CHAPTER 18

HEAT AND COLD

18-1 INTRODUCTION

Humans tolerate a limited range of thermal environments. At one extreme, there is excessive cold and low temperatures; at the other, there is excessive heat and high temperature. Only a narrow region in the middle is thermally comfortable. The farther thermal conditions deviate from the region of comfort, the greater the likelihood of injury and the faster injury will occur.

Humans, like other warm-blooded animals, have internal thermal regulation systems. The rate at which metabolic heat is produced in the body must be balanced by the rate at which heat is lost to the environment. If heat is lost too quickly, one becomes cold; if heat is lost too slowly or is added to the body, one becomes hot. The body has limited means for adjusting the rate at which heat is lost. The rate of cooling is increased by sweating and more blood flowing near the skin. To prevent heat loss, peripheral blood flow is reduced and shivering occurs.

Heat and cold injuries and illnesses are related to the ability of the body to transfer heat to or from the environment or objects the body contacts. The thermal environment can create heat-exchange problems for the entire body (heat stress or cold stress conditions) or for local areas of the body. Thermal injuries and illnesses resulting from excessive heat and high temperatures are more frequent than those associated with cold conditions.

18-2 HEAT TRANSFER

Heat exchange between the body and the environment primarily involves convection, radiation, and evaporation. Conduction is another method of heat transfer, but it is of little significance in air environments. However, in an underwater environment, it is the dominant method of heat transfer. Conduction is also important when the body contacts an object of extreme temperature.

For whole-body heat exchange, metabolic heat, M, must be balanced with the environment through convection, C, radiation, R, and evaporation, E. Heat exchange between the body and the environment can be expressed in simplified form as

$$M \pm C \pm R - E = \mathrm{O}. \quad (18\text{-}1)$$

Some heat is gained or lost through storage in the body mass, as evidenced by increases or decreases in body temperature. A precise heat balance equation also would include expressions for change in body mass and the resultant heat gain or loss. Body mass

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increases through intake of food and drink and decreases through excretion and urination. A precise balance would include an expression for peripheral blood flow and an expression for evaporative loss through respiration. It also would recognize that the body is seldom in a steady-state condition. A person's activity and the resulting heat produced by metabolism changes frequently. Changes in blood flow and sweating occur often. The heat balance equation would have to be adjusted for different individuals. The effect of clothing, acting as insulation, would need to be included. Nevertheless, Equation 18-1 provides the basis for understanding the heat transfer concept. It allows us to make quantitative estimates of what occurs in a thermal environment. It allows one to compute with reasonable accuracy whether an environment is likely to cause illness or injury.

Metabolism

The rate at which heat is produced in the body is determined by the activity being performed. Cells in the body burn oxygen and nutrients in performing their functions, and heat is produced in the chemical process of combustion. In general, the body is inefficient at converting fuel energy to work. As a result, most metabolic energy is converted to heat. A minimum amount of cellular activity is required just to maintain life. Cells produce more heat with increased activity, and the total amount of heat produced by the body is determined by the activity of the body. During sleep, the body of an average person burns approximately 70 to 75 kcal/hr and converts it to heat, whereas during very heavy exercise or work, 720 kcal/hr or more of heat may be produced. Typical values of oxygen consumption for various activities are listed in Table 18-1.

Convection

Convection is the transfer of heat by movement of air over the surface of a body. One empirically derived equation for convective heat transfer between a human body and the environment in warm-to-hot environments is

$$C = 1.0\ V^{0.6}(T_a - T_s), \tag{18-2}$$

where

C is convection heat transfer (kilocalories per hour),

V is air speed (meters per minute),

T_a is air temperature, dry bulb (degrees Celsius), and

T_s is skin surface temperature (degrees Celsius).

This is an approximation and, although this equation may not be accurate for all thermal conditions, it helps us understand the convective component in Equation 18-1. Equation 18-2 assumes a surface area for the human body of 1.8 m^2, which is an average value, and it needs to be corrected for actual body surface area and the effect of clothing when more precise calculations are necessary.

From Equation 18-1, it should be noted that convection, C, can add or remove heat from the body. The direction of heat transfer and the appropriate sign in Equation 18-1 can be established by noting the temperature difference between air and the body surface (see Equation 18-2). If the skin temperature is higher than the surrounding air, heat will be removed from the body. If the air temperature is higher then skin temperature, heat will be added to the body, adding to the burden of metabolic heat that must be removed through radiation or evaporation to maintain a constant body temperature.

TABLE 18-1 Metabolic Costs (Oxygen Consumption) for Selected Activities

Activity	Cost (kcal/hr)
General	
Light work	Up to 200
Moderate work	200–350
Heavy work	350–500
Resting	
Sleeping	70–75
Sitting quietly	80–100
Standing, relaxed	110
Walking, running	
Walking on the level	
3.2 km/hr	190
4.0 km/hr	230
4.8 km/hr	265
5.6 km/hr	300
6.4 km/hr	350
Running, 11.3 km/hr	810
Work	
Desk work	115
Driving a car	
Light traffic	80
Heavy traffic	190
Sheet metal work	200
Carpentry	230
Truck and automobile repair	250
Welding	180
Shoveling	410
Sweeping floors	235
Cleaning windows	225
Sawing wood by hand	480
Recreation	
Volleyball	210
Tennis	425
Swimming	400–550
Dancing, moderately	150
Basketball	515

Adapted from Conzolazio, C. F., Johnson, R. E., and Pecora, L. J., *Physiological Measurements of Metabolic Functions in Man*, McGraw-Hill, New York, 1963.

Air speed affects the rate of heat transfer by means of convection. Whether heat is being added or removed, a fourfold increase in air speed will approximately double the rate of heat transfer. Note that having a fan blow air over the body when the air temperature is higher than skin temperature actually adds heat to the body by convection. As we will see, increased air speed also can affect the rate of evaporative loss, which may produce a net heat loss when air temperature is higher than skin temperature.

The temperature of the skin is not constant with time and is not uniform over the entire body surface. Vasoconstriction and vasodilation influence cutaneous blood flow and skin temperature. Air temperature, too, affects the skin temperature. Because Equation

18-2 requires a single estimate of skin temperature, a value of 35°C is used for heat stress conditions.

Radiation

The body exchanges heat with its surroundings through radiation. Thermal radiation is highest for wavelengths in the infrared region. Radiation involves the geometric relationship between the surfaces of two bodies. The surface of one body must be able to "see" the other surface for radiant energy to be exchanged. For infrared radiation, air is essentially transparent.

Radiative heat transfer is a function of the fourth power of the absolute temperature of the surfaces involved. An approximation used for heat transfer from the human body in warm-to-hot environments is

$$R = 11.3(T_w - T_s), \tag{18-3}$$

where

R is radiation (kilocalories per hour),

T_w is mean radiant temperature of the solid surroundings (degrees Celsius), and

T_a is skin surface temperature (degrees Celsius).

Although Equation 18-3 is accurate in a limited range of thermal conditions, like Equation 18-2, it helps us to understand the radiative heat transfer component of Equation 18-1.

Like convection, radiation can add heat to the body or remove it. If the mean radiant temperature of the surrounding surfaces (usually walls) is higher than the skin temperature, heat will be added. If the skin temperature is greater than the mean radiant temperature of the surrounding surfaces, heat will be removed. By carefully noting the direction of heat transfer in Equation 18-3, the appropriate sign for R can be inserted in Equation 18-1. In Equation 18-3, a single estimate of skin temperature is required. A value of 35°C is commonly used for heat stress conditions.

Evaporation

Humans have the capability to sweat as a means for cooling the body. Sweat glands in the skin secrete sweat, which is primarily water containing some dissolved salts. Sweat gland activity is controlled by the hypothalamus in the brain. The level of physical activity and other factors influence the number of sweat glands active at one time. Sweat increases as the thermal regulation system in the body requires increased cooling to remove heat. As the water evaporates from the skin, cooling results from the change of state from liquid to vapor. There is considerable variation in sweat rates among individuals.

The maximum amount of cooling that can be achieved through sweating is a function of air speed and the ability of the surrounding air to accept additional moisture. An estimate of maximum cooling capacity for warm-to-hot environments is

$$E_{max} = 2.0V^{0.6}(PW_s - PW_a), \tag{18-4}$$

where

E_{max} is the maximum evaporative heat loss (kilocalories per hour),

V is the air speed (meters per minute),

PW_s is the vapor pressure of water at skin temperature (millimeters of mercury), and

PW_a is the vapor pressure of water at air temperature (millimeters of mercury).

Equation 18-4 helps us understand evaporative heat loss, even if it may not be accurate for all thermal conditions. In hot, humid conditions, the vapor pressures in air and at the skin surface are nearly the same. Cooling through evaporation of sweat then is limited by the environment. In hot, dry environments, the difference in vapor pressures is large and evaporation is rapid. In hot, dry conditions where evaporation is rapid, the actual cooling of the body may be limited by the maximum rate at which sweat is produced.

Vapor pressures can be determined through the use of a psychrometric chart. Dry-bulb air temperature and wet-bulb air temperature or relative humidity must be known. A psychrometric chart is provided in Figure 18-1.

Clothing and Insulation

Clothing slows down the rate of heat transfer between the body and the environment. In most cases, clothing is used as insulation to slow the loss of heat from the body. Various fabrics have different insulation value. Aluminized reflective clothing may help to reduce radiant heat gain from intense radiant sources, such as a fire or open flame operation. Fabrics that inhibit moisture loss may eliminate evaporation as a means of heat loss when the air inside the fabric becomes saturated with moisture. Equipment, such as vortex coolers and water-cooled underwear, may be required to remove heat from the "microclimate" inside some types of clothing assemblies.

Heavy or restrictive clothing may add to thermal problems by increasing the metabolic work required to move the clothing. An activity that is considered light work may become heavy work when special or heavy clothing is worn. Restrictive clothing may make wearers less agile, and loose clothing is more likely to become caught in equipment

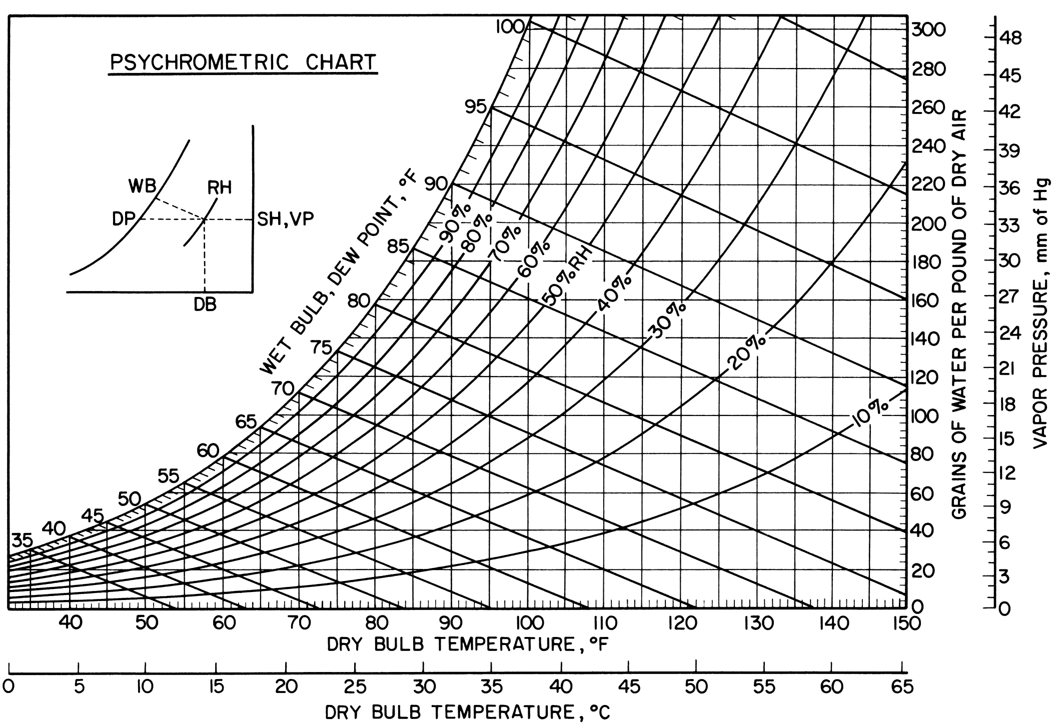

Figure 18-1. Psychrometric chart.

and machines. Special clothing may be used to insulate a person from local heat transfer problems, such as burns from hot objects and hot particles or frost injury from very cold objects.

The insulation value of a clothing assembly is given in units called clo. Clo values for clothing assemblies are determined by measuring the heat transfer from a heated manikin in controlled laboratory conditions. Table 18-2 provides clo values for some clothing assemblies.

For cold environments, the amount of clothing required can be estimated from

$$I_{req} = \frac{13.3(T_s - T_a)}{M}, \tag{18-5}$$

where

I_{req} is the clothing insulation required (clo),

T_s is the skin surface temperature (degrees Celsius),

T_a is the air temperature (degrees Celsius), and

M is the metabolic rate (kilocalories per hour).

Equation 18-5 assumes a body surface area, *SA*, of 1.8 m^2 as an average value. Adjustments in the body surface area may be required for accuracy. Body surface area is computed from the empirical equation of DuBois:

TABLE 18-2 Insulation Value of Different Clothing Assemblies

Clothing Assembly	I_{cl} (clo)
Nude	0
Shorts	0.1
Typical tropical clothing assembly	
Shorts, open-neck shirt with short sleeves, light socks, and sandals	0.3–0.4
Light summer clothing	
Long light-weight trousers, open-neck shirt with short sleeves	0.5
Light working assembly	
Athletic shorts, woolen socks, cotton work shirt (open-neck), and work trousers, shirttail out	0.6
U.S. Army fatigues, men’s	
Light-weight underwear, cotton shirt and trousers, cushion sole socks, and combat boots	0.7
Typical business suit	1.0
Typical business suit plus cotton coat	1.5
Light outdoor sportswear	
Cotton shirt, trousers, t-shirt, shorts, socks, shoes, and single-ply poplin (cotton blend) jacket	0.9
Heavy traditional european business suit	
Cotton underwear with long legs and sleeves, shirt, woolen socks, shoes, suit including trousers, jacket, and vest	1.5
Heavy wool pile assembly	
Polar weather suit	3–4

From Fanger, P. O., *Thermal Comfort*, Danish Technical Press, Copenhagen, 1970.

TABLE 18-3 Approximate Insulation Value of Air Film at Different Air Speeds

I_f (clo)	Air Speed (km/hr)
0.7	Calm
0.5	1.8
0.3	6.0
0.1	16.1
Negligible	65.0

$$SA = 71.84 \times 10^{-4}(W^{0.425})(H^{0.725}), \tag{18-6}$$

where

SA is the body surface area (square meters),

W is the weight of the person (kilograms), and

H is the height of the person (centimeters).

Skin temperature for comfort in the cold is approximately 33°C. This value can be used as an average skin temperature in Equation 18-5, although exposed skin would have a lower temperature.

The available insulation is made up of the insulation value of the clothing assembly plus a film of still air at the outer surface of the clothing,

$$I_a = I_{cl} + I_f, \tag{18-7}$$

where

I_a is the available insulation (clo),

I_{cl} is the insulation value of a clothing assembly (clo), and

I_f is the insulation value of the film of still air at the clothing surface (clo).

The film of still air and its insulation value diminishes rapidly as air speed increases. Table 18-3 lists some typical insulation values for the film of air at different air speeds.

For a known environment and activity, the insulation that must be provided by a clothing assembly can be determined by combining Equations 18-5 and 18-7 and solving for I_{cl}:

$$I_{cl} = I_{req} - I_f. \tag{18-8}$$

18-3 HEAT

Hazards

The effects of high temperatures and hot environments on humans can be grouped into two categories: heat illnesses and burns. Heat illnesses mainly are caused by excessive exposures to hot environments. Burns result from contact with hot materials or surfaces or from excessive irradiance of the skin by heat-producing wavelengths of radiant energy.

Heat Illnesses

Excessive exposure to hot environments can result in behavioral changes, an elevated core temperature of the body (hyperthermia), failure of the temperature regulatory mechanism, circulatory failure, depletion of water and body salts, and inflammation of sweat glands. These and other symptoms characterize the heat illnesses described in the following text.

Heat Stroke or Sunstroke This illness is primarily a failure of the thermal regulatory mechanism in the body and is manifested by the termination of sweating. The skin becomes hot and dry, the body temperature rises, and mental confusion, loss of consciousness, convulsions, or coma may result. Immediate and rapid cooling is required. Delays in treatment can be fatal.

Sunstroke is heatstroke resulting from excessive exposure to the sun.

Heat Hyperpyrexia This illness is a milder form of heatstroke in which there is partial rather than complete failure of sweating. Some sweating may continue to occur. Other manifestations of heatstroke are also less severe.

Heat Syncope Standing individuals who are not acclimatized to hot environments may faint because the redistribution of blood to peripheral tissue reduces the blood flow to the brain. The condition is corrected by removal to a cooler location and having the victim lie down.

Heat Exhaustion or Heat Prostration Excessive loss of water through sweating and inadequate circulation may result in fatigue, nausea, headache, or giddiness. This illness is characterized by cold, clammy skin. Urine is concentrated and low in volume. The primary cause is inadequate water intake during exertion in hot environments. Victims can be treated by removing them to a cooler location, having them rest, and replacing body fluids.

Heat Cramps This illness is characterized by painful muscle cramps during or after exertion in hot environments. The cramps are caused by excessive loss of body salts during sweating. Treatment involves replacing depleted body salts. Commercial fluids, sometimes called sports drinks, containing chemicals lost through sweating are useful.

Heat Rash This disorder, often called prickly heat, is characterized by small, blister-like eruptions on the skin that have a prickly sensation during heat exposure. Sweat glands become plugged, sweat is retained, and inflammation results. The skin must be kept dry and heat exposure avoided during treatment.

Heat Fatigue Some individuals, particularly those who are not acclimatized, may exhibit reduced performance of sensorimotor, mental, and vigilance tasks when exposed to heat. Other behavioral changes (reduced work effort, reducing clothing, or seeking cooler conditions) also may result as discomfort and physiological strain from hot environments are noted. In many cases, acclimatization and training may reduce behavioral effects to some extent.

Indices of Heat Stress

The idea of thermal comfort is based on subjective evaluations of thermal environments by room occupants. Individuals rate conditions as cold, cool, neutral, warm, or hot. An early thermal comfort scale was the Effective Temperature Scale. More recently, comfort information is based on Operative Temperature. The comfort zone for a given set of humidity, air speed, metabolic rate, and clothing insulation conditions is the range of operative temperatures that provide acceptable thermal environmental conditions or is the combination of air temperature and mean radiant temperature that people find thermally acceptable. ASHRAE publishes procedures for calculating operative temperature.[1]

Heat stress is concerned with hot environments outside the comfort zone, primarily those that result in physiological (blood flow, internal body temperature, sweating) changes. These changes are indicators of heat strain, a term referring to the physiological changes brought on by heat stress conditions of the physical environment.

A number of heat stress indices have been developed to predict whether exposures to hot environments will result in excessive heat strain. One index is the heat stress index (HSI). Another is the wet-bulb globe temperature index (WBGT). The HSI is probably a more accurate predictor of heat strain. However, instrumentation and calculations required for a WBGT assessment are much simpler. Because of its simplicity for field use, the WBGT is used more often. Both the HSI and WBGT decision tables apply to 8-hr exposures.

For weather purposes, the National Weather Service established the Heat Index (HI). It takes into account both heat and humidity to give an indication of how hot it feels to people when the air temperature is more than 57 degrees. The HI is computed from the following:

$$\begin{aligned} \text{HI} = &-42.379 + 2.04901523 \times T_a + 10.14333127 \times RH - 0.22475541 \times T_a \times RH \\ &- 0.00683783 \times T_a^2 - 0.05481717 \times RH^2 + 0.00122874 \times T_a^2 \times RH \\ &+ 0.00085282 \times T_a \times RH^2 - 0.00000199 \times (T_a \times RH)^2, \end{aligned} \tag{18-9}$$

where T_a is the air temperature (degrees Farenheit) and RH is the relative humidity (percent).

Heat Stress Index The HSI compares the amount of sweat that must be evaporated to balance the heat loss equation (Equation 18-1) for a given set of environmental conditions with the maximum amount of sweat that can actually be evaporated for those conditions:

$$HSI = E_{req} \times \frac{100}{E_{max}}, \tag{18-10}$$

where

HSI is a dimensionless index number,

E_{req} is the evaporative heat loss required (kilocalories per hour), and

E_{max} is the maximum evaporative heat loss (kilocalories per hour).

E_{req} can be computed by combining Equation 18-1 with Equations 18-2 and 18-3; E_{max} is computed from Equation 18-4. In Equations 18-2 and 18-3, the skin surface temperature can be assumed to be 35°C.

The implications for various values of HSI are provided in Table 18-4. The decision of whether an environment is safe or whether corrective actions are needed can be based on an assessment of the environment in question using HSI and Table 18-4. Environmental conditions that result in values for HSI greater than those explained in Table 18-4 may exist, and they indicate that conditions are excessive for everyone. Values less than those in Table 18-4 indicate cold conditions to which HSI does not apply.

Wet-Bulb Globe Temperature Index The WBGT index was developed as a simple-to-use method for determining if military troops were likely to suffer from heat illnesses in hot environments. Only two or three measurements are needed: wet-bulb (static) tem-

TABLE 18-4 Heat Stress Index Implications[a]

HSI	Implications of 8-hr Exposures
–20	Mild cold strain.
–10	
0	No thermal strain.
+10	Mild to moderate heat strain. Small decrements in motor, mental, and vigilance tasks. Little effect for performance of heavy physical work.
20	
30	
40	Severe heat strain. A threat to health unless workers are physically fit. Unacclimatized workers need a break-in period. Medical selection of workers desirable to screen out those with existing physiological impairments.
50	
60	
70	Very severe heat strain. Only a small percentage of the population can be expected to qualify for this work. Special protective measures needed to prevent heat illnesses from occurring.
80	
90	
100	The maximum strain tolerated daily by fit, acclimatized young men.

[a] Adapted from Belding, H. S., and Hatch, T. F., "Index for Evaluating Heat Stress in Terms of Resulting Physiological Strains," *J. Amer. Soc. Heating and Ventilating Eng.*, 27:129ff (1950).

perature (WB), dry-bulb temperature (DB), and globe temperature (GT). WBGT values are computed from one of two equations, depending on the presence of a solar load:

$$\text{WBGT} = 0.7\text{WB} + 0.2\text{GT} + 0.1\text{DB (with a solar load)} \tag{18-11}$$

and

$$\text{WBGT} = 0.7\text{WB} + 0.3\text{GT (with no solar load).} \tag{18-12}$$

If a person is exposed to a sequence of differing thermal environments during an 8-hour period, an average WBGT value can be computed from

$$\text{WBGT}_{\text{avg}} = \frac{(\text{WBGT}_1 \times t_1) + (\text{WBGT}_2 \times t_2) + \cdots + (\text{WBGT}_\text{n} \times t_\text{n})}{t_1 + t_2 + \cdots + t_\text{n}}. \tag{18-13}$$

Permissible heat exposure threshold limit values (TLVs) have been established by the American Conference of Governmental Industrial Hygienists (ACGIH)[2] and are presented in Table 18-5. Refer to the recommendations for additional details. Knowledge of the metabolic activity (see Table 18-1) and the WBGT allows a person to decide from the TLVs if adjustments in work are needed. The TLVs assume a person is wearing light summer clothing (long-sleeved shirt and pants with reasonable air flow), has adequate water and salt intake, and has a deep-body temperature at or below 38°C. The thermal conditions in the rest area are assumed to be roughly the same as the work area.

If a worker is wearing clothing that is heavier than a light summer assembly, the computed WBGT is adjusted upward depending on the clothing assembly. For woven cloth overalls, 3.5° are added to WBGT and 5° are added for double-cloth overalls. The use of Table 18-5 and these adjustments are not applicable to encapsulating suites or garments that are impermeable or highly resistant to water vapor or air movement through the fabric.

Full acclimatization results when someone has experience continued physical activity under heat-stress conditions similar to those anticipated for a task. Typically, full acclimatization requires up to 3 weeks of exposure. Table 18-5 differentiates between acclimatized and unacclimatized workers.

TABLE 18-5 Screening Criteria for Heat Stress Exposures[a,b] (°C, WBGT)

	Acclimatized				Unacclimatized			
Work Demands	Light	Moderate	Heavy	Very Heavy	Light	Moderate	Heavy	Very Heavy
100% work	29.5	27.5	26		27.5	25	22.5	
75% work, 25% rest	30.5	28.5	27.5		29	26.5	24.5	
50% work, 50% rest	31.5	29.5	28.5	27.5	30	28	26.5	25
25% work, 75% rest	32.5	31	30	29.5	31	29	28	26.5

[a] From *Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2004.
[b] Refer to the publication for additional details related to implementation.

Burns

The body is capable of removing heat from the skin or other body tissue at a rate that is mainly related to blood flow through the tissue. If heat is added to local tissue through contact with a hot object (conduction), from exposure to sources of high radiant energy (radiation), or from exposure to hot air (convection) at a rate that is faster than the removal rate, the tissue must store the energy. The tissue temperature will rise, resulting in discomfort, pain, or tissue damage. If the heat transfer rate is high, the elevation of local skin temperature can occur in seconds or less.

Human skin has a reflectance ranging from 5% up to 70% for wavelengths in the region from $0.2–2.0 \times 10^{-6}$ m. This reflectance depends to some extent on skin color. Above and below these wavelengths, the skin acts essentially as a black body and absorbs all radiant energy. Radiation in the microwave and infrared range causes heating of tissue.

Burn Classifications Burn classifications describe the depth of tissue that has been damaged. The outer layer of the skin is called the epidermis and the inner layer, containing hair follicles and sweat glands, is called the dermis. Below the skin, in the subcutaneous region, is a network of blood vessels serving the skin.

In the past, burns have been classified as first, second, or third degree, based mainly on visual characteristics of the wound. More recently, burns are classified as partial-thickness or full-thickness burns. These two classifications schemes are detailed in Table 18-6.

Other classifications of burns account for the portion of the body surface area injured, the part of the body injured, age of the injured person, and other factors. Beside thermal burns, other kinds of burns can occur. Electricity flowing over or through the body causes a variety of injuries, including thermal damage. Contact with chemicals may produce damage to the skin and other tissues that are classified as chemical burns. Electrical and chemical injuries are discussed elsewhere. Contact with very cold, cryogenic liquids also can cause tissue damage similar to that resulting from high temperatures.

Heat and Temperature The normal internal temperature of the body is approximately 37.5°C, whereas the skin temperature is approximately 35°C. Elevation of tissue temperatures will result in damage or destruction, depending on the length of time the tissue remains at an elevated temperature. When the total heat transfer is such that the core temperature of the body is elevated for a sufficient length of time, death can result, even though

TABLE 18-6 Burn Depth Classifications

Degree of Burn	Wound Thickness	Characteristics
First	Superficial	Erythema (reddening), pain; partial healing occurs in 5–10 days
Second	Deep	Blisters, pain; partial healing occurs in 2 weeks to 1 month
Third	Full	Skin destroyed, subcutaneous and possibly deeper tissue destroyed, lack of pain; extended period of healing

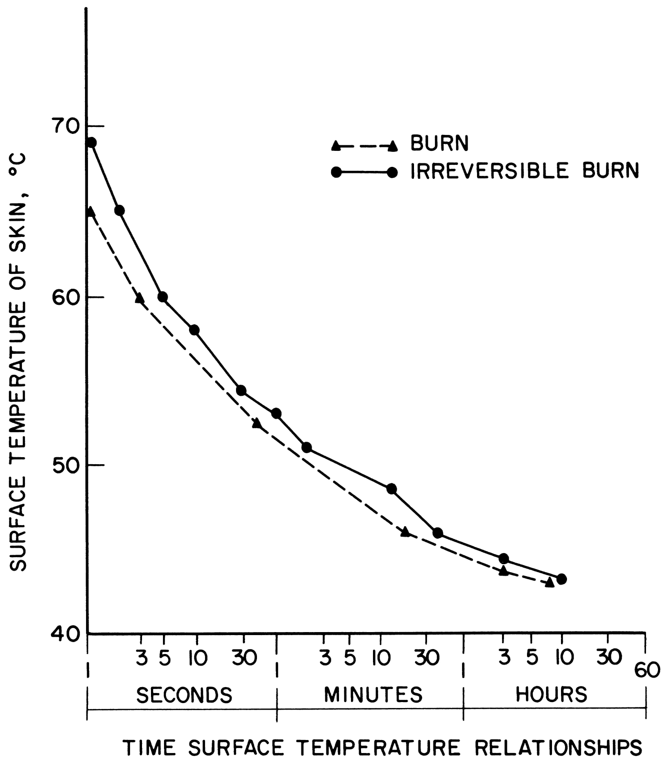

Figure 18-2. Relationships between skin surface temperature and time of exposure required for burns. (Used with permission from Artz, C. P., Moncrief, J. A., and Pruitt, B. A., *Burns*, W. B. Saunders Co., Philadelphia, PA, 1979.)

the surface temperature does not produce pain. An example is immersion in a bath for an extended period at a temperature of 43°C. People have died of such an exposure in hot tubs. However, local tissue damage will occur when the skin surface temperature is 44°C or more. Pain occurs when the temperature reaches 45°C, and a skin temperature of 46°C is reported to be intolerably painful. The relationship between skin surface temperature and exposure time that will cause burns is shown in Figure 18-2. Figure 18-3 presents the relationship between irradiance of the skin and exposure time in terms of pain.

Controls

Heat stress and thermal injuries can be reduced or eliminated by controlling the source, modifying the environment, adjusting the work or activity, providing protective equipment, and meeting physiological and medical needs of workers.

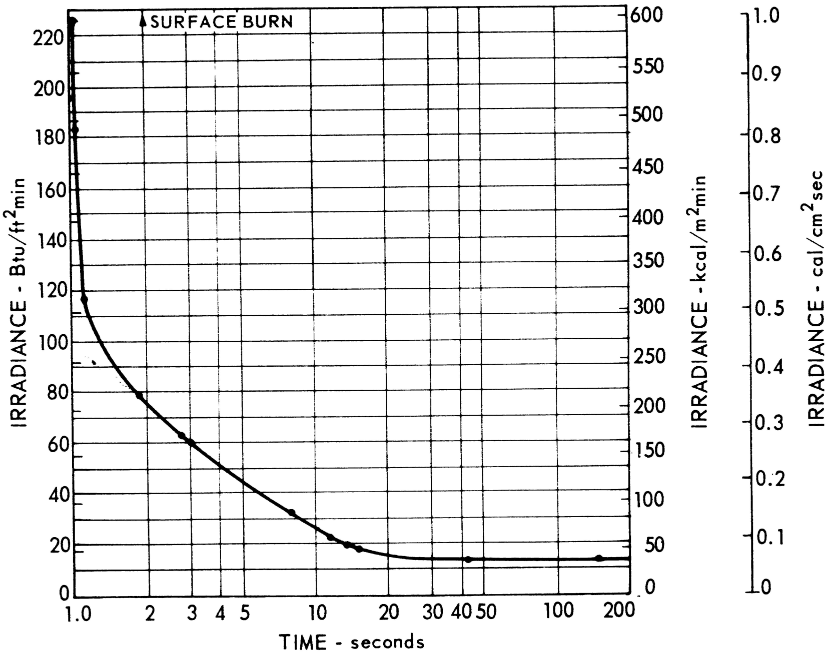

Figure 18-3. Relationship between irradiance and time of exposure for strong pain. (From Webb, P., *Bioastronautics Data Book*, NASA SP3006, National Aeronautics and Space Administration, Washington, DC, 1964.)

Controlling the Source Keeping heat sources and hot surfaces away from occupied areas will reduce the chance of heat buildup or contact. For example, placing an oven in a separate area can reduce the heat added to a work area. Insulation applied to a hot surface or object will prevent air from becoming hot and people from coming into contact with the hot surfaces. Not only is the hazard reduced, but in many cases, insulation conserves energy.

In some operations, materials and processes have temperatures that are higher than necessary. Reducing temperatures may reduce or eliminate thermal hazards.

Modifying the Environment The physical parameters involved in heat stress are air temperature, air velocity, mean radiant temperature, and vapor pressure. When these parameters cannot be modified by adjustments at the source, ventilation may reduce heat stress. Ventilation, the process of supplying air from some location other than the stressful environment, may be limited as a solution by the heat capacity and temperature of the ventilation air. An assessment of the supply air and thermal conditions must be made to estimate the effectiveness of ventilation. When ventilation is not effective, a final control is cooling of air with air conditioning equipment.

For environments with intense radiant sources, shielding may reduce the radiation reaching a person, because radiant energy travels in a straight line and air is not heated by it directly. In other cases, the distance between a person and the radiant source can be lengthened to reduce radiation levels, because radiation intensity diminishes with the square of the distance.

Barrier guards will prevent people from coming into contact with hot surfaces or becoming close to operations where hot material is found.

Adjusting Activities People can modify activities to reduce heat stress. Metabolic heat generation can be reduced by making work easier and by providing power tools and equipment to reduce the work effort required.

Another way to adjust the work is to limit the time of exposure to hot environments and to provide adequate periods of rest, both of which reduce the heat buildup in the body. The TLVs in Table 18-5 recommend this approach. Workers may be rotated through different jobs so that only a portion of their work is in stressful environments. That way productivity is not lost.

Providing Protective Equipment For hot environments, water-cooled clothing (helmets, underwear, and full uniforms) can be used. Air-cooled clothing, which relies on air lines and vortex devices for cooling, is usually less expensive and may provide sufficient cooling capacity in some environments. Pressurized air suitable for cooling is not necessarily safe for breathing.

In environments with intense radiation, reflective clothing may be helpful, and protective eye wear that reflects or filters harmful wavelengths may be needed. A wide variety of aluminized fabrics are available. Two types of reflective suits used for fires are called proximity suits and entry suits. Use of proximity suits is limited to approaching the heat source. Entry suits have an insulation layer inside to prevent contact burns and to reduce the rate of heat buildup. Without internal cooling, most full garments would create excessive conditions inside the suit in a short time.

Protective clothes may solve some heat problems and may add to others. In selecting protective clothing, one should remember that protective clothing does not remove the hazard; its effectiveness depends on the wearer's cooperation for effectiveness and may increase the metabolic rate for the activity. The metabolic work required to do physical work while wearing heavy clothing can be significantly higher than for the same activity without the clothing. Heat and moisture buildup inside a garment can create a hazardous local thermal environment that is not present outside the garment.

Insulated materials can be used to prevent burns that result from contact with hot objects or splashes of hot material or from heat transfer by conduction. Gloves, pads, and other kinds of insulated clothing items are available in fabrics with a variety of thermal characteristics.

Physiological and Medical Controls Heat strain can be reduced to some extent by ensuring that people replace lost body salts and water. Medical examinations may help identify those who are greater risks for heat stress because of age, physical condition, or existing health problems. High-risk people can be kept out of heat-stress environments. A program of acclimatization can also be used to improve to some degree the capacity of individuals to perform in hot environments. In extreme environments, continuous medical monitoring may be required to ensure that deep body temperatures do not exceed a limit of 38°C (as recommended by ACGIH and others) and that other physiological responses (heart rate, sweat rate) are not excessive.

18-4 COLD

The body has a very limited capacity to adjust for cold environmental conditions. Adjustments in blood circulation may conserve body heat, and shivering slightly increases metabolic heat production.

Hazards

Cold can produce local tissue damage and can reduce the core temperature of the body (hypothermia). Cold-related illnesses and diseases are described in the following text.

Trenchfoot When a person is exposed for several days to temperatures sensed as cold (but well above freezing), when the skin is moist, and when there is inactivity, trenchfoot is likely to occur. The prolonged exposure causes vasoconstriction in the feet and legs, which initially produces a pale appearance and numbness. After the initial paleness, swelling and pain occur. The numbness may continue for several weeks after the feet are warmed.

Chilblains An itching and painful reddening of the skin is caused by congestion of the capillaries when tissues are exposed to the cold. Symptoms are particularly found in exposed areas, such as the fingers, ears, or toes.

Cold Urticaria (Hives) In some people, coldness in tissue causes histamine to be released in the tissue, producing itchy, red blotches in the skin. In some cases, the exposure results in swelling of tissue and other histamine reactions (vomiting, rapid heart rate, swelling of breathing passages).

Frostbite When the temperature of tissue reaches or goes below the freezing point, frostbite results and tissue is damaged. The degree of damage depends on the depth of tissue frozen. Mild damage may result if only superficial layers are frozen. Skin is usually white or grayish yellow in appearance. Pain may be present, but often a victim is unaware of the frostbite.

Hypothermia A general lowering of the body temperature results in a variety of symptoms. As the core temperature is lowered from a normal temperature of approximately 37.5°C, shivering appears initially. Numbness, disorientation and confusion, amnesia, and impairment of judgment occur as core temperatures are lowered. When temperatures reach 26° to 30°C, unconsciousness, cardiac arrhythmia, muscular rigidity, ventricular fibrillation, respiratory arrest, and death are likely to occur. However, people have survived when the body temperature has reached lower values.

Indices of Cold Stress

There are few indices of cold stress. Some time ago, the National Safety Council published recommended exposure limits for cold environments (see Table 18-7). Earlier in this chapter, the effect of wind speed on the rate of convective cooling was noted. In cold environments, heat loss by convection is the most significant means of cooling. The effect of wind action on cooling has resulted in an indicator of cold stress called windchill, recently updated to Wind Chill Temperature Index. OSHA[3] uses a conceptual equation to help visualize danger from cold exposure called the Cold Stress Equation. The concept is: low temperature + wind speed + wetness = injuries and illnesses. The concept groups combinations of air temperature or water temperature (from wet or damp clothing) and wind speed into zones of danger: little danger, danger, and extreme danger. The combinations appear in Table 18-8.

TABLE 18-7 Exposure Limits for Cold Temperatures[a]

Temperature Range (°C)	Minimum Daily Exposure
–1 to –18	No exposure time limit if the person is properly clothed.
–18 to –35	Total cold-room work time: 4 hr; alternate 1 hr in and 1 hr out of the chamber.
–35 to –57	Two periods of 30 min each, at least 4 hr apart. Total cold-room work time allowed: 1 hr (*Note*: Some difference exists among individuals. One report recommends 15-min periods not more than four periods per work shift; another limits periods to 1 hr out of every 4, with a low chill factor, i.e., no wind; a third says that continuous operation for 3 hr at –54°C has been experienced without ill effect.)
–57 to –73	Maximum permissible cold-room work time: 5 min over an 8-hr working day. For these extreme temperatures, the wearing of a completely enclosed headgear, equipped with a breathing tube running under the clothing and down the leg to preheat the air, is recommended.

[a] Adapted from Alpaugh, E. L., *Fundamentals of Industrial Hygiene*, National Safety Council, Chicago, IL, 1971.

TABLE 18-8 OSHA Cold Stress Equation Zones (approximate)

Temperature, °F (°C)	Wind Speed (mph)			
	0–10	10–20	20–30	30–40
30 (–1.1)	LD	LD	LD	LD
20 (–6.2)	LD	LD	LD	LD
10 (–12.2)	LD	LD	D	D
0 (–17.8)	LD	D	D	D
–10 (–23.3)	LD	D	D	D
–20 (–28.9)	D	D	D	ED
–30 (–34.4)	D	D	ED	ED
–40 (–40)	D	ED	ED	ED
–50 (–45.6)	D	ED	ED	ED

LD = little danger (freezing to exposed flesh within 1 hr); D = danger (freezing to exposed flesh within 1 minute); ED = extreme danger (freezing to exposed flesh within 30 seconds).

Windchill

This index was derived from measurements of the rate of cooling of a container of water. The cooling power of wind at some temperature is compared with the equivalent cooling power of relatively still air at another temperature. The mathematical equation developed from the study (its validity has been questioned) is

$$\text{windchill} = [(100V)^{1/2} - V + 10.45] \times (33 - T_a), \tag{18-14}$$

where

windchill is that part of the total cooling that is primarily the result of the wind action in cold environments (kilocalories per square meter per hour),

V is the wind speed (meters per second),

10.45 is the arbitrary constant,

33 is the skin temperature (degrees Celsius), and

T_a = air temperature (degrees Celsius).

	Actual Thermometer Reading - °F									
	50	40	30	20	10	0	-10	-20	-30	-40
Wind speed - mph	Equivalent Temperature - °F									
calm	50	40	30	20	10	0	-10	-20	-30	-40
5	48	37	27	16	6	-5	-15	-26	-36	-47
10	40	28	16	4	-9	-21	-33	-46	-58	-70
15	36	22	9	-5	-18	-36	-45	-58	-72	-85
20	32	18	4	-10	-25	-39	-53	-67	-82	-96
25	30	16	0	-15	-29	-44	-59	-74	-88	-104
30	28	13	-2	-18	-33	-48	-63	-79	-94	-109
35	27	11	-4	-20	-35	-49	-67	-82	-98	-113
40	26	10	-6	-21	-37	-53	-69	-85	-100	-116
Over 40 mph (little added effect)	Little Danger (for properly clothed person)				Increasing Danger (Danger from freezing of exposed flesh)			Great Danger		

Figure 18-4. Windchill chart.

A windchill chart showing equivalent temperatures for different wind speeds is provided in Figure 18-4. Calm means that the wind velocity is very low, but not zero.

In 2001, the National Weather Service published a new Wind Chill Temperature or Wind Chill Temperature (WCT) Index equation that is now used as a better estimate for warning people about the danger of cold air temperatures combined with wind. The new formula, based on exposure of the human face, is

$$\text{NWS Wind Chill Temperature Index} = 13.12 + (0.6215 \times T_a) - (11.37 \times V_{10}^{0.16}) + (0.3965 \times T_a \times V_{10}^{0.16}), \quad (18\text{-}15)$$

where

WCT is degrees Celsius,

T_a is the air temperature (degrees Celsius), and

V_{10} is the wind speed at 10 meters (standard anemometer height), in kilometers per hour).

Compared with windchill temperatures, the WCT Index results in a slightly higher temperature for most wind speeds and is a more reliable indicator of potential danger.

Controls

Controls for preventing injury from cold environments include changes to the environment, adjustments in activities, and protective clothing.

Modify the Environment For environments that can be controlled, it may be feasible to warm the air temperature or provide radiant heat sources. In some situations, reductions in wind speed may be possible by providing windscreens or enclosures.

Adjust Activities The easiest way to protect someone from the cold is to minimize the duration of exposure. Frequent breaks to warm up may be needed and rests should be in warm environments.

Provide Protective Clothing Adequate amounts of clothing can provide the insulation necessary to retain body heat (previously discussed in Section 18-2). The outer layer of clothing should provide a windscreen, but also allow moisture to escape. Sweating because of too much insulation or condensation of sweat in clothing should be avoided. Inner fabrics should absorb moisture so that the skin is not wet. Attention should be given to protection of body extremities (hands, head, and feet). Because the hands have a relatively large surface area and a large portion of the blood flow through the body goes to the head, both can have a high rate of heat loss. If practical problems of power supply, connections, and controls can be resolved, electrically heated clothing can be used.

When contacting, handling, or using solids and liquids at subfreezing temperatures, protective clothing should be worn to prevent freezing of local tissue or freezing of moist skin to frozen objects. Fabrics, clothing, and protective equipment should be selected to provide protection appropriate to the hazards involved.

18-5 MEASUREMENT

Before the degree of hazard for a thermal environment can be determined, measurements of conditions must be made. A variety of instruments are needed to assess the thermal environment.

Air Temperature

The simplest device for measuring air temperature (dry bulb) is a thermometer. Battery-powered, portable instruments with analog or digital readouts can also be used. Sensors are often thermocouple or thermistor devices.

Humidity

Relative humidity is difficult to measure directly. Although accurate humidity instruments are available, humidity levels often are determined through the use of dry-bulb and wet-bulb temperature readings and a psychrometric chart.

Wet-bulb temperatures are determined by placing a clean, wetted sock over the bulb of a thermometer and rapidly moving the bulb through the air (or blowing air over the bulb) to provide cooling by evaporation of the moisture from the sock. The temperature reading will be lower than a dry-bulb reading. Special kits are available for holding two thermometers (one wet-bulb and one dry-bulb) on a sling and whirling them around. This is a sling psychrometer. Other devices are stationary and air motion is provided by a fan that blows air over the wetted bulb. When making wet-bulb readings for WBGT, however, the wet-bulb thermometer must be held stationary.

Mean Radiant Temperature

The mean radiant temperature of surrounding surfaces can be determined by measuring the temperature and area of each surface and averaging them. This is a rather cumbersome and often impractical approach. An alternative is to use a black globe thermometer. The temperature inside a 15-cm (6-in) diameter hollow copper sphere, painted matte black on the outside, provides a good estimate of the mean radiant temperature. After a 25- to 30-min period in which the globe has been at a fixed location in an environment, a steady-state condition is reached inside the globe. The rate at which radiant energy is absorbed is balanced by convective heat loss from the sphere. The temperature inside the sphere can be measured by the sensor of any dry-bulb instrument located at the approximate center of the sphere.

Air Speed

Many different types of anemometers are available for measuring air speed. Desirable features for assessing thermal conditions are portability, durability, and ruggedness. Also important are having a nondirectional sensor, sensitivity at low speeds, and fast response time. Instruments with a heated sensing device (heated thermocouple, heated thermistor, hot wire) provide these features.

Body Temperature

For most hot and cold environments there is no need to monitor the body temperature. In extremely hot or cold environments and where people are confined or isolated from assistance, core temperature monitoring may be necessary to ensure that upper or lower limits are not exceeded and that personnel are removed from stressful conditions before severe physiological damage occurs. Activities may be restricted by direct leads between the person and the instrument, a difficulty that can be solved through the use of a telemetry system.

Another problem is tolerance of core temperature sensors by the wearer. Because oral temperature is not very accurate and reliable when measurement of core temperature is critical, rectal probes often are used. The least objectionable sensor is a tympanic sensor, which uses a thermistor bead or small thermocouple that is placed in the ear canal against or very near the eardrum and is held in place by a custom-molded ear plug. Tympanic temperature closely follows core temperature. Digital thermomemters also can add convenience for temperature readings.

EXERCISES

1. Estimate how long a person can be exposed to each of the following conditions before burns will result or strong pain occurs:

(a) direct skin contact with a surface at 60°C

(b) thermal radiation of 300 kcal/m^2/min on the skin

2. With air movement at 1.46 km/hr and a relative humidity of 50%, what combination of dry-bulb and wet-bulb temperatures will be comfortable for most people?

3. Compute the heat stress index for the following conditions and determine if any precautions are warranted:

(a) M = 350 kcal/hr, V = 14 km/hr, T_a = 31°C, $T_w = T_a$, relative humidity at the skin = 100%, and relative humidity of the air = 80%.

(b) M = 200 kcal/hr, V = 5 km/hr, T_a = 21°C, $T_w = T_a$, relative humidity at the skin = 70%, and relative humidity of the air = 40%.

4. Compute the WBGT index for the following and recommend any controls that might be appropriate:

(a) WB = 23°C, GT = 35°C, DB = 31°C, continuous heavy workload, solar load.

(b) WB = 15°C, GT = 40°C, continuous light workload, no solar load.

5. Compute the time weighted average WBGT if a worker doing continuous light work is subjected to the following conditions as a sequence during an 8-hr workday:

   Condition 1: WBGT = 35°C, duration = 100 min

   Condition 2: WBGT = 24°C, duration = 20 min

   Condition 3: WBGT = 30°C, duration = 60 min

   Condition 4: WBGT = 40°C, duration = 40 min

6. Compute the windchill cooling rate for the following conditions and find an equivalent temperature for calm air (1 km/hr). What danger exists, if any, for each windy condition?

   (a) $V = 25$ km/hr, $T_a = 0$°C

   (b) $V = 10$ km/hr, $T_a = -10$°C

7. An employee is required to work in the cold. Determine the insulation required and estimate the insulation that must be provided by the clothing assembly for each set of conditions.

   (a) Hard work, $T_a = -15$°C, calm air

   (b) Moderate workload, $T_a = -25$°C, V = 6 km/hr

8. For the conditions in Exercise 7, estimate the adjustment in insulation required if the employee had the following height and weight:

   (a) height = 152 cm, weight = 39 kg

   (b) height = 191 cm, weight = 115 kg

9. Power line workers experience the following conditions while repairing electrical distribution lines following a storm: −10°F air temperature, 18 mph winds. Determine the degree of danger for these conditions.

10. For the conditions in Exercise 9, what is the WCT Index?

REVIEW QUESTIONS

1. Describe the fundamentals of heat exchange between the human body and the environment for

   (a) convection

   (b) conduction

   (c) radiation

   (d) evaporation

2. Identify the physical parameters involved in heat transfer from the human body.

3. What mechanisms can the body use for increasing heat loss? Discuss the limitations of each.

4. Discuss the advantages and disadvantages of clothing in terms of the impacts on thermal balance.

5. What effect does air motion have on heat exchange? How effective is air as an insulator?

6. Under what conditions will turning on a fan add to the heat of metabolism?

7. What is mean radiant temperature?

8. What injuries and illnesses can result from exposure to heat? Describe their symptoms.

9. What instrumentation is required for determining the heat stress index and the WBGT index? How are they different?

10. Describe the classifications schemes for burns and typical characteristics for each class.

11. What controls can be used to eliminate or reduce hazards from heat?

12. What is the maximum deep body temperature that should not be exceeded when working in hot environments?

13. What injuries and illnesses can result from exposure to cold? Describe their symptoms.

14. What is windchill? How is it different from Wind Chill Temperature Index?

15. What controls can be used to minimize or eliminate hazards from cold?

16. What instrumentation is required to measure

(a) dry-bulb air temperature?

(b) wet-bulb air temperature?

(c) mean radiant temperature?

(d) air speed?

(e) body temperature?

17. Define

(a) hyperthermia

(b) hypothermia

18. What are the symptoms of the following disorders?

(a) heat stroke

(b) heat exhaustion

(c) heat syncope

(d) heat cramps

(e) heat rash

(f) trenchfoot

(g) chilblains

(h) cold urticaria

(i) frostbite

NOTES

1 ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2004; and *ASHRAE Handbook—Fundamentals*, Chapter 8, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, updated periodically.

2 *Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices*, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, updated annually.

3 OSHA 3156, *The Cold Stress Equation*, U.S. Department of Labor, Occupational Safety and Health Administration, 1998.

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