1.10. Example of MRT calculation.

Answers (English Units)

1. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(48 \times 130) + (67 \times 60) + (72 \times 170)}{360}$

$= 62°F$

2. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(48 \times 90) + (67 \times 80) + (72 \times 190)}{360}$

$= 65°F$

3. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(85 \times 130) + (80 \times 60) + (77 \times 170)}{360}$

$= 80°F$

Answers (SI Units)

1. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(9 \times 130) + (19 \times 60) + (22 \times 170)}{360}$

$= 17°C$

2. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(9 \times 90) + (19 \times 80) + (22 \times 190)}{360}$

$= 18°C$

3. $\text{MRT} = \dfrac{\Sigma T\theta}{360}$

$= \dfrac{(29 \times 130) + (27 \times 60) + (25 \times 170)}{360}$

$= 27°C$

The MRT for office workers should be in the range of 65° to 80°F (18° to 27°C), depending on the clothing worn and the activity. In winter, levels of wall, roof, and floor insulation together with window treatments such as double glazing, blinds, and drapes in accordance with good design practice and current energy codes should generally result in indoor surface temperatures that are no more than 5°F (2.8°C) below the indoor air temperature.

Air Movement

Air motion significantly affects body heat transfer by convection and evaporation. Air movement results from free (natural) and forced convection as well as from the occupants' bodily movements. The faster the motion, the greater the rate of heat flow by both convection and evaporation.

When ambient temperatures are within acceptable limits, there is no minimum air movement that must be provided for thermal comfort. The natural convection of air over the surface of the body allows for the continuous dissipation of body heat. When ambient temperatures rise, however, natural air flow velocity is no longer sufficient and must be artificially increased, such as by the use of fans. Typical human responses to air motion are shown in Table 1.4.

In general, insufficient air motion promotes stuffiness and air stratification. Stratification causes air temperatures to vary from floor to ceiling. When air motion is too rapid, unpleasant drafts are felt by the room occupants. The exact limits to acceptable air motion in the occupied zone are a function of the overall room conditions of temperature, humidity, and MRT, along with the temperature and humidity conditions of the moving air stream.

A noticeable air movement across the body when there is perspiration on the skin may be regarded as a pleasant cooling breeze. When the surrounding surface and room air temperatures are cool, however, it will probably be considered a chilly draft. The neck, upper back, and ankles are most sensitive to drafts, particularly when the entering cool air is 3°F (1.5°C) or more below normal room temperature.

Every 15 fpm increase in air movement above a velocity of 30 fpm is sensed by the body as a 1° temperature drop. Air systems are usually designed for a maximum of 50 fpm in the occupied zone, but that is typically exceeded at the outlet of air registers.

Cool air can impinge on an occupant in two general cases: Air that is warm when introduced into the room may cool off before reaching the occupant, or the air is intended to cool the occupant under overly warm ambient conditions. In either case, when the temperature of the air impinging on an occupant is below the ambient temperature, the individual becomes more sensitive to air motion and may complain of drafts. Therefore, careful attention must be given to air distribution as well as velocity.

The tendency of warm air to rise can greatly affect occupant comfort due to convective air motion, and thus influences the correct placement of the heat source in a room. The consideration of proper air distribution discussed in Chapter 6 affects the placement of outside air openings for natural ventilation, of radiation devices, and of air registers. Air outlet design is determined by the air distribution pattern it is intended to create.

Besides the removal of heat and humidity, another function of air motion in alleviating stuffiness is the dispersion of body odors and air contaminants. The subject of air quality is addressed separately later in this chapter.

THERMAL COMFORT STANDARDS

Thermal Indices

Thermal sensations can be described as feelings of being hot, warm, neutral, cool, cold, and a range of classifications in between. There have been numerous attempts to find a single index—integrating some or all of the environmental factors—that could be used to determine thermal comfort conditions (for a given metabolic rate and amount of clothing). The following are the most common of these indices still in use.

Dry- and Wet-Bulb Temperatures

The simplest practical index of cold and warmth is the reading obtained with an ordinary dry-bulb thermometer. This long-established gauge is fairly effective in judging comfort for average humidity (40 to 60 percent RH), especially in cold conditions.

In the heat, when humidity greatly affects the efficiency of body temperature regulation by sweating, the significance

TABLE 1.4 SUBJECTIVE RESPONSE TO AIR MOTION

Air Velocity		
fpm	m/s	Occupant Reaction
0 to 10	0 to 0.05	Complaints about stagnation
10 to 50	0.05 to 0.25	Generally favorable (air outlet devices normally designed for 50 fpm in the occupied zone)
50 to 100	0.25 to 0.51	Awareness of air motion, but may be comfortable, depending on moving air temperature and room conditions
100 to 200	0.51 to 1.02	Constant awareness of air motion, but can be acceptable (e.g., in some factories) if air supply is intermittent and if moving air temperature and room conditions are acceptable
200 (about 2 mph) and above	1.02 and above	Complaints about blowing of papers and hair, and other annoyances

of the dry-bulb temperature is limited. The wet-bulb temperature represents an improvement over the simple dry-bulb temperature by taking humidity into account.

Globe Thermometer Temperature

The *globe thermometer temperature* combines the effects of radiation and air movement. It uses a 6-inch (150-mm)-diameter black globe. The equilibrium temperature of the globe is a single temperature index describing the combined physical effect of dry-bulb temperature, air movement, and net radiant heat received from the surrounding surfaces.

The globe temperature is an approximate measure of operative temperature. It is usually used as a simple device for determining MRT.

Operative Temperature

Operative temperature is the uniform temperature of an imaginary enclosure in which the occupant would exchange the same heat by radiation and convection as in the actual environment. An alternative definition of operative temperature is an average of MRT and dry-bulb temperatures weighted by the respective radiation and convection heat transfer coefficients.

Humid operative temperature is the uniform temperature of an imaginary environment at 100 percent RH with which the occupant would exchange the same heat by radiation, convection, conductance through clothing, and evaporation as in the actual environment.

New Effective Temperature

Effective temperature is not an actual temperature in the sense that it can be measured by a thermometer. It is an experimentally determined index of the various combinations of dry-bulb temperature, humidity, radiant conditions, and air movement that induce the same thermal sensation. Those combinations that induce the same feeling of warmth or cold are called thermo-equivalent conditions.

The *new effective temperature* (*ET**) of a given space is defined as the dry-bulb temperature of a thermo-equivalent environment at 50 percent RH and a specific uniform radiation condition. The thermo-equivalent heat exchange is based on clothing at 0.6 clo, still air (40 fpm = 0.2 m/s or less), 1-hour exposure time, and a sedentary activity level (approximately 1 met). Thus, any space has an ET* of 70°F (21°C) when it induces a sensation of warmth like that experienced in still air at 70°F (21°C), 50 percent RH, and the proper radiant conditions.

ET* is, in general, a reliable indicator of discomfort or dissatisfaction with the thermal environment. If ET* could be envisioned as a thermometer scale, it would appear as in Figure 1.11.

The Comfort Chart

The comfort chart, shown in Figure 1.12, correlates the perception of comfort with the various environmental factors known to influence it. The dry-bulb temperature is indicated along the bottom. The right side of the chart contains a dew-point scale, and the left side a wet-bulb temperature scale indicating guide marks for imaginary lines sloping diagonally down from left to right. The lines curving upward from left to right represent RHs.

ET* lines are also drawn. These are the sloping dashed lines that cross the RH lines and are labeled in increments of 5°F. At any point along any one of these lines, an individual will experience the same thermal sensation and will have the same amount of skin wetness due to regulatory sweating. Clo levels at which 94 percent of occupants will find acceptable comfort are also indicated.

Notice that the comfort chart in Figure 1.12 is derived from what is called the psychrometric chart. A description of the psychrometric chart and its importance is addressed in Chapter 2.

Two *comfort envelopes* or zones are defined by the shaded regions on the comfort chart—one for winter and one for summer. The thermal conditions within these envelopes are estimated to be acceptable to 80 percent of the occupants when wearing the clothing ensemble indicated. To satisfy 90 percent of the people, the limits of the acceptable comfort zone are sharply reduced to one-third of the above ranges. The zones overlap in the 73° to 75°F (23° to 24°C) range. In this region, people in summer dress tend to be slightly cool, while those in winter clothing feel a slightly warm sensation.

Figure 1.12 generally applies when altitudes range from sea level to 7,000 feet (2,134 m), MRT is nearly equal to dry-bulb air temperature, and air velocity is less than 40 fpm (0.2 m/s). Under these conditions, thermal comfort can be defined in terms of two variables: dry-bulb air temperature and humidity.

Mean radiant temperature is actually just as important as air temperature in affecting comfort. When air movement in an indoor environment is low, the operative temperature is approximately the average of air temperature and MRT. When the MRT in the occupied zone significantly differs from the air temperature, the operative temperature should be substituted for the dry-bulb temperature scale along the bottom of Figure 1.12.

The comfort chart is primarily useful for occupants with

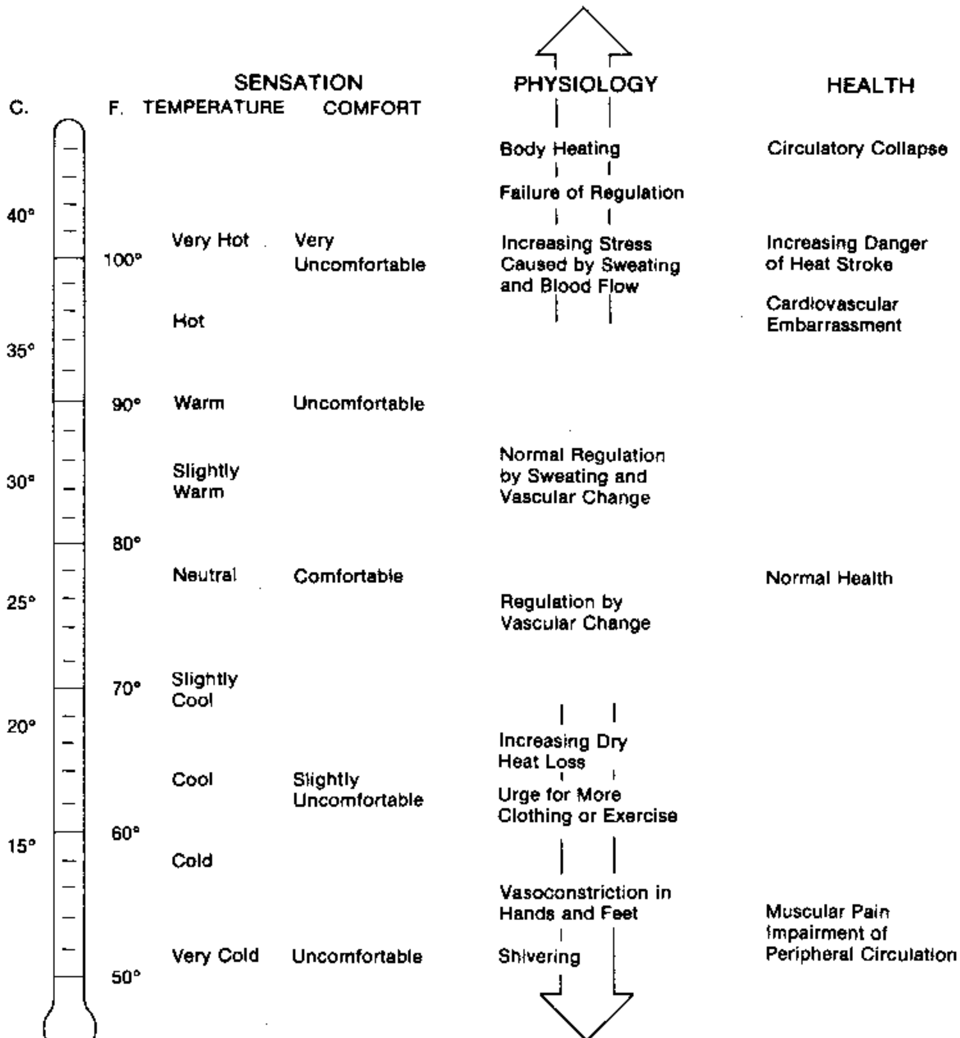

FIGURE 1.11. The ET* scale correlated to physiological reactions, comfort, and health.

a minimum of 1 hour of exposure, 0.6 clo (standard shirt-sleeve indoor office clothing), and a 1-met (seated or sedentary) activity level. It is secondarily useful at higher temperatures to identify when there is a risk of sedentary heat stress. Although the ET* scale is based on 1-hour exposure, data show no significant changes in response with longer exposures unless the limits of heat stress—ET* greater than 90°F (32°C)—are approached. As the ET* lines show, humidity between about 20 and 55 percent RH has only a small effect on thermal comfort. Its effect on discomfort increases with both temperature and the degree of regulatory sweating. Evaporative heat loss near the comfort range is only about 25 percent of the total heat loss. As the temperature increases, this percentage grows until the ambient temperature equals skin (and clothes) temperature, at which point evaporation accounts for 100 percent of the heat loss.

The upper and lower humidity limits on the comfort envelope of Figure 1.12 are based on considerations of respiratory health, mold growth, and other moisture-related phenomena in addition to comfort. Humidification in winter must be limited at times to prevent condensation on cold building surfaces such as windows.

The environmental parameters of temperature, radiation,

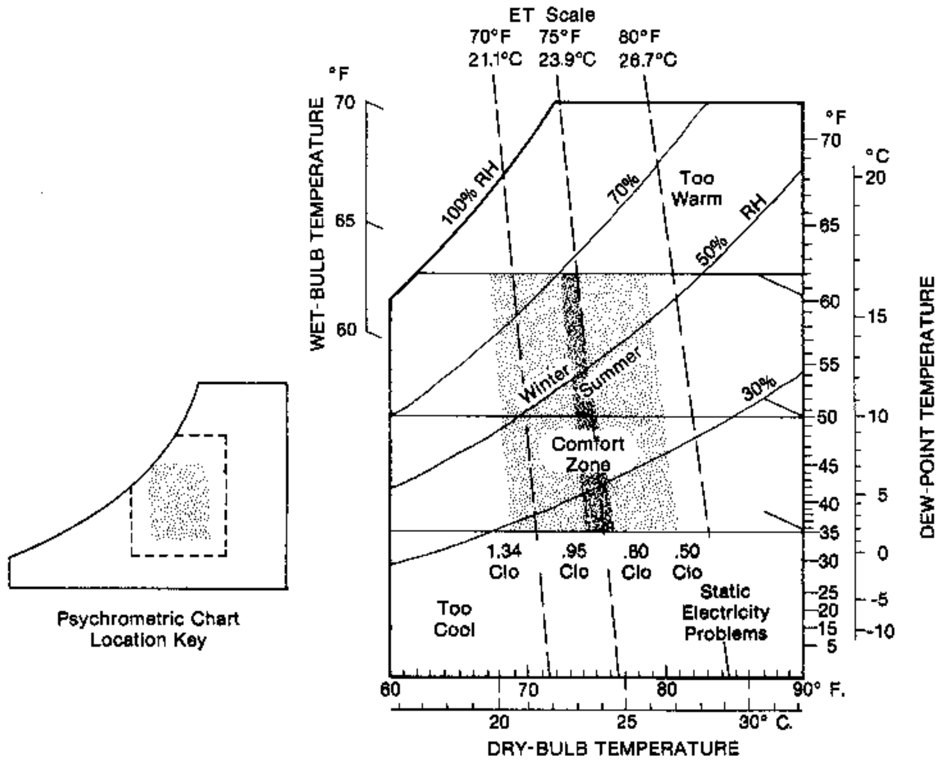

FIGURE 1.12. The comfort chart.

humidity, and air movement necessary for thermal comfort depend upon the occupant's clothing and activity level. The comfort chart was developed from ASHRAE research, which has usually been limited to lightly clothed occupants (0.5 to 0.6 clo) engaged in sedentary activities. The reasoning behind this approach is that 90 percent of people's indoor work and leisure time is spent at or near the sedentary activity level. In line with this rationale, the comfort envelope defined in Figure 1.12 strictly applies only to sedentary and slightly active, normally clothed persons at low air velocities, when the MRT is equal to air temperature. For other conditions, the comfort zone must be adjusted accordingly.

For example, comfort can be maintained at temperatures as low as 68°F (20°C) for an individual wearing a clothing ensemble measuring less than 1.34 clo if he or she gets up and moves around for at least 10 minutes out of every half hour. On the other end of the scale, comfort conditions may be extended upward to 82°F (28°C) with a fan-induced air velocity of 160 fpm (0.8 m/s).

Within the comfort envelope of Figure 1.12, there is no minimum air movement necessary for thermal comfort. However, the maximum allowable air motion is lower in the winter than in the summer. In the wintertime, the average air movement within the occupied zone should not exceed 30 fpm (0.15 m/s). If the temperature is less than the optimum or neutral sensation temperature, slight increases in air velocity or irregularity of air movement can cause uncomfortable localized drafts. While possibly of little consequence in an active factory, this can create significant problems in professional buildings, religious buildings, and other places where people are seated and wearing light indoor clothing.

In the summer, the average air movement in the occupied zone can go as high as 50 fpm (0.25 m/s) under standard temperature and humidity conditions. Above 79°F (26°C), comfort can be maintained by increasing the average air motion 30 fpm for each °F (0.275 m/s for each °C) of increased temperature up to a maximum of 160 fpm (0.8 m/s). At that point, loose paper, hair, and other light objects start blowing around.

As average steady-state activity increases above the sedentary or slightly active (1.2-met) levels, sweating increases. To maintain comfort, clothing must be adjusted as indicated in Table 1.5, the air motion must be increased, or the operative temperature must be decreased.

The development of reliable thermal comfort indices has

TABLE 1.5 CLOTHING ADJUSTMENTS FOR DIFFERENT ACTIVITY LEVELS

Activity Level (met)	Adjusted Clothing Level[a] (clo)
1	0.6
2	0.4
3	0.3

[a] These clothing adjustments will permit the comfort chart (Figure 1.12) to remain valid for the given activity level.

been very important for the effective control of the thermal environment using no more energy and equipment than is necessary. The five variables affecting comfort for a given activity or room function are dry-bulb temperature, humidity, MRT, air movement, and clothing. Sometimes when one of these conditions is out of the comfort range, adjusting one or more of the other conditions will restore comfort with the addition of little or no additional energy.

The most commonly recommended design conditions for comfort are:

ET* = 75°F (24°C)
Dry-bulb air temperature = MRT
Relative humidity = 40% (20 to 60% range)
Air velocity less than 40 fpm (0.2 m/s)

ASHRAE's Thermal Comfort Standard

ASHRAE's Standard 55, *Thermal Environmental Conditions for Human Occupancy,* describes the combinations of indoor space conditions and personal factors necessary to provide comfort. It addresses the interactions between temperature, thermal radiation, humidity, air speed, personal activity level, and clothing.

The standard recommends conditions that have been found experimentally to be acceptable to at least 80 percent of the occupants within a space. The operative temperature range for building occupants in typical winter clothing (0.8 to 1.2 clo) is specified as 68° to 74°F (20° to 23.5°C). The preferred temperature range for occupants dressed in summer clothes (0.35 to 0.6 clo) is 73° to 79°F (22.5° to 26°C).

These values are based on 60 percent RH, an activity level of approximately 1.2 met, and an air speed low enough to avoid drafts. The standard includes a chart that relates the allowable air speed to room air temperature and the turbulence of the air. For each 0.1 clo of increased clothing insulation, the acceptable temperature range is lowered by 1°F (0.6°C). However, as the temperature decreases, comfort depends more and more on maintaining a uniform distribution of clothing insulation over the entire body, especially the hands and feet. For sedentary occupancy of more than an hour, the operative temperature should not drop below 65°F (18°C).

Design Considerations

The comfort chart is useful for determining design conditions to be met by a building envelope and its *heating, ventilation, and air conditioning* (HVAC) equipment. But considerable judgment must still be exercised if this chart is to be employed as a guide. For example, noticeably uneven radiation from hot and cold surfaces, temperature stratification in the air, a wide disparity between air temperature and MRT, a chilly draft, contact with a warm or cool floor, and other factors can cause local discomfort and reduce the thermal acceptability level of the space. Although a person may feel thermally neutral in general—preferring neither a warmer nor a cooler environment—thermal discomfort may exist if one part of the body is warm and another is cold.

This relates to both the building envelope design and the system for HVAC. A higher air temperature may be necessary to compensate for extensive cold glass areas. Or if large radiant heating panels are contemplated, a lower air temperature might be allowable, since radiant gain to the body will permit greater convective and evaporative losses. Direct sunlight from large windows or skylights *requires* lower room air temperature in order to compensate for the high radiant gain. In order to avoid having to lower the air temperature in the summer, the windows or skylights could be shaded. When radiant surfaces are too cool for comfort, the air temperature must be increased from 0.3° to 1° for every 1° reduction in MRT, depending on room conditions.

Since the comfort chart is the result of observations of healthy, clothed, sedentary subjects, spaces to be conditioned for very active, ill, or nude persons may require considerably different conditions for comfort than those indicated. Table 1.6 suggests some guidelines for winter heating and summer cooling design temperatures in various types of spaces. These should serve as points of departure according to the following discussion. The condition, clothing, and activity level of the occupants, as well as the humidity, MRT, and air motion conditions in the space, must also be taken into consideration.

People engaged in physical work need a lower effective temperature for comfort than do sedentary ones. The greater the activity and the more clothing worn, the lower the effective temperature must be for comfort. Although the latent heat liberated by people engaged in any physical activity

TABLE 1.6 GUIDELINE ROOM AIR TEMPERATURES

Type of Space	°F Summer	°F Winter	°C Summer	°C Winter
Residences, apartments, hotel and motel guest rooms, convalescent homes, offices, conference rooms, classrooms, courtrooms, and hospital patient rooms	74–78	68–72	23–26	20–22
Theaters, auditoriums, churches, chapels, synagogues, assembly halls, lobbies, and lounges	76–80	70–72	24–27	21–22
Restaurants, cafeterias, and bars	72–78	68–70	22–26	20–21
School dining and lunch rooms	75–78	65–70	24–26	18–21
Ballrooms and dance halls	70–72	65–70	21–22	18–21
Retail shops and supermarkets	74–80	65–68	23–27	18–20
Medical operating rooms[a]	68–76	68–76	20–24	20–24
Medical delivery rooms[a]	70–76	70–76	21–24	21–24
Medical recovery rooms and nursery units	75	75	24	24
Medical intensive care rooms[a]	72–78	72–78	22–26	22–26
Special medical care nursery units[a]	75–80	75–80	24–27	24–27
Kitchens and laundries	76–80	65–68	24–27	18–20
Toilet rooms, service rooms, and corridors	80	68	27	20
Bathrooms and shower areas	75–80	70–75	24–27	21–24
Steam baths	110	110	43	43
Warm air baths	120	120	49	49
Gymnasiums and exercise rooms	68–72	55–65	20–22	13–18
Swimming pools	75 or above	75	24	24
Locker rooms	75–80	65–68	24–27	18–20
Children's play rooms	75–78	60–65	24–26	16–18
Factories and industrial shops	80–85	65–68	27–29	18–20
Machinery spaces, foundries, boiler shops, and garages	—	50–60	—	10–16
Industrial paint shops	—	75–80	—	24–27

[a] Variable temperature range required with individual room control.

rises sharply, the liberated sensible heat changes very little. For example, an average man seated at rest in a room at 80°F DB gives off 180 Btuh of sensible heat and 150 Btuh of latent heat, or a total of 330 Btuh (27°C, 53 W, 44 W, and 97 W, respectively). Now, if he engages in light bench work, he will liberate 220 Btuh of sensible heat and 530 Btuh of latent heat (64 W and 155 W). This represents a sensible heat increase of about 20 percent but a latent increase of about 250 percent.

When air temperature is low, convective heat loss increases with air motion associated with increased activity, thereby decreasing the heat load on the body evaporative system and resulting in a wider range of activity before discomfort is felt. The maximum range of activity in which people feel comfortable is therefore achieved by minimizing dry-bulb temperature and RH while compensating with an MRT sufficient to maintain comfort.

Short-term acclimation plays an important part in determining the best conditions for comfort. In summer, the body's heat-controlling mechanisms become adjusted to the higher outdoor temperature, so a period of time is required for their readjustment to the lower temperature and humidity of a conditioned indoor environment. During acclimatization to the cooler interior, the body experiences a greatly lessened rate of perspiration and the blood vessels recede from the skin surface. A conditioned space maintained to be comfortable for longer periods of occupancy may be too cool for a person who has just left the oppressive heat of the outdoors. If one passes quickly to the hot, humid outside conditions again, a greater sensation of discomfort results than was originally experienced outside because perspiration cannot increase immediately and blood vessels do not move quickly to the skin surface to promptly balance the body heat production and loss.

In spaces of short-time occupancy, such as stores or public lobbies, it is best to maintain a relatively warm, dry climate in which the perspiration rate will change only a small amount. A rough guideline is to reduce the inside-to-outside temperature difference at least 5°F (2.8°C) for occupancy times of less than 1 hour. In this way, the body's thermal control system can easily revert to meet the outside condition by increasing moisture loss and heat loss from the blood vessels already at the surface.

Where the periods of occupancy are long, such as in offices, the body becomes accustomed to the conditioned environment, and the comfort chart may be used to establish appropriate conditions. In many commercial facilities, the temperatures and humidities to be maintained must be a compromise between those necessary to ensure the comfort of employees and those necessary to avoid too great a contrast between indoor and outdoor temperatures for the customers.

Even though restaurants can be classified as short-occupancy environments, the digestion of food increases the metabolic rate, requiring cooler temperatures and/or humidities. In some air-conditioned factories, half-hour lunch periods, lunch rooms, and cafeteria service discourage employees from leaving the air-conditioned building, thus avoiding the need for physiological readjustment.

The economical selection and operation of HVAC equipment require that indoor design conditions involve the smallest change possible from the outside environment while maintaining comfort. In winter, the problem is usually one of raising air temperature and humidity. In summer, the reverse problem exists: Cooling and dehumidification must be accomplished, and the smallest change that can be accommodated in terms of comfort should be sought. Therefore, in winter, conditions near the lower left-hand corner of the comfort zone should be selected, while in summer those near the upper right-hand corner should be chosen.

Other distinctions between winter and summer that must be taken into consideration in selecting design conditions are:

- The MRT of perimeter and top-floor spaces are lower in winter than in summer due to the influence of outdoor air conditions on the building shell.
- Conventions of clothing insulation are different in winter and summer.
- Expectations (psychological and physiological acclimatization) of indoor thermal conditions vary according to season.

Individual Variability

Thermal comfort standards (ASHRAE or any other) usually give a particular value or range of conditions for general application and make no provision for individual differences. However, there are no conditions that will provide comfort for all people. Under the same conditions of temperature and humidity, a healthy young man may be slightly warm, while an elderly woman may be cool. A pedestrian stepping into an air-conditioned store experiences a welcome sense of relief from the blazing summer heat, while the active clerk who has been in the store for several hours may be a bit too warm for comfort. Dancers out on the dance floor may feel quite warm, while their friends seated at a nearby table are comfortable or even slightly cool.

Men generally feel warmer than women on initial exposure to a given temperature but later feel cooler, approaching women's thermal sensations after 1 to 2 hours in the environment. Elderly subjects exposed to conditions of the comfort envelope seem to have responses nearly identical to those of college-age subjects.

Comfort conditions seem independent of the time of day or night. Workers prefer the same thermal environment during a night shift as during the day. Individuals are normally consistent in their thermal preference from day to day, but preferences differ considerably between individuals.

Different countries may have different comfort standards as a result of particular climate extremes and of the relative economics of providing and running heating and cooling systems. And different clothing customs can also be a dominant factor. Even within a country, different conventions of dress for men and women or style preferences among individuals can lead to greatly different comfort requirements.

While different countries have different standards, and geographical location may account for a spread of a few degrees in the most desirable ET*, variations in sensation among individuals within a particular environment tend to be greater than variations due to a difference in geographical location. Apart from general categorical differences, individuals vary greatly in their physiological reaction to their thermal environment. Under the same thermal conditions, some individuals may feel too hot, while others wearing identical clothing feel too cold.

The psychology of *expectancy*—the level of comfort occupants are accustomed to—plays an important part in attitudes towards ambient conditions. People are also sensitive to different aspects of their environment. Moreover, people who believe they are uncomfortable are just as uncomfortable as they would be were they physiologically uncomfortable.

There is no one set of conditions that will satisfy all occupants. Each person has a distinct perception of too hot, too cold, and comfortable. The objective in designing a common thermal environment is to satisfy a majority of occupants and to minimize the number of people who will inevitably be dissatisfied.

TEMPERATURE AND HUMIDITY EXTREMES

As conditions become warmer or colder than the comfort zone, thermal sensations gradually increase and are accompanied by increasing discomfort and strains on the cardiovascular system, respiratory system, and other internal systems involved in bodily thermal regulation. When the thermal exposure is sufficiently intense, pain occurs in conjunction with failure of the body's thermal regulation capability, which can eventually lead to death.

Figure 1.11 relates the various human responses of temperature sensation, comfort, health, and physiology for sedentary subjects over a wide range of thermal conditions represented by the ET* scale. The physiological consequences signify that regulation of the thermal environment is more important than just for providing comfort; there are serious health purposes, too. At the high end of the scale, there is heat stress to contend with and, in extremely cold conditions, a variety of respiratory ailments, incapacity, and heart failure.

Heat Stress

Heat stress occurs when one gains heat faster than one can lose it. When this condition persists without relief, there is the danger that workers, such as those in hot industries, can experience heat prostration.

A person's tolerance to high temperature may be limited if he or she cannot (1) sense temperature, (2) lose heat by regulatory sweating, and (3) move heat by blood flow from the body core to the skin surface where cooling can occur.

Pain receptors in the skin are normally triggered by a skin surface temperature of 115°F (46°C). Although direct contact with a metal surface at this temperature is painful, much higher dry air temperatures can be tolerated since the layer of air at the skin surface provides some thermal insulation. Tolerance times for lightly clothed men at rest in environments with dew points lower than 85°F (30°C) are listed in Table 1.7.

Many individuals find exposure to dry air at 180°F (85°C) for brief periods in a Finnish sauna bath stimulating. Cooling by evaporation of sweat makes short exposures to such extremely hot environments tolerable. However, temperatures of 122°F (50°C) may well be intolerable when the dew-point temperature is greater than 77°F (25°C).

TABLE 1.7 HIGH AMBIENT TEMPERATURE TOLERANCE TIMES

Air DB Temperature	Tolerance Time
180°F (82°C)	almost 50 minutes
200°F (93°C)	33 minutes
220°F (104°C)	26 minutes
239°F (115°C)	24 minutes

Source: Data from ASHRAE *Handbook of Fundamentals 1989.*

The tolerance limit actually represents the body heat-storage limit. The voluntary tolerance limit for an average-sized man is about 2.5°F (1.4°C). Individuals who remain in the heat and continue to work beyond this point increase their risk of heat exhaustion. Collapse can occur at a 5°F (2.8°C) rise in internal body temperature.

The tolerance limit to extreme heat is also affected by the cardiovascular system. In a normal, healthy subject, heart rate and cardiac output increase in response to a hot environment in an attempt to maintain blood pressure and supply blood to the brain. At a heart rate as high as 180 beats per minute, there may not be enough time between contractions to fill the chambers of the heart as completely as required. As the heart rate increases further, cardiac output may drop lower, providing an insufficient amount of blood to the skin for heat loss and, perhaps more importantly, an inadequate blood supply to the brain as less blood is pumped. At some point, the individual will faint or black out from heat exhaustion.

An accelerated heart rate may also result from inadequate blood return to the heart caused by the accumulation of blood in the skin and lower extremities. In this case, cardiac output is limited because not enough blood returns to fill the heart between beats. This frequently occurs when an overheated individual, having worked hard in the heat, suddenly stops working. The muscles suddenly are no longer massaging the blood past the valves in the veins back toward the heart. Dehydration from sweating compounds the problem by reducing the fluid volume in the vascular system.

If the body core temperature goes too high—above 106°F (41°C)—proteins in the delicate nerve tissues in the hypothalmus of the brain, which helps regulate body temperature, may be damaged. Inappropriate vascular constriction, cessation of sweating, increased heat production by shivering, or some combination of these may result. Such *heat stroke* damage is frequently irreversible and carries a high risk of fatality.

A final problem is hyperventilation, or overbreathing, which occurs predominantly in hot-humid conditions. This exhaling of more carbon dioxide from the blood than is desirable can lead to tingling sensations and skin numbness, possibly resulting in vascular constriction in the brain with occasional loss of consciousness.

The Heat Stress Index (HSI) was developed to provide an indication of the severity of the ambient environment on workers. It consists of a ratio of the evaporative heat loss required to maintain thermal equilibrium (E_{req}) divided by the maximum possible evaporation rate in the given environment (E_{max}). When HSI is greater than 100, body heating occurs; when it is less than 0 (negative), body cooling occurs.

The upper limit reported for E_{max} is

$$6 \text{ mets} = 110 \text{ Btuh/ft}^2 = 350 \text{ W/m}^2.$$

For an average-sized man, this corresponds to

$$2{,}388 \text{ Btuh} = 700 \text{ W} = 602 \text{ kcal/hr},$$

or approximately 17 g/min of sweating.

The physiological and health implications associated with HSI values are described in Table 1.8. HSI serves as a reliable reference for planning worker environments in hot industries. Graphic correlations between dry-bulb temperature, humidity, MRT, air movement, and HSI are available for this purpose.

Response to Extreme Cold

The effect of exposure to extreme cold depends on the maintenance of the thermal balance. People exposed to cold can lose heat faster than they produce it for only a limited time. Such a “heat debt” results in a drop in body temperature, which is sensed as “acutely uncomfortable” when it reaches 4.7°F (2.6°C). An adequate level of clothing insulation for any given cold environment reduces body heat losses enough to maintain the thermal balance. The extent to which clothing adjustment is practical is dictated by clothing customs and the limits of restricted mobility for the intended activity.

When vascular constriction is unable to prevent body heat loss, a second, automatic, more efficient defense against cold is shivering. It may be triggered by low deep-body temperature, low skin temperature, rapid change of skin temperature, or some combination of all three. Shivering is usually preceded by an imperceptible increase in muscle tension and by noticeable “goose bumps” produced by muscle contraction in the skin. It begins slowly in small muscle groups, and

TABLE 1.8 PHYSIOLOGICAL AND HEALTH IMPLICATIONS OF 8-HR EXPOSURES TO VARIOUS HEAT STRESSES

Heat Stress Index	Effect on Male Subjects
−20	
−10	Mild cold strain.
0	No thermal strain.
+10 20 30	Mild to moderate heat strain. Where a job involves higher intellectual functions, dexterity, or alertness, subtle to substantial decrements in performance may be expected. Little decrement in performing heavy physical work.
40 50 60	Severe heat strain involving a threat to health unless subject is physically fit. Break-in period required for men not previously acclimatized. Some decrement in performance of physical work is to be expected. Medical selection of personnel is desirable because these conditions are unsuitable for people with cardiovascular or respiratory impairment, or with chronic dermatitis. These working conditions are also unsuitable for activities requiring sustained mental efforts.
70 80 90	Very severe heat strain. Only a small percentage of the population may be expected to qualify for this work. Personnel should be selected: (a) by medical examination, and (b) by trial on the job (after acclimatization). Special measures are needed to ensure adequate water and salt intake. Amelioration of working conditions by any feasible means is highly desirable, and may be expected to decrease the health hazard while increasing job efficiency. Slight “indispositions,” which in most jobs would be insufficient to affect performance, may render workers unfit for this exposure.
100	The maximum strain tolerated daily by fit, acclimatized young men.

Source: John Blankenbaker, “Ventilating Systems for Hot Industries,” *Heating/Piping/Air Conditioning,* Vol. 54, No. 2, February 1982, p. 58. (Reproduced from the original: H.S. Belding and T.F. Hatch, “Index for Evaluating Heat Stress in Terms of Resulting Physiological Strains,” *Heating/Piping/Air Conditioning,* August 1955, pp. 129–136.) Used by permission of Reinhold Publishing, a Division of Penton/IPC.

may initially increase total heat production 50 to 100 percent from resting levels. As body cooling increases, additional body segments are involved. Ultimately, violent whole-body shivering may result in a maximum heat production of about six times resting levels, rendering the individual totally ineffective.

There are two means at our disposal for adapting to cold: accustomization and acclimatization. Accustomizing is learning how to survive in cold environments. Acclimatizing is a physiological process in response to long exposure to cold. The physiological changes involve (1) hormonal changes that cause the metabolism of free fatty acids released from fat tissue, (2) maintaining circulatory heat flow to the skin, resulting in a greater sensation of comfort, and (3) improved regulation of heat to the extremities, reducing the risk of cold injury. These physiological changes are generally small and are induced only by repeated uncomfortable exposures to cold. Nonphysiological factors, such as the selection of adequate protective clothing, are generally more useful than dependence on these physiological changes.

Proper protection against low temperatures may be attained either by maintaining high metabolic heat production through activity, or by reducing heat loss with clothing or some other means of controlling the body's microclimate. Spot radiant heat, an "envelope" of hot air for work at a fixed location, or heated clothing are all practical possibilities. The extremities, such as fingers and toes, pose more of a problem than the torso, because, as thin cylinders, they lose heat much more rapidly and, especially in the case of fingers, are difficult to insulate without hampering mobility. Vascular constriction reduces circulatory heat input to extremities by over 90 percent.

As far as insulating material for protective clothing is concerned, radiation-reflective materials can be quite effective, especially if they seal the body from cold air currents at the same time. Otherwise, insulation is primarily a function of clothing thickness. The greater the fiber thickness, the greater the thickness of the insulating trapped air.

AIR QUALITY AND QUANTITY

Besides the thermal conditions of an environment, comfort and health also depend on the composition of the air itself. For example, people feel uncomfortable when the air is odorous or stale.

The quality of air in a space can even seriously affect its ability to support life. Under heavy occupancy of a space, the concentration of carbon dioxide can rise to deleterious levels. In addition, excessive accumulations of some air contaminants become hazardous to both plants and animals.

Air Contaminants

Air normally contains both oxygen and small amounts of carbon dioxide (0.03 percent), along with varying amounts of particulate materials referred to as *permanent atmospheric impurities.* These materials arise from such natural processes as wind erosion, evaporation of sea spray, and volcanic eruption. The concentrations of these materials in the air vary considerably but are usually below the concentrations caused by human activity.

Air composition can change drastically. In sewers, sewage treatment plants, tunnels, and mines, the oxygen content of air may become so low that it cannot support human life. Concentrations of people in confined spaces, such as theaters, require the removal of carbon dioxide given off by respiration and replacement with oxygen.

At atmospheric pressure, oxygen concentrations of less than 12 percent or carbon dioxide concentrations greater than 5 percent are dangerous even for short periods. Smaller deviations from normal concentrations can be hazardous under prolonged exposures.

Artificial contaminants are numerous, originating from a variety of human activities. Contaminants in the indoor environment, of which tobacco is a prime example, are of particular concern to building designers.

Air contaminants can be particulate or gaseous, organic or inorganic, visible or invisible, toxic or harmless. Loose classifications are (1) dust, fumes, and smoke, which are chiefly *solid* particulates (although smoke often contains liquid particles); (2) mist and fog, which are *liquid* particulates; and (3) vapors and gases, which are *nonparticulates.*

Dust consists of solid particles projected into the air by natural forces such as wind, volcanic eruption, or earthquakes, or by human activities. *Fumes* are solid airborne particles usually 100 times smaller than dust particles, commonly formed by condensation of vapors of normally solid materials. Fumes that are permitted to age tend to agglomerate into larger clusters. *Smoke* is made up of solid or liquid particles about the same size as fumes, produced by the incomplete combustion of organic substances such as tobacco, wood, coal, and oil. This class also encompasses *airborne living organisms* which range in size from submicroscopic viruses to the larger pollen grains. Included are bacteria and fungus spores, but not the smallest insects.

Mist is defined as very small airborne droplets of a liquid that are formed by atomizing, spraying, mixing, violent chemical reactions, evaporation, or escape of a dissolved gas when pressure is released. Sneezing expels or atomizes very small droplets containing microorganisms that become air contaminants. *Fog* is very fine airborne droplets usually formed by condensation of vapor. Fogs are composed of droplets that are smaller than those in mists, but the distinction is insignificant, and both terms are commonly used to indicate the same condition.

Tobacco Smoke

Tobacco smoke is the most common indoor pollutant. A growing percentage of the public is finding it extremely objectionable. Smokers and nonsmokers are segregated in public restaurants, on airplanes, and on many other modes of public transportation. But isolation of the smoker does not solve the problem as long as the nonsmoker breathes the same air circulated by a common air handling system. It only results in better dilution.

Tobacco smoke is an extremely complex mixture of combustion products that consist of particulate matter (visible smoke) and gaseous contaminants. The gas constituents of tobacco smoke include nitrogen dioxide, formaldehyde, hydrogen sulfide, hydrogen cyanide, ammonia, and nicotine. All of these gases are irritants, carcinogens, or toxic substances in sufficient concentration. These gases combine to form the "odor" portion of tobacco smoke and can be extremely noxious at high concentrations. The particulate component of tobacco smoke contains tens of trillions of fine particles of tar and nicotine per cigarette.

Formaldehyde

Formaldehyde, a colorless, strong-smelling gas, is used in the manufacture of synthetic resins and dyes, and as a preservative and disinfectant. Carpeting and panelboard in newly constructed or renovated buildings may give off small quantities of formaldehyde gas for many years.

At full strength, formaldehyde gas is lethal. In buildings, it can reach concentrations that may cause irritation, discomfort, and with long exposure, more severe effects.

Aeroallergens

Hay fever, asthma, eczema, and contact dermatitis are allergic disorders. An allergic person has an altered capacity to react to substances such as foods, dust, pollens, bacteria, fungi, medicines, and other chemicals, and exposure to them may result in adverse symptoms. But environmental conditions such as dust, irritating gases, or changes of temperature and humidity can precipitate asthmatic attacks in allergic individuals, even without exposure to specific allergens.

Fortunately, pollen grains discharged by weeds, grasses, and trees, which are responsible for hay fever, are even larger than ordinary dust particles and can be readily filtered out of the air. Most grains are hygroscopic, varying in size and weight with the humidity.

Airborne Microorganisms

Bacteria and other airborne microorganisms can cause infections and diseases in humans. Yeasts and molds in the air can contaminate many food products and can cause expensive damage in the food industry. Microorganisms often become airborne by attaching themselves to dust particles which are then suspended in the air by nearby activity.

The most successful methods of controlling airborne microorganisms are *dust control, air sterilization,* and carefully designed *ventilation.* In critical areas such as operating rooms, special down-draft ventilation is employed. Air sterilization by in-duct radiation with ultraviolet light is sometimes used in premature nurseries or laboratories but is difficult to maintain. In general, wherever the risk of airborne infection is high, such as medical-treatment and research areas, air movement must be designed so as to avoid moving potentially infected air into uninfected areas. This is accomplished by using outdoor air, avoiding air movement from one room to another, and special cleaning of recirculated air.

Radioactive Air Contaminants

Radioactive contaminants may be particulate or gaseous and are physically similar to any other air contaminants. Many radioactive materials would be chemically toxic if present in high concentrations, but it is their radioactivity that generally necessitates limiting their concentration in the air.

A distinction should be made between radioactive materials and the radiation emitted from them. Radioactive particulates and gases can be removed from the air by filters and other devices, whereas the gamma radiation from such material is able to penetrate solid walls. The hazardous effects of most radioactive air contaminants occur when they are taken into and retained inside the body.

Special problems make radioactive materials distinctive among contaminants. For example, radon and other radioactive gases may decay, producing radioactive particulates; in some materials the opposite occurs. The contaminants may generate enough heat to damage filtration equipment, or they may spontaneously ignite. The concentrations at which most radioactive materials are hazardous are far lower than those of other materials, so special electronic instruments must be used to detect them.

For sensitive industrial plants, such as those in the photographic industry, contaminants must be prevented from entering the plant. If radioactive materials are handled inside a plant, the contaminant should be removed from the air as close to the source as possible before the air is released outdoors. Where X-ray and radiation therapy equipment is used, the room itself and the air ducts to and from the room must be lined with lead to contain the radiation.

Odors

Odors are important in the enjoyment of food, in the attraction of one person to another, and in a person's evaluation of whether the surroundings are clean and well maintained. Malodors may signal poor maintenance, if not actually unsafe conditions, such as spoiled food or the presence of natural gas or other toxic substances.

Any given odor is not always desirable. What is pleasant in one context may be objectionable in another; what appeals to one person may nauseate another. Although one odor may seem inherently more pleasant than another, all odors become unpleasant at high levels of perceived intensity. Odor control must therefore be directed at the general attenuation of odor levels.

Our olfactory sensitivity often makes it possible to detect and thus eliminate potentially harmful substances at concentrations below dangerous levels. While foul-smelling air is not necessarily unhealthy, the sheer unpleasantness of an odor can initiate symptoms such as nausea, headache, and loss of appetite, even if the air is not toxic. In such cases, the stronger the odor, the more intense the symptoms. Even a mild but recognizable odor may arouse uneasiness among a room's occupants.

Discomfort in occupied areas may result from the intake of outdoor air containing automobile exhaust, furnace effluents, industrial effluents, or smog. Industrial spaces may have odors from chemical products, such as printing ink, dyes, and synthetics, as well as from manufactured products. Offices, assembly rooms, and other enclosed, densely occupied spaces can contain objectionable body odors and tobacco smoke. Smoking produces a large variety of odorous compounds and irritants, and it also impairs visibility. Odors can result from wetted air-conditioning coils or certain metals and coatings used on the coils. Odors may be caused by linoleum, paint, upholstery, rugs, drapes, or other room furnishings. Food, cooking, and decomposition of animal and vegetable matter are also frequent sources.

Spaces frequently retain occupancy odors from people long after occupancy has ceased, since odors accumulate on the furnishings during occupancy and are later released to the space. Cotton, wool, rayon, and fir wood have each been found to have odor-absorbing capabilities, and each gives off odors at a varying rate, depending on temperature and RH. Odors emanating from these sources can be decreased by lowering temperature and RH. Where the odor sources are the materials themselves, as in the case of linoleum, paint, rubber, and upholstery, a reduction in RH decreases the rate of odor release.

Odor *perception* is also affected by temperature and humidity, but in the opposite direction. The perception of smoke, cooking, body odors, and many other vapors decreases as humidity *increases.* This effect is more pronounced for some odorants than for others. An increase in temperature slightly reduces some odors, such as cigarette smoke.

Adaptation to odors takes place rapidly during the initial stages of exposure. While the perceptible odor level of cigarette smoke decreases with exposure time, irritation to the eyes and nose generally increases. The irritation is greatest at low RH. In order to keep odor perception and irritation at a minimum, the optimum RH for a conditioned space is 45 to 60 percent.

When the concentration of an odorous vapor is so low as to be imperceptible, the air is said to be *odor-free.* Therefore, to abate an odor condition, it is necessary to (1) remove the offending gases or vapors or adequately reduce their concentration below perceptible limits, or (2) interfere with the perception of the odor.

Odor may be removed from the air by physical or chemical means. The available methods include ventilation with clean outdoor air; air washing or scrubbing; adsorption by activated charcoal or other materials; chemical reaction; odor modification; oxidation; and combustion. Equipment is available to accomplish any of these methods.

Ventilation is the exhausting of space air containing objectionable gaseous odors, irritants, particulates that obscure vision, and toxic matter and replacing this air with clean outdoor air. Except in mild climates, introducing outdoor air adds substantially to heating and cooling needs, so it is desirable to minimize such ventilation. Moreover, increasing air pollution has reduced outdoor air quality below the minimum acceptable limits in some areas, and thus the outdoor air cannot be used directly for ventilation.

Adsorption is the physical attaching of a gas or vapor onto an activated solid substrate. While *ab*sorption can be visualized as the action of a sponge, *ad*sorption is more like the action of a magnet upon iron filings.

Theoretically, odors can be eliminated by oxidation. However, while oxidizing gases such as ozone and chlorine can neutralize odors in water, the concentrations of these gases required for air deodorization would be so high that they would be toxic to human occupants. The primary effect of ozone generators as used for deodorizing is to reduce the sensitivity of the occupants' sense of smell rather than reduce the actual odor concentration.

An alternative to removal or destruction of objectionable odorants is to introduce other chemicals that will (1) modify the perceived odor quality to make it more acceptable or (2) reduce the perceived malodor intensity to an acceptable level. The first alternative is known as *odor masking;* the second is called *counteraction.* A mixture of odorants—malodorant and "counteracting agent"—will generally smell less intense than the sum of the intensities of the unmixed components. Given the correct proportions, the mixture may, in fact, smell less intense than the malodorant alone. This is the objective of counteraction.

General guidelines on the use of counteractants are:

1. They should not be used as a substitute for ventilation.
2. They usually work best against weak malodors and should be used only after ventilation or some other procedure has reduced the malodor to a low level.
3. They are usually quite odorous themselves, and are formulated to mask as well as to counteract.
4. Since quality masking is one of their functions, the perceived quality of the counteractant should be chosen with care.
5. The counteractant should not be permitted to mask or otherwise interfere with warning odors, such as the odor of leaking natural gas.

Ventilation

The concentration of indoor air contaminants and odors can be maintained below levels known to impair health or cause discomfort, by the controlled introduction of fresh air to exchange with room air. This is known as ventilation.

Humans require fresh air for an adequate supply of oxygen, which is necessary for metabolism of food to sustain life. Carbon and hydrogen in foods are oxidized to carbon dioxide and water, which are eliminated by the body as waste products. The rate at which oxygen is consumed and carbon dioxide generated depends on physical activity, and the ratio of carbohydrates, fats, and protein eaten.

It was once thought that the carbon dioxide content of the air from respiration was responsible for the condition of stale air experienced in places of concentrated occupancy. Actually, the sense of staleness is primarily a result of the buildup of heat, moisture, and unpleasant odors given off by the body.

While high carbon dioxide levels are responsible for headaches and loss of judgment, acute discomfort from odors, and health problems from other sources of air contamination usually occurs long before the carbon dioxide concentration rises that high. The generally accepted safe limit is a 0.5 percent concentration for healthy, sedentary occupants eating a normal diet. This corresponds to 2.25 CFM (cubic feet per minute) of outdoor air per person where the outdoor air contains a normal proportion of carbon dioxide.

To allow for individual variations in health, eating habits, and activity level, and the presence of other air contaminants, with a margin of safety, ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality,* specifies a minimum of 15 CFM (8 L/s) of outdoor air per person.

Every building, without exception, contains one or more of the following contaminants: asbestos, benzene, carbon monoxide, chlordane, formaldehyde, lead, mercury, nitrogen dioxide, ozone, particulates, radon, and sulfur dioxide. For example, carpeting, draperies, upholstery fabrics, some insulation products, shelving, particle board, and laminated woods are manufactured in part from formaldehyde-based materials. Formaldehyde then outgases from these building materials and other products. Other objectionable and even dangerous contaminants are tobacco smoke and ammonia fumes emitted from blueprint machines. In addition, human occupants naturally generate carbon dioxide, water vapor, particulates, biological aerosols containing infectious and allergenic organisms, and other contaminants.

Outdoor air ventilation requirements for various indoor spaces are summarized in ASHRAE Standard 62.1, and reprinted in Table B6.3 in Appendix B. In most cases, the predominant contamination is presumed to be in proportion to the number of persons in the space, and for these applications, ventilation rates are presented in CFM (L/s) per person. Where ventilating rates are listed as CFM/ft^2 (L/s·m^2), contamination is primarily due to other factors. The table also lists suggested occupant densities for use in determining ventilation rates when the actual number of occupants is not known.

These ventilation rates are believed to provide a generally acceptable level of carbon dioxide, particulates, odors, and other contaminants common to those spaces when the outdoor air is of an acceptable quality. Where human carcinogens or other harmful contaminants are suspected of being present in the occupied space, other relevant standards such as those of the Occupational Safety and Health Administration (OSHA) or the Environmental Protection Agency (EPA) must supersede the rates presented in Table B6.3.

The ventilation rate actually needed to provide satisfactory air quality depends on ventilation effectiveness. Ventilation effectiveness depends on the design, performance, and location of the supply outlet and return inlet. When some of the supply air flows directly to the return inlet without passing through the occupied zone of a room, the effectiveness of the ventilation is reduced. When outdoor air passes through the system without ever being used to dilute contaminants in the occupied zone, the energy used to heat, cool, and circulate the air is also wasted.

When spaces are unoccupied, ventilation is generally not required unless it is necessary to prevent an accumulation within the space of contaminants which would be hazardous to returning occupants or injurious to the contents or structure.

In some cases, outdoor air is so polluted as to be unacceptable as ventilation air. If the concentration of contaminants in the outdoor air exceeds acceptable levels, the air must be cleaned or treated before being introduced into the space. Elaborate ventilating systems with recirculation and treatment may considerably reduce pollution below prevailing ambient levels. Except for certain critical areas like hospital operating rooms, cleaning and recirculation of air within a building is permitted as long as the concentration of all contaminants of concern is maintained within specified acceptable levels.

Standard 62.1 includes an alternative performance method of providing acceptable indoor air quality. It specifies maximum allowable contaminant concentrations which can be tested for and corrected by an air-cleaning system. Air-cleaning systems can reduce both particulate and gaseous contaminants. This approach may be taken if, for example, the introduction of outdoor air must be curtailed to conserve energy or because of unacceptable outside air quality.

Normally, pollution levels inside buildings are slightly lower than those concurrently found outdoors. Peak concentrations indoors are lower and occur somewhat later than those outdoors. However, indoor production of carbon dioxide, formaldehyde, radon, tobacco smoke, and other contaminants can make indoor levels higher than ambient outdoor levels.

In recent years, illnesses due to high concentrations of indoor contaminants have received increased attention and emphasis. Some of these pollutants, such as asbestos dust, radon gas, benzines, chlorinated hydrocarbons, vapors of formaldehyde and mercury, paper copying and ink fumes, outgasing from plastics, and fire-retardant chemicals, are generated by the building, its contents, and its site. Some are produced by unvented indoor combustion or sewer gases. Some are released into the indoor environment by applications of adhesives, paint, cleaning compounds, and maintenance activities. Still others are the products of tobacco smoking, substances given off by human bodies, and fumes arising from food preparation. These contaminants are commonly found in most buildings, but the problem arose because of inadequate ventilation.

Prior to 1973, inexpensive energy for heating and cooling enabled designers to introduce high quantities of outdoor air into buildings to replace or dilute dangerous or simply odorous gases. Since then, building designers and code officials have responded to higher fuel costs by tightening up structures, that is, increasing insulation, reducing air leakage through the building envelope, and decreasing mechanical ventilation rates.

Air quality was initially ignored, and the objective was simply to minimize air exchange between indoors and outdoors. This led to the point where the concentration of contaminants rose in some cases to levels harmful to public health.

This became known as the *indoor air quality* (*IAQ*) *problem* or *sick building syndrome.* In response, research studies and experiments established levels of outdoor air ventilation needed to achieve acceptable indoor air quality.

Designers are now trying to achieve a balance between energy conservation and acceptable IAQ. Some means of reducing energy consumption while still providing adequate ventilation are:

- Heat recovery between exhaust and make-up outside air
- Tracking occupancy (providing only the ventilation necessary for the current number of people in the building)
- Opening outside air dampers 1 hour after occupancy (where permitted) to take advantage of the dilution capacity of large volumes of room air, and the natural dissipation of contaminants during long vacant periods
- Segregating smokers (on a separate, higher-ventilated HVAC system), preferably located in perimeter areas

When ventilation air is brought in from outdoors, it may be by either mechanical (active) or natural (passive) means. In spaces with low-density occupancy and exterior walls, sufficient outside air may be introduced by leakage through doors and windows. Interior zones and heavily populated areas, however, require the introduction of ventilated air by mechanical equipment. Also, if the outside air needs to be conditioned, it should be passed through the conditioning equipment first and then delivered to the space.

Whether ventilation air is brought in from outside or is predominantly recirculated, it must still be introduced at a rate sufficient to remove objectionable odors and contaminants from the space. With proper air distribution, the motion of the ventilation air blends with the room air, creating a unified thermal condition. And as the air gently passes by the occupants, it carries away heat, humidity, and odors given off by the body. This should result in a feeling of freshness.

SUMMARY

The human body is essentially a constant-temperature device. Heat is continuously produced by bodily processes and dissipated in an automatically regulated manner to maintain the body temperature at its correct level despite variations in ambient conditions. In terms of physiology, the experience of comfort is the achievement of thermal equilibrium with the minimum amount of body regulation.

The human body normally rejects heat to the environment using evaporative cooling (sweating) and the heat transfer mechanisms of radiation, convection, and conduction (see Chapter 2 for further discussion of these heat transfer mechanisms).

The relative roles of these heat transfer mechanisms are determined by the individual's metabolism, clothing, and activity level, as well as by the surrounding environmental conditions of radiation, humidity, air temperature, and air motion. The acceptable value of each of these features is not fixed, but can vary in conjunction with one or more of the others. It is possible for the body to vary its own balance of losses, for example, through increased sweating; or the insulating value of the clothing worn can be varied to a limited degree to compensate for conditions beyond the body's ability to make its own adequate adjustment.

The comfort of a given individual is affected by many variables. Health, age, activity, clothing, gender, food, and acclimatization are all determining factors of the comfort conditions for any particular person. Since these factors will not be identical for all people, room conditions are provided under which a majority of the expected occupants will feel comfortable.

In addition to its thermal climate, the air quality of each indoor environment affects the sense of comfort. Air may contain a variety of possible contaminants that may or may not be harmful to human occupants. Along with possible toxicity, contaminants can impart odors to the space, and the toxicity and odor intensity are often related to the concentration of impurities. To reduce health hazards and eliminate objectionable odors, concentrations of impurities are controlled either by dilution from outside air ventilation or by treatment of the air in an air conditioning system, or by both. Proper fresh air distribution throughout a space is important for mixing the air in order to achieve acceptable overall quality, and for keeping the air steadily moving around the occupants to carry away heat, moisture, and odors generated by them.

KEY TERMS

Comfort conditioning
Process air conditioning
Comfort
Body heat balance
Evaporative cooling
Thermal comfort
Heat
Sensible heat
Specific heat
Thermal radiation
Conduction
Convection
Latent heat
Latent heat of fusion
Latent heat of vaporization
Radiant heat
Enthalpy
British thermal unit (Btu)
Btuh (Btu/hr)
Joule
Watt (W)
Dry-bulb (DB) temperature
Wet-bulb (WB) temperature
Dew-point temperature
Mean radiant temperature (MRT)
Radiation
Met
Clo
Operative temperature
Optimum operative temperature
Thermal acceptability limit
Drift
Ramp
Occupied zone
Absolute humidity
Humidity ratio (specific humidity)
Degree of saturation
Percentage humidity
Relative humidity (RH)
Wet-bulb depression
Globe thermometer temperature
Operative temperature
New effective temperature (ET*)
Comfort envelope
Heating, ventilation, and air conditioning (HVAC)
Expectancy
Heat stroke
Permanent atmospheric impurities
Dust
Fumes
Smoke
Airborn living organisms
Mist
Fog
Dust control
Air sterilization
Ventilation
Odor masking
Counteraction
Indoor air quality (IAQ) problem (sick building syndrome)
ASHRAE

STUDY QUESTIONS

1. Explain the difference between heat and temperature. What are the conventional (U.S.) and SI units for each?

2. What are the numerical temperature and humidity limits to the ASHRAE comfort zone for sedentary, lightly clothed occupants? What are the air motion and MRT presumptions for these limits?
3. What is the MRT in the horizontal plane for an occupant in a space with all glass on one side at 45°F (7°C), and symmetrical interior partitions on the other side at 70°F (21°C), disregarding the effect of lighting and other surfaces in the space?
4. At what ET* is there a risk of sedentary heat stress?
5. What are the three principal functions of ventilation relating to carbon dioxide concentration; odorous and noxious contaminants; and body heat, moisture, and odors?
6. Name five common interior finish products that outgas formaldehyde.
7. What effect does smoking have on ventilation requirements for comfort and health?
8. List two reasons for restricting the introduction of outdoor air for ventilation.

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