**Chapter Two**

# Principles of Thermal Comfort

Almost all buildings are designed and constructed for the purpose of sheltering and facilitating the activities of human beings. In most cases these activities are performed within the building itself and therefore require the designer to carefully consider the thermal comfort needs of the occupants. One can further argue that if the building occupant is the focus of our attention, then the starting point for the thermal design of a building should be the human body and its thermal interactions with the immediate environment.

## 2.1 Heat Transfer between Body and Environment

The human being is a form of heat engine that derives its energy from the combustion of food, a process referred to as *metabolism*. To achieve comfort under varying climatic conditions it is necessary to regulate the amount of heat lost from, or gained by, the human body (Figure 2.1). From a general viewpoint our body is able to lose heat in three ways:

- Through outward radiation to colder surroundings, such as colder surfaces and a colder sky.
- Through outward convection or conduction to air below skin temperature and by direct contact with colder objects (e.g., bare feet on a concrete floor).
- Through evaporation from the respiratory tract and from skin perspiration.

**The human body is a form of heat engine that derives its energy from the combustion of food (i.e., metabolism).**

- **Thermal comfort depends on heat transfer between human body and environment.**
- **Heat loss may occur through outward radiation (to sky and colder surroundings), evaporation (from breathing and perspiration), and outward convection (air below skin temperature) or conduction (feet on cold floor).**
- **Direct solar radiation may exceed 300 BTU/SF/HR on a horizontal surface.**
- **Deep body temperature (i.e., temperature of blood) is approximately 98.6˚F (skin temperature is about 92˚F).**

Figure 2.1: The human heat engine

**Environmental temperature is one of the most critical factors governing human comfort and survival.**

- **Our ability to survive in environmental temperatures ranging from -60˚F to 130˚F is due to our technical skills (shelter and clothing).**
- **Our deep body temperature must not vary by more than ± 1% for thermal comfort and -2˚F to +6˚F for health and survival.**
- **Clothing is an effective mechanism for insulating the body in cold climates and for providing some individual control under most conditions.**

Figure 2.2: Environmental adjustment

When exposed to the external environment the human body is involved in heat transfer driven by infra-red radiation of short wave-length (i.e., solar radiation) and long wave-length (i.e., thermal radiation). The intensity of direct solar radiation can be in excess of 300 BTU/SF per hour on a horizontal surface. The amount of surface of the human body exposed to the sun varies with the altitude of the sun and the posture assumed. Generally speaking, for a standing person the maximum exposure to radiation in a warm climate will occur between 9 to 10 am in the morning and between 2 to 3 pm in the early afternoon.

The ground and surrounding objects will exchange radiant heat with the human body if their temperatures are at variance with that of the body surface. For example, in hot dry climates the ground and surrounding surfaces may become appreciably warmer than the human body, so that the amount of heat gained by radiation can become critical. Unfortunately, this radiation tends to be of the long-wave length type and is therefore readily absorbed by the skin.

Transfer of heat between the skin and surrounding air will occur by convection and conduction, with the rate of transfer depending very much on the degree of air movement. The latter tends to replace the air next to the skin with fresh air, thereby increasing the amount of heat lost from the human body if the temperature of the air is less than that of the skin. Air movement also increases the amount of heat lost by evaporation, since it replaces the saturated air in contact with the skin with fresh air.

Therefore, to achieve a comfortable thermal environment it becomes necessary to regulate the heat lost from the human body by cooling or heating the air surrounding the skin or the surface of the skin directly. The fact that we have been able to adjust to a surprisingly wide range of climates (i.e., from the cold ice-bound Arctic regions to the hot and humid tropical rainforests) is largely due to a number of technical skills that we have been able to apply in the construction of shelters and the manufacture of clothing (Figure 2.2). While the shelter must be considered the more important means of environmental control, at least from a qualitative point of view clothing provides a highly desirable degree of individual control within the sheltered environment.

## 2.2 Some Physiological Considerations

The range of temperatures to which the human body can adjust without discomfort is actually quite small. This is due to the fact that the zone of thermal comfort for the human body is restricted to the temperature range in which the deep body temperature can be regulated by the control of blood flow in the skin and underlying tissue. In medical terms this is referred to as the *vaso-motor control* mechanism. Should the temperature gradient between the skin and surrounding air be negative (i.e., if the air temperature is lower than the body temperature) the vaso-motor control mechanism will constrict blood vessels so that the amount of heat lost from the blood is reduced. Conversely, in the case of a positive temperature gradient blood vessels will automatically dilate, and so proportionally increase heat loss from the blood (Figure 2.3).

The normal deep body temperature of the human body is approximately 98.6°F, which is kept constant by the vaso-motor control mechanism to within 1% in the case of a healthy person. While virtually any fall in deep body temperature can have disastrous consequences, a little more latitude exists on the high side. The human body can operate with reasonable efficiency up to a deep body temperature of about 103°F.

Immediately outside the vaso-motor control range the body resorts to involuntary muscular activity in the form of shivering to increase heat production, and evaporation from the skin and respiratory system (as well as insensible or osmotic perspiration) for increased heat loss (Figure 2.4). Both shivering and sweating are, however, associated with discomfort and must therefore be regarded as emergency measures (Figure 2.5). Furthermore, they must be described as inexact, slow in response and wasteful to the body in either food or water and salt intake.

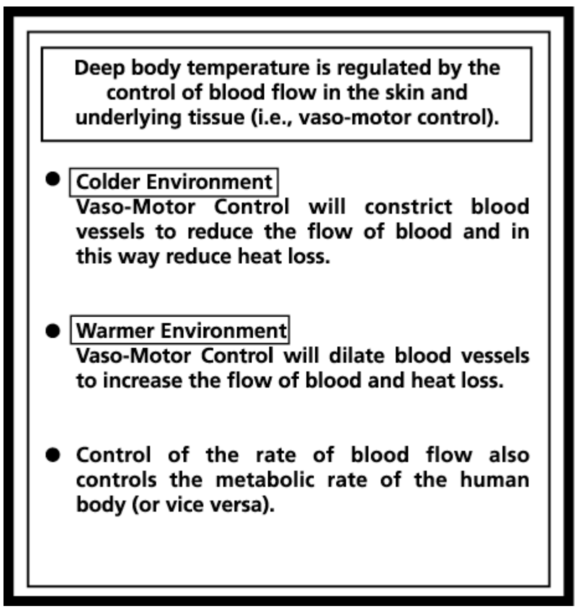


Figure 2.3: Vaso-motor control mechanism

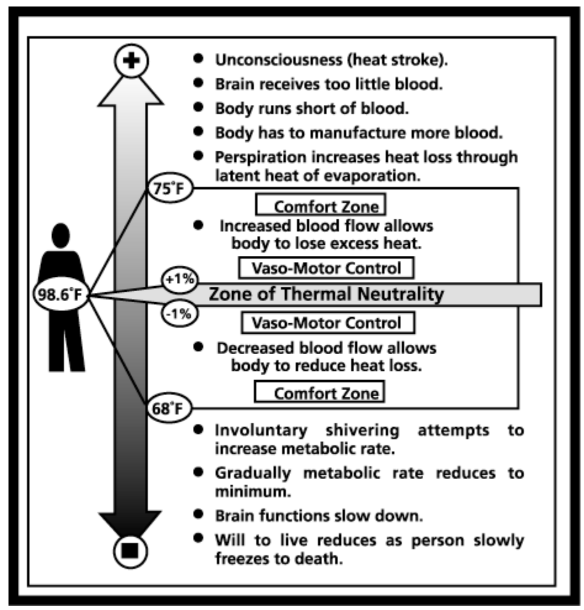


Figure 2.4: Human comfort and discomfort

From a general point of view, the operation of the human body as a heat engine that exchanges heat with the environment by convection, radiation and evaporation is described by the following equation:

$$M = E \pm C \pm R \pm S \qquad (2.1)$$

Where: M = heat produced by metabolism

E = heat exchanged by evaporation

C = heat exchanged by convection

R = heat exchanged by radiation

S = storage

It is an essential requirement of comfort that any variations in the amount of storage are made solely to meet involuntary physiological responses, such as the diurnal temperature rhythm, and that the heat exchange due to evaporation should be as small as possible. Subject to these restrictions, however, some flexibility and therefore convenient degree of control may be obtained by the adjustment of the remaining variables in equation (2.1).

Although the rate of metabolism is normally almost entirely governed by the work performed or the activity of the person, there is no doubt that adjustments can be and are often made to achieve thermal comfort. The architect can do much to avoid the unnecessary expenditure of energy, thereby limiting the rate of metabolism. For example, in residential buildings consideration of floor levels (e.g., avoidance of split floor levels), space layout (e.g., minimization of walking distances and comfortable height shelving), ceiling height, and natural air movement provide the designer with some control over the metabolic rate of the occupants.

Heat exchange by evaporation will involve sweating and must therefore be avoided wherever possible. Thought must also be given to the facilitation of perspiration under conditions that require a considerable amount of heat loss from the body. High levels of humidity tend to occur in laundries, kitchens and bathrooms, as well as in a large number of industrial manufacturing environments. Under these conditions the body must rely on its ability to lose large amounts of heat by evaporation (Figure 2.5). Since the rate of evaporation depends on air movement and vapor pressure, the importance of orientation, ventilation and dehumidification cannot be overstated (Figure 2.6).

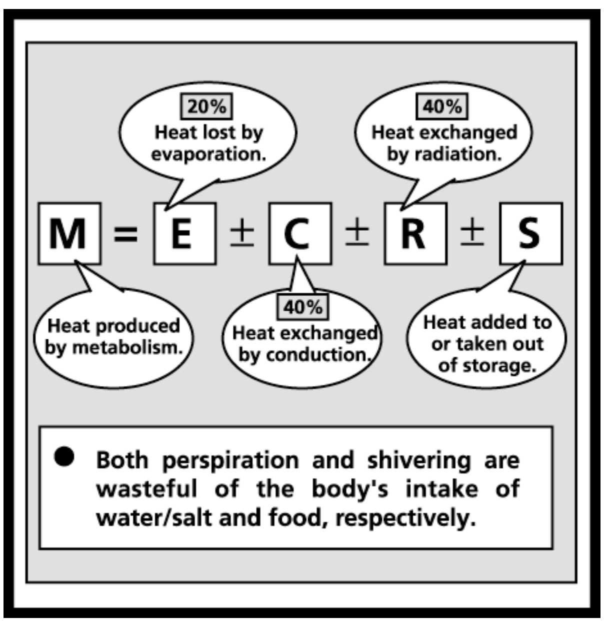


Figure 2.5: Proportional heat exchange

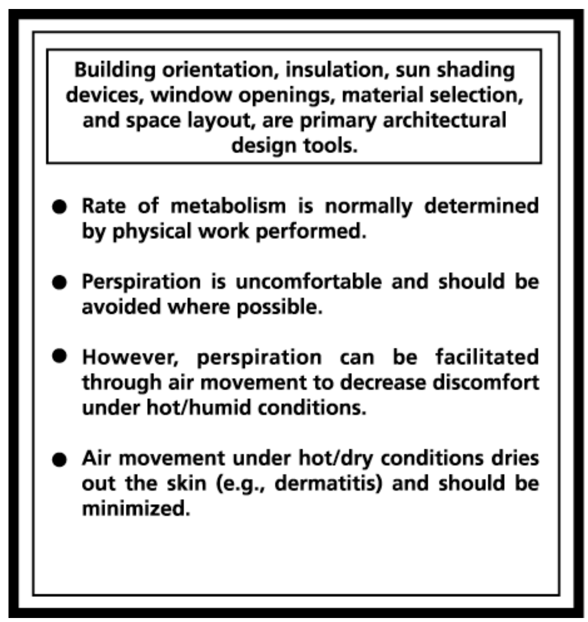


Figure 2.6: Thermal comfort control factors

The rate of convection is very much influenced by air movement, and although it is normally desirable to facilitate heat loss by convection in hot humid climates, care must be taken to avoid exposure to wind in hot dry climates. The latter would cause the skin to dry out and could ultimately lead to dermatitis or similar skin complaints (Figure 2.6).

The degree of solar radiation control that may be exercised by orientation, shading, reflective surfaces, and so on, is well known and will be elaborated on in later sections.

It suffices here to mention that careful consideration of the use of trees, screens, sunshading devices, and especially treated glass to produce a comfortable thermal environment is mandatory during the early planning stage of any building project.

Fortunately, in a given work space most of the occupants will be expending approximately equal amounts of energy. Furthermore, fashion has a tendency to restrict individual clothing variations, although the absence of one or more garment, such as a coat or cardigan, will allow some degree of individual control. This small degree of personal control seems to be essential, since it is most unlikely that any centrally controlled environment will satisfy more than two-thirds of the occupants.

For normally clad, sedentary adults the preferred temperature that will satisfy approximately 80% of building occupants is 73°F. Of the remainder half will consider this temperature to be too warm and half too cold (Figure 2.7). Accordingly, compliance with a federally (US Government) mandated internal temperature standard of 68°F (i.e., in winter) for all public buildings will require most building occupants to wear more clothing.

We may then define the zone of thermal neutrality for a person as the condition or range of conditions in which the body is not required to take any particular action to maintain its heat balance. Should the rate of heat loss increase through a fall of air temperature or increased air movement, the flow of blood through the skin will decrease. Consequently, the temperature of the skin will fall so that the deep body temperature can remain constant. With further increases in heat loss, the rate of metabolism will be increased by involuntary shivering or voluntary muscular activity (Figure 2.4). Conversely, if the rate of heat dissipation is reduced, the flow of blood through the skin will increase and balance with be achieved by a proportionate rise in skin temperature. Beyond this point, evaporative cooling is brought into play by operation of the sweat glands.

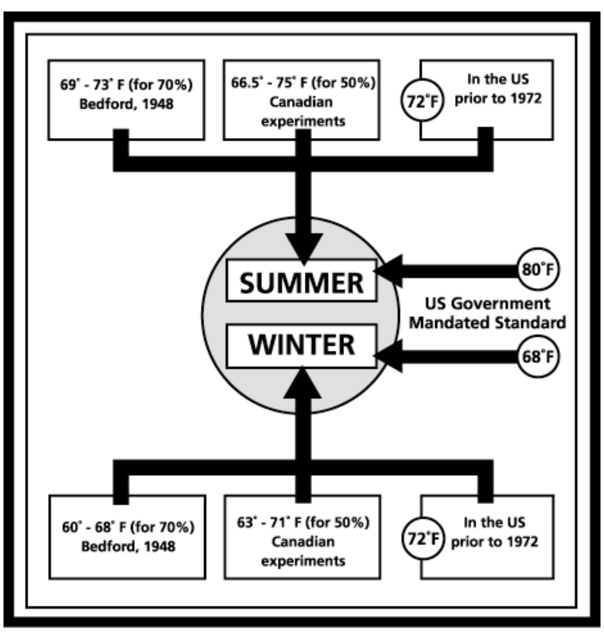


Figure 2.7: Objective comfort temperatures

**The desire of women for slightly warmer conditions in both winter and summer is due to differences in clothing.**

**Age:** The elderly are particularly sensitive to extremes in temperature.

**Diet:** Very high and very low calorie diets appear to slightly reduce heat tolerance.

**Health:** Any infection will reduce the ability to resist thermal stress.

**Work Efficiency:** The amount of muscular activity is directly related to individual heat tolerance. This is the most important factor contributing to individual differences.

**Acclimatization:** Appears to be due to behavioral adjustments (e.g., greater work efficiency) and not due to physiological changes.

Figure 2.8: Impacts on thermal comfort

The zones of thermal neutrality for adult persons at rest under varying clothing conditions may be broadly defined as follows:

normally clothed ………………………………….. 70°F to 75°F

lightly clothed …………………………………….. 80°F to 85°F

without clothing ………………………………….81°F to 86°F

During sleep the metabolic rate is at its lowest value and therefore a warmer environment is required. The temperature of an occupied bed is approximately 85°F, although bedroom temperatures around this value are found to interfere with sleep owing to excessive environmental warmth. In cold conditions the body temperature during sleep can be maintained only by increased insulation. Such insulation is normally provided in the form of blankets. If hot water bottles or similar unit heaters are used in bed, they are preferably applied to the feet. If these methods fail then the body will resort to shivering for the production of heat energy. In hot conditions we have to ask the question: "What is the highest temperature compatible with sleep?" Observations have shown that for sound sleep, entirely devoid of covering, the temperature in still air must exceed 80°F. The presence of any substantial degree of air movement will increase this temperature considerably.

## 2.3 More about Individual Differences

Generally speaking, women require slightly warmer conditions than men both in winter and in summer. However, experiments have shown that such differences can be explained in terms of clothing (Figure 2.8). It was found that interchange of the clothing appropriate to each sex produced negligible differences in the thermal sensations experienced by men and women.

Little is known about the preferences of children. The main difficulty here is that the metabolic rate of children varies appreciably from moment to moment, due to rapid changes in activity. Infants on the other hand are particularly susceptible to changes in environmental temperature. Both heat and cold can be equally disastrous, especially since infants are unable to call attention to their needs.

The elderly are another group who are particularly sensitive to extremes of temperature. It is generally recognized that with increasing age the temperature span to which elderly persons can adapt narrows down appreciably.

Further, it is well known that even individuals of the same sex and age vary in their susceptibility to heat. These differences may be attributed to a number of contributing factors (Figure 2.8):

***Diet:*** There is reason to believe that a high calorie diet somewhat reduces heat tolerance generally. The same applies to a very low-calorie diet.

***Efficiency:*** The mechanical efficiency with which a person performs a task appears to be one of the most important factors contributing to individual differences of heat tolerance. In other words, the amount of muscular activity bears a direct relationship to individual heat tolerance.

***Health:*** Any disease or infection within the body system will reduce the ability of the body to resist stress.

***Acclimatization:*** The belief that in tropical countries persons will be satisfied with higher temperatures in a controlled building environment than persons living in temperate climates, appears to be quite erroneous. The role which acclimatization plays in heat tolerance can be explained in terms of short range and long-range conditioning factors. Improvement in the means of losing heat from the body occurs in the short term, while reduction in heat production due to greater efficiency in the performance of work occurs over a longer term. However, it has been found that when acclimatized subjects are given a free choice of temperature, their preferences vary little from those persons who are not acclimatized.

When the human body fails to lose heat at the same rate as it is gaining heat, the results can be disastrous and we are said to be suffering from heat stress. In this sense stress is an attribute of the environment, and by analogy with Hooke's law it is the pressure applied (Figure 2.9). Strain, on the other hand is an attribute of the occupants of the environment and is related to the physiological deformation resulting from the application of the stress. Stresses such as high or low temperature, glare and noise are usually cumulative, so that even low levels of a number of these factors, although innocuous in themselves, may give rise to a high level of discomfort when summated.

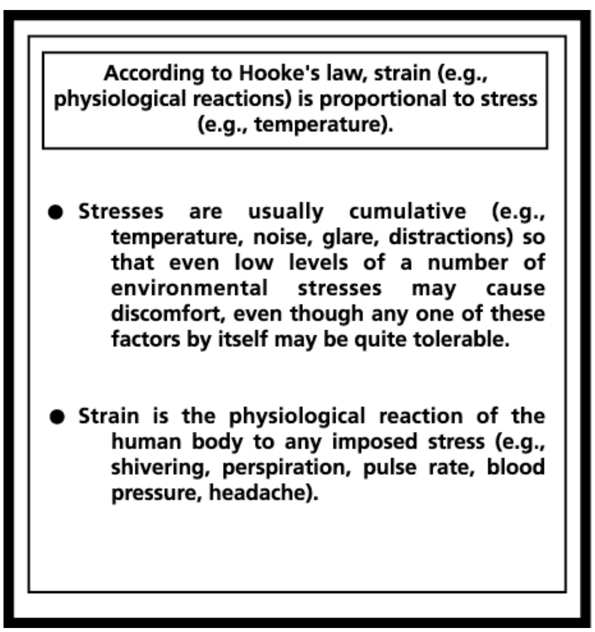


Figure 2.9: Hooke's law applied to the thermal environment

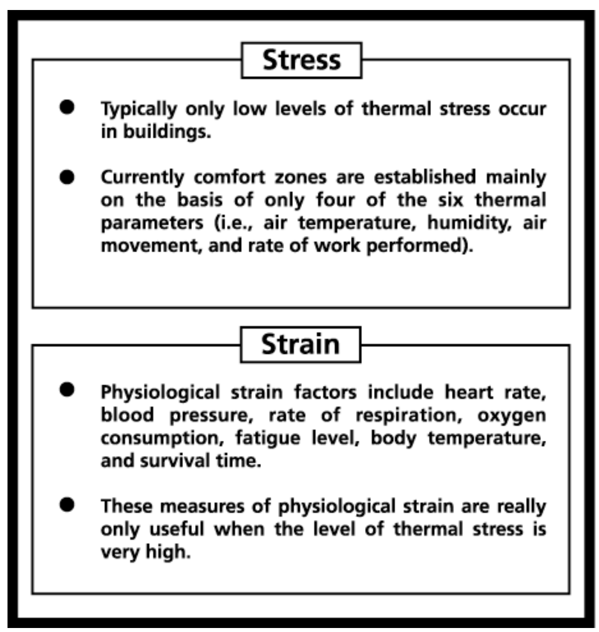


Figure 2.10: Thermal stress and strain relationships

Even though vaso-motor control provides us with an excellent heat-regulating mechanism that seldom allows the body temperature to rise to a dangerous level, this mechanism makes severe demands upon our body. In hot climates, it is these demands of temperature regulation whenever we experience difficulty in dissipating heat that will eventually lead to heat stress in the following stages (Figure 2.4):

- By virtue of the vaso-motor control mechanism the blood vessels of the skin and underlying tissues dilate to increase the rate of heat loss from the body.
- More blood passes through the skin to cool it, thus more blood must be manufactured.
- The ability to make blood is, however, limited with the result that there will tend to be a blood shortage.
- The brain being at the highest point of the body may be deprived of a sufficient supply of blood. Heat exhaustion will eventually result, accompanied by the characteristic symptoms of headache, nausea and finally unconsciousness.

While the human body has a remarkable sweating capacity and is able to lose as much as four gallons of water per day, this must be replaced by drinking. Under such circumstances the already precarious blood supply is still further depleted and the affinity to heat exhaustion is precariously increased.

## 2.4 Measurement of the Thermal Environment

The assessment of the thermal environment is one of the oldest judgments made by man, although it is only since the German physicist Gabriel Fahrenheit (1686-1736) devised a satisfactory temperature scale in 1714 that we have been able to assign numerical values to prevailing environmental conditions. The Industrial Age focused attention on the assessment of environmental stress by determination of the intensity of thermal stress present in a given situation. This change in outlook was accompanied by the emergence of standards of acceptable working conditions accepted by employers, driven by the demands of workers and their unions.

Stress may be measured either in physical terms using the parameters, temperature, humidity, pressure, and so on, or by determining the physiological strain produced. In the latter case, heart rate, blood pressure, rate of respiration, oxygen consumption, fatigue, body temperature, and survival time, are all available parameters for the measurement of strain (Figure 2.10). However, these measures of physiological strain are satisfactory measures of stress only when the level of stress is very high. Accordingly, if and when it can be satisfactorily measured comfort remains the most useful measure of the lower levels of stress which normally occur in buildings.

While the influential role of temperature, humidity, air movement, and mean radiant temperature in determining thermal comfort was already well established, the interest in production rates added two further thermal parameters, namely the rate of work performance and the clothing worn. To date, it has not been possible to combine all six of these parameters into a single *index of thermal stress*, although there are a number of indices that incorporate at least two or three of these parameters (Figure 2.11).

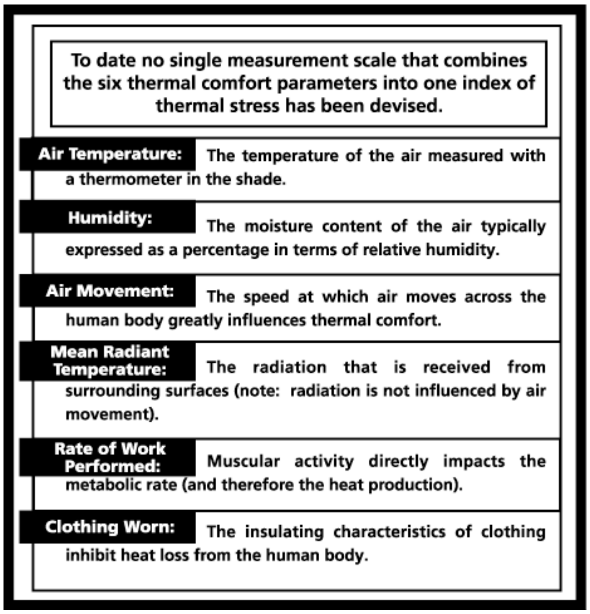


Figure 2.11: The thermal comfort parameters

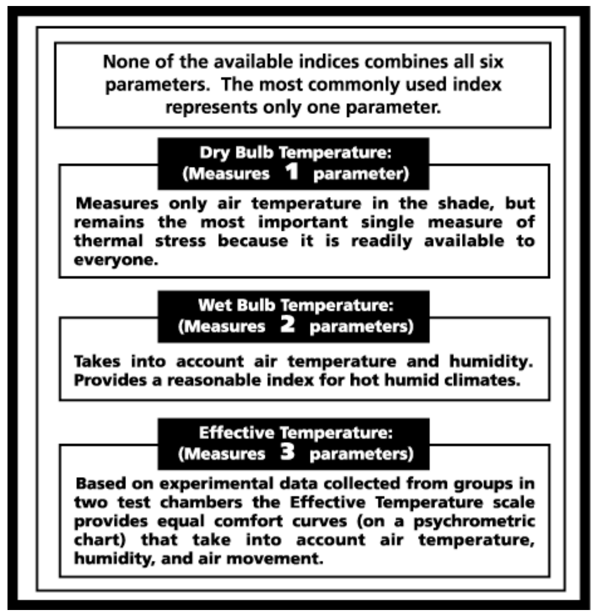


Figure 2.12: Very common thermal indices

Accordingly, comfort zones are established mainly on the basis of four of the six parameters of thermal stress, namely, air temperature, humidity, air movement and rate of work performed. The question then remains: "Which of the available indices should be applied to assess the severity of any particular environment?" Before we can delve into this question more deeply it is appropriate to briefly survey the principal indices available today.

***Dry-Bulb Temperature:*** Despite its obvious shortcomings, since it takes into account only one parameter (i.e., temperature), dry-bulb temperature remains the most important single measure of thermal stress (Figure 2.12). Weather forecasts that we hear daily on our radios and see on our television screens utilize temperature (i.e., dry-bulb temperature) as one of the principal indicators of tomorrow's weather conditions.

***Wet-Bulb Temperature:*** This thermal indicator takes into account two factors, namely, temperature and humidity, while the important effects of air movement and radiation are disregarded. It provides a reasonable measure of the physiological effects of hot-humid environments.

***Effective Temperature:*** The Effective Temperature scale was initially established as a series of equal comfort curves, based on experimental data by Houghton and

Yaglou (1923). The temperature and humidity in one test chamber was adjusted until the degree of comfort or discomfort experienced by a trained group of observers was judged to be identical to that experienced in an adjacent test chamber maintained at a different temperature and humidity (Figure 2.12). Combinations of dry-bulb and wet-bulb temperatures were then plotted on a psychrometric chart to obtain curves of equal comfort. The intersection of any one of these curves with the dew point defined an *effective temperature*. These early experiments on Effective Temperature were followed by further work that also took into account such factors as clothing and muscular activity. Today, effective temperature may be described as an index that provides in a single numerical value a convenient measure of the interrelated effects of temperature, humidity and air movement. Further, by the provision of a normal and basic scale, it makes some allowance for the effect of clothing. In the mid-1950s it was demonstrated that by the addition of a simple monogram, Effective Temperature can also take into account the rate at which a person is performing work.

***Equivalent Temperature:*** Proposed in the early 1930s, Equivalent Temperature is defined as the temperature of a uniform enclosure in which, in still air, a sizeable black body at 75°F would lose heat at the same rate as in the environment in question (Figure 2.13). Accordingly, equivalent temperature is a measure of the combined effect of the temperature and movement of the air and the temperature of the surroundings. An instrument, called a *eupathoscope*, was invented to measure Equivalent Temperature. It consists of a blackened copper cylinder 22 inches high and 7.5 inches in diameter, the surface of which is maintained by internal electric heaters at a constant temperature of 75°F, to measure Equivalent Temperature. A few years later Bedford (1936, 1951) devised a monogram to more conveniently determine the Equivalent Temperature of an environment if the individual thermal parameters are known.

***Globe-Thermometer Temperature:*** This thermal index was introduced in the late 1920s as a means of measuring the combined effect of air temperature, air movement and mean radiant temperature. Unfortunately, the Globe-Thermometer Temperature index can give misleading measurements under certain thermal conditions. First, in cold climates an increase in air movement will produce a rise in the temperature reading. Second, when the air and surrounding walls are of the same temperature the globe-thermometer will continue to show this temperature regardless of changes in air movement. For these reasons its use as a measure of thermal stress has been largely abandoned, although it remains to the present day one of the most successful methods of determining the mean radiant temperature of the surroundings of a building space.

***Predicted 4-Hour Sweat Rate (P4SR):*** This index was developed at the National Hospital, London in the late 1940s. Basically, P4SR is in the form of a monogram that is derived from experimental data and expresses the stress imposed by a hot environment in terms of the amount of sweat secreted by fit, acclimatized, young men when exposed to the environment under consideration for a period of four hours (Figure 2.14). As such, P4SR represents a considerable advance over other previous indices, since it takes into consideration not only the environmental parameters of temperature, air movement and humidity, but also the rate of energy expended and the clothing worn. However, P4SR is not suitable as a comfort index because it applies only when perspiration occurs.

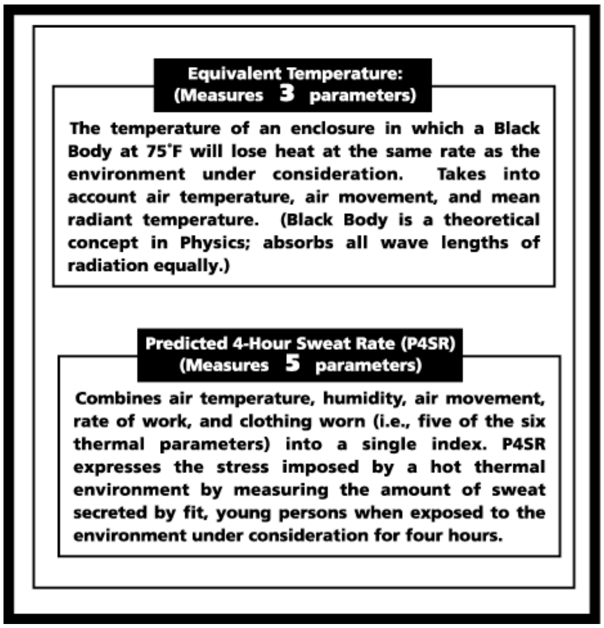


Figure 2.13: Less common thermal indices

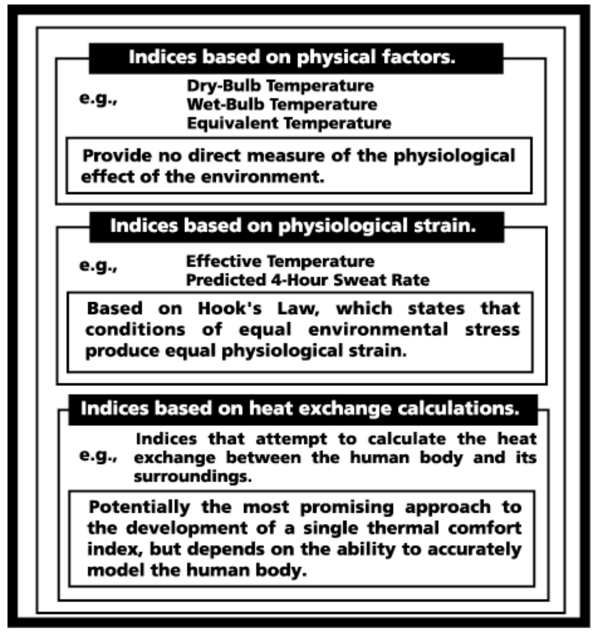


Figure 2.14: Groups of thermal indices

***Wet-Bulb Globe-Thermometer Index:*** This index was devised in the 1950s for the US Army as a means of preventing heat casualties at military training centers. As a single thermal index, it incorporates the effects of air temperature, humidity, air movement and solar radiation as defined by the following equation:

**WBGT = 0.7 WB + 0.2 GT + 0.1 DB……………………………(2.2)**

Where: WB = wet-bulb temperature

GT = globe-thermometer reading

DB = dry-bulb temperature

This index has considerable merit due to its simplicity and the fact that it can be applied out of doors.

These are only some of the many available indices for the assessment of the thermal environment. MacPherson (1962) describes 19 indices. Since many of these indices are based on similar principles, it is convenient to establish three fundamental groups (Figure 2.14), as follows:

***Indices based on the measurement of physiological factors*** such as Dry-Bulb Temperature, Wet-Bulb Temperature, Equivalent Temperature, and Globe-

Thermometer Temperature. Although all of these indices take into account air temperature and some combine this with air movement or humidity, they provide no direct measure of the physiological effect produced by the environment.

***Indices based on physiological strain*** including Effective Temperature and later modifications, Predicted Four Hour Sweat Rate (P4SR), and the Wet-Bulb Globe-Thermometer index are based on the assumption, by analogy with Hooke's law, that conditions of equal environmental stress will produce equal physiological strain. It is common practice to express the relationship between stress and strain in the form of monograms.

***Indices based on the calculation of heat exchange*** such as Operative Temperature and Standard Operative Temperature, Index for Evaluating Heat Stress, and the Thermal Acceptance Ratio, which attempt to calculate the heat exchange between the human body and its surroundings. Although the precise calculation of the quantity of heat transferred is fairly uncertain, and the relationship between this and the severity of the environment is a matter of debate, there seems little doubt that these indices potentially provide the most satisfactory approach to the development of a single comfort index.

We are therefore confronted with a wide range of indices of thermal stress, from which we must make a choice for the measurement of any particular environment. Furthermore, the assessment of the environment must be based on the measurement of all of the parameters, whether they are directly due to the environment such as air temperature and air movement, or are attributes of the exposed persons, as in the case of clothing and work performance.

## 2.5 Selecting the Appropriate Index

The following guidelines (Figure 2.15), while perhaps oversimplifying the problem, are generally accepted for the selection of indices of thermal stress for specific conditions:

- The index must cover the correct range of temperatures. The Equivalent Temperature scale (Figure 2.13), for example, does not extend beyond 75°F, while the Predicted 4-Hour Sweat Rate (Figure 2.13) and the Wet-Bulb Temperature (Figure 2.12) apply only to conditions where sweating occurs.
- If an index is required for the comparison of two or more situations in which a number of factors are identical (e.g., rate of work and air movement) then there is no advantage in selecting an index which incorporates these factors.
- If there remains a choice of two indices, the simpler one should be chosen. For example, in some cases the Dry-Bulb Temperature will suffice as an index. Often when defining comfort conditions of office

workers for the purpose of air conditioning, air temperature alone will provide a satisfactory measure of the environment. The occupants are usually clad alike and engaged in similar physical tasks, while air movement would normally not vary greatly in a sealed environment. Further, there will not be any significant difference between the temperature of the air and enclosing walls unless the latter embody a heating system. Humidity may be safely disregarded on the basis that since we are dealing with comfort conditions, sweating must not occur and therefore any evaporative heat loss which could be affected by the ambient humidity is mainly confined to water loss from the lungs. Such heat loss constitutes less than 25% of the total heat transfer in comfort conditions. This is confirmed by the experimental work of Bedford, Yaglou and Koch who have demonstrated that changes of up to 50% in relative humidity will produce a change of less than 2°F in the Dry-Bulb Temperature. Obviously, these circumstances are considerably altered in hot, wet environments encountered in mills, laundries and mines. There, the heat exchange is chiefly due to evaporation and it is likely that Wet-Bulb Temperature, which takes into account air temperature and humidity, will provide an adequate means of assessing the environment.

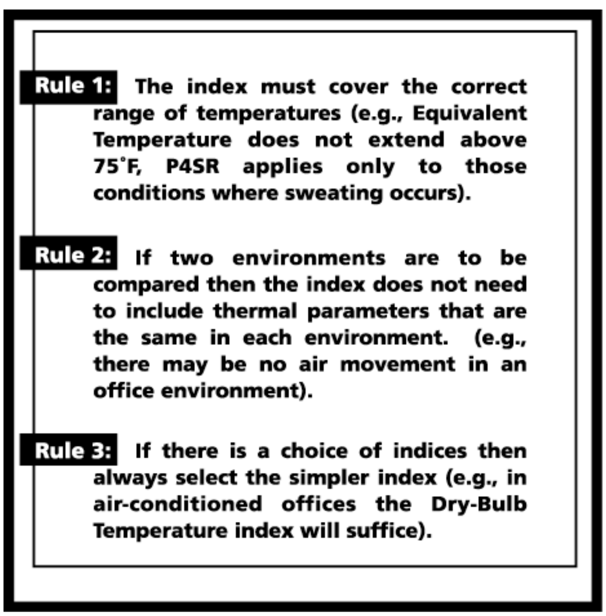


Figure 2.15: Index selection rules

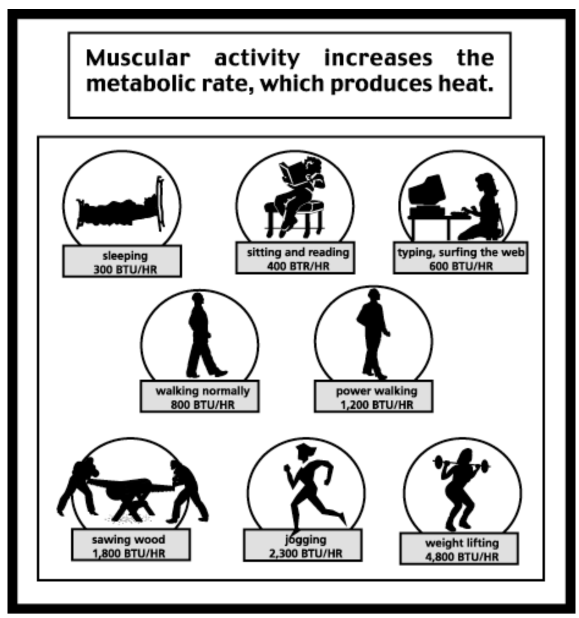


Figure 2.16: Typical metabolic rates

- If considerable variations in air movement are likely to occur in the environment under consideration, or if the air is hot and dry, then both the Predicted 4-Hour Sweat Rate and the Effective Temperature may be applied. However, if such an environment contains a significant radiation component, the Effective Temperature scale must be corrected for radiation.

## 2.6 Thermal Comfort Factors

While the similarity between the comfort zone and the zone of thermal neutrality (at which by definition the human body takes no particular action to maintain its heat balance) is evident, both are very much subject to individual preferences, clothing, activity and age. In fact, the problem of individual differences encountered in the assessment of the comfort zone has become increasingly more complex. Although clothing can be effectively used to provide individual variation, it is well to remember that our garments serve many other purposes besides thermal comfort (i.e., social convention, fashion, availability of materials, and so on). Recent investigations in the Arctic region have demonstrated that in the absence of social convention the human being is able to adjust by means of clothing to any reasonable indoor temperature. Under these circumstances it was found to be quite useless to define a comfort or preferred temperature zone. Obviously, a certain amount of latitude exists in the case of protection against cold conditions. In hot climates, people usually wear the minimum clothing that convention will permit and thus there exists far less latitude in the adjustment of individual differences by means of clothing.

In general terms, we can define the requirements of a comfortable thermal environment, as follows:

***General Thermal Effects*** of the environment attributable to the parameters of air temperature, relative humidity and air movement. According to Bedford, a habitable space should be: as cool as is possible within the comfort zone; be subject to adequate air movement, although both monotony and local droughts must be avoided; and, have an ambient relative humidity within the wide range of 30% to 70%. Further we can distinguish between two overall thermal problems. If a space is *too cold* then this is most likely due to a low air temperature with or without excessive air movement. On the other hand, if a space is *too hot* then this may be attributable to either of the combinations of high air temperature and high humidity or insufficient air movement and excessive radiation.

***Local Thermal Effects*** such as excessive local warmth are to be avoided. Undue temperature gradients that may occur due to differences in temperature at different heights of a space will cause discomfort, although it is generally accepted that the floor should be at the highest temperature with the temperature gradient gently decreasing toward the ceiling. Excessive loss of heat from body extremities such as the feet and the local overheating of the heads of occupants by radiant heat, are two common sources of discomfort.

***Density of Occupation*** will not only have an effect on air temperature and humidity by virtue of the heat and moisture contributed to the environment by the occupants, but also strongly influence the subjective concepts of *freshness* and *stuffiness*. As our standards of thermal comfort become more sophisticated a thermally comfortable environment will not be acceptable unless it is accompanied by a quality of freshness. Although it is generally recognized that freshness is related to coolness, absence of unpleasant odors, slight air movement and a psychologically desirable feeling of change, and that stuffiness is partly defined by a degree of hotness, the presence of unpleasant odors and the absence of air movement, little scientific information has been collected on either of these comfort factors.

***Activity of the Occupants*** may involve muscular activity, which will increase the metabolic rate and therefore the body will produce more heat. This additional heat must be dissipated by the body at an increased rate so that thermal neutrality is immediately restored. Accordingly, the comfort zone for persons engaged in heavy physical work is different from that required for office workers (Figure 2.16). The approximate rates of heat production for various degrees of activity have been established on the basis of experiments:

| | | | |
|---|---|---|---|
| sleeping person | = | 300 | BTU/hr. |
| sitting person | = | 400 | BTU/hr. |
| typing or writing | = | 600 | BTU/hr. |
| walking slowly | = | 800 | BTU/hr. |
| walking briskly | = | 1,200 | BTU/hr. |
| hand sawing | = | 1,800 | BTU/hr. |
| medium jogging | = | 2,300 | BTU/hr. |
| severe exertion | = | 4,800 | BTU/hr. |

Most of the attendant heat loss from the body takes place by radiation (40%) and convection or conduction to air (40%). However, since the surface of the body is always slightly moist, a further loss will take place by evaporation (20%). The latter component will substantially increase whenever large scale perspiration sets in.

## 2.7 The Psychrometric Chart

The thermodynamic interactions of the various properties of moist air such as temperature, humidity and enthalpy (i.e., the total energy content of the moist air in terms of heat and pressure) are complex and difficult to visualize. It was not until the early 1900s that Willis Carrier[1], an American engineer, formulated the theoretical equations that allowed all of these properties to be represented graphically in a single diagram that became known as the Psychrometric Chart. As seen in Figure 2.17, the chart shows these properties in relationship to each other so that just knowing the dry-bulb and wet-bulb temperatures one can easily determine other dependent properties such as the relative humidity and the actual moisture content of the air in grains[2] per LB or CF of air.

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[1] The Psychrometric Chart was primarily developed by Willis Carrier who found Carrier HVAC that became a prominent HVAC company. In 1904, Carrier created a chart to analyze and represent the properties of air in different states of humidity and temperature. His work formed the foundations of modern HVAC design and practices.

[2] The ‘grain’ is a miniature weight unit in the Inch-Pound system of units, where 1 grain is approximately equal to one 7000th of a pound (i.e., 0.002285 ounces or 0.0001428 LB, since there are 16 ounces in one pound).

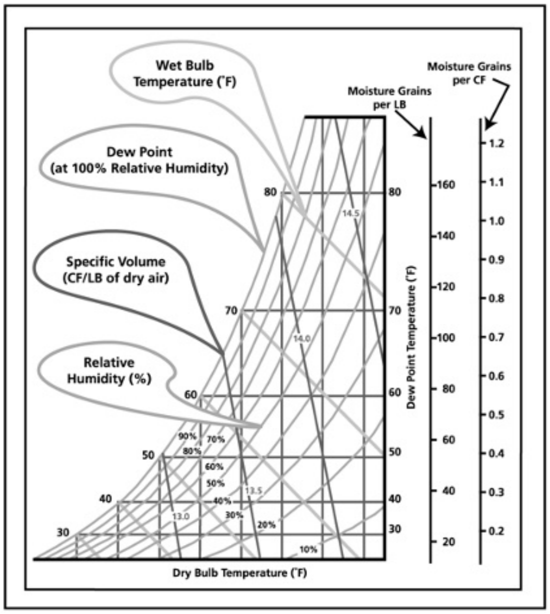


Figure 2.17: Principal moist air properties represented in the Psychrometric Chart

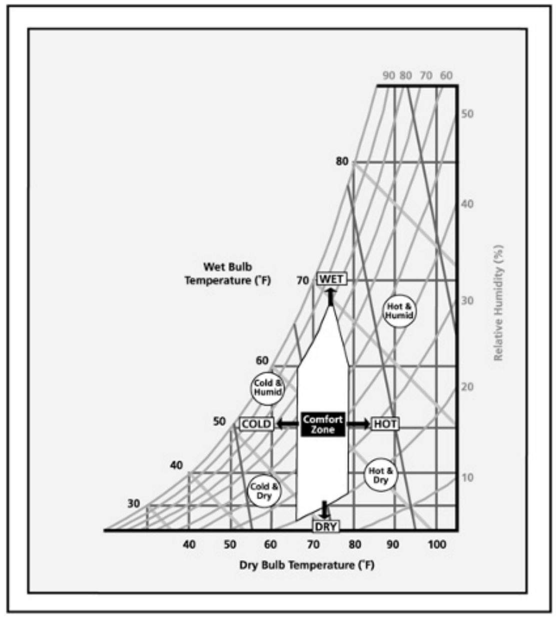


Figure 2.18: Depiction of the boundaries of the comfort zone

It is not necessary to know the complex equations that were devised by Carrier and that enabled him to develop the Psychrometric Chart to be able to use the valuable information that it provides for determining the boundaries of the thermal comfort zone (Figure 2.18) and the impact that changes in the thermal environment will have on those boundaries.

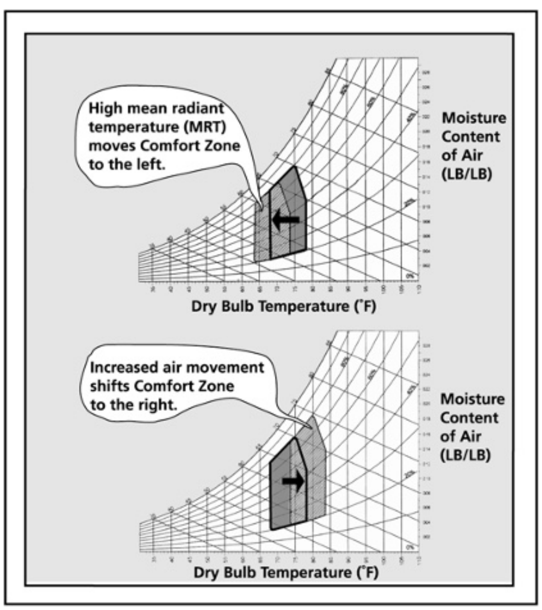


Figure 2.19: Extending the comfort zone through focused radiation and air flow

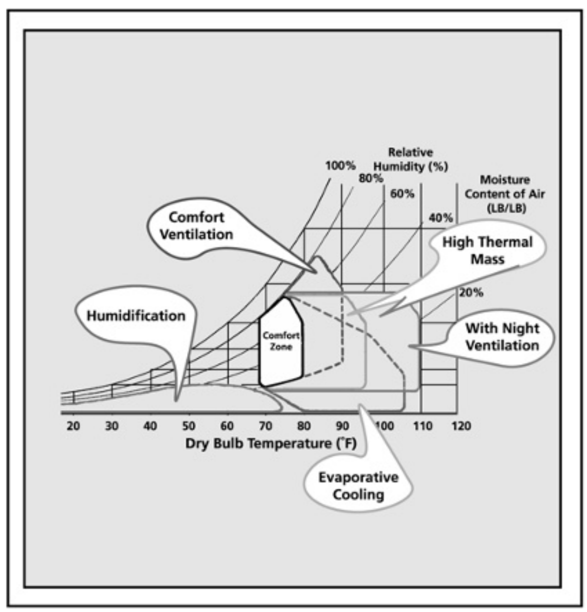


Figure 2.20: Other opportunities for extending the comfort zone boundaries

Figures 2.19 and 2.20 show how the Psychometric Chart can be used to visualize the impact of available passive and mechanical methods for extending the thermal comfort zone, such as: compensating for lower air temperatures with radiant heating; and, compensating for higher air temperatures and increased relative humidity with natural cross-ventilation or evaporative cooling.

The key parameters of the thermal environment that can be easily measured and from which in fact all of the psychrometric data for any particular barometric pressure can be deduced, are dry-bulb temperature and wet-bulb temperature. Dry-bulb temperature measures the actual air temperature with a common thermometer. Wet-bulb temperature is measured with a thermometer that has a wet wick placed over its bulb. It is called a sling thermometer because it is whirled around as it measures the temperature of the air when it is fully saturated with moisture. Therefore, the wet-bulb temperature is always lower than the dry-bulb temperature unless the relative humidity is 100%. It should be noted that psychrometric data is dependent on barometric pressure. For this reason, there are separate psychrometric charts for sea level and high-altitude conditions.

## 2.8 Questions Relating to Chapter 2

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at back of the book.

1. **The zone of thermal comfort for human beings is restricted to the temperature range in which the deep body temperature can be regulated by *vaso-motor* control, which is essentially the control of __________________. If the air temperature is lower than the body temperature the vaso-motor control mechanism will ____________________ so that the amount of heat lost from the ____________________ is reduced. Choose the missing words.**

    A. the heart rate; reduce the metabolic rate; body.
    B. the blood flow; constrict the blood vessels; blood.
    C. the metabolic rate; increase the metabolic rate; body.
    D. the pulse rate; reduce the heart rate; skin.
    E. All of the above (i.e., A, B, C and D) are incorrect.

2. **The normal deep body temperature of a human being is about X˚F, which is kept constant by the vaso-motor control mechanism to within Y% in the case of a healthy person.**

    A. X = 98˚F; Y = 1%
    B. X = 75˚F; Y = 5%
    C. X = 100˚F; Y = 0.1%
    D. X = 89˚F; Y = 10%
    E. X = 72˚F; Y = 1%

3. **Which (if any) of the following statements is <u>not correct</u>?**

    A. The human body can operate with efficiency up to a deep body temperature of about 103˚ F (≈ 40˚ C).

B. If the air temperature is higher than the body temperature, the blood vessels will tend to dilate.

C. Both shivering and sweating are produced by the vaso-motor control mechanism and are slow in response, wasteful, and inexact.

D. Both shivering and sweating are involuntary muscular activities which increase heat production and increase the ability of the human body to lose heat, respectively.

E. All of the above statements (i.e., A, B, C and D) are correct.

4. **Which (if any) of the following statements is <u>not correct</u>?**

A. It is an essential requirement of thermal comfort that any variations in the amount of storage are made solely to meet involuntary physiological responses.

B. The rate of evaporation from the human body depends largely on air movement.

C. Care must be taken to avoid exposure of the skin to air movement in hot, humid climates.

D. The operation of the human body as a heat engine is described by the equation:

$$M = E \pm C \pm R \pm S$$

where: M = heat produced by metabolism
E = heat exchanged by evaporation
C = heat exchanged by convection
R = heat exchanged by radiation
S = storage

E. All of the above statements (i.e., A, B, C and D) are correct.

5. **For normally clad, sedentary adults the preferred ambient air temperature that will satisfy approximately 80% of persons is:**

A. 65˚ F (≈ 18˚ C)

B. 58˚ F (≈ 14˚ C)

C. 73˚ F (≈ 23˚ C)

D. 85˚ F (≈ 29˚ C)

E. 88˚ F (≈ 31˚ C)

6. **Which (if any) of the following statements is <u>not correct</u>?**

A. In cold conditions the body temperature during sleep can only be maintained by increased insulation.

B. Observations have shown that for sound sleep, persons entirely devoid of any type of covering will require an air temperature of about 80˚F regardless of the degree of air movement.

C. Although women normally require slightly warmer conditions than men, both in summer and winter, this apparent difference between the sexes can be explained in terms of clothing.

D. All of the above statements (i.e., A, B and C) are correct.

E. All of the above statements (i.e., A, B and C) are incorrect.

7. **Individual differences in thermal response may be explained by a number of contributing factors. Which (if any) of the following do you <u>not consider</u> to be a contributing factor?**

   A. Diet.

   B. Efficiency of task performance.

   C. Health.

   D. Age.

   E. All of the above (i.e., A, B, C and D) are contributing factors.

8. **Which (if any) of the following would you <u>not consider</u> to be one of the six (6) parameters of thermal stress:**

   A. Surface temperature

   B. Humidity

   C. Air temperature

   D. Mean radiant temperature

   E. All of the above (i.e., A, B, C and D) are parameters of thermal stress.

9. **Which (if any) of the following would you <u>not consider</u> to be a parameter for the measurement of physiological strain.**

   A. Blood pressure

   B. Rate of respiration

   C. Body temperature

   D. Heart rate

   E. All of the above (i.e., A, B, C and D) are valid parameters for the measurement of physiological strain.

10. **To date, it has not been possible to combine all of the six (6) parameters of thermal stress into a single index. If the number in parenthesis behind each of the following indices indicates the number of parameters which this index takes into account, then which (if any) of the following are not correct.**

   A. Effective temperature (3)

   B. Equivalent temperature (3)

   C. Dry bulb temperature (1)

   D. Wet bulb temperature (2)

E. All of the above (i.e., A, B, C and D) are correctly stated.

11. **Which (if any) of the following statements is <u>not correct</u>?**

A. Effective temperature is not a satisfactory comfort index for hot, humid climatic conditions.

B. A person performing vigorous exercises would produce approximately 4000 BTU of heat per hour, which is about ten times the rate of heat production for a seated person.

C. Severe temperature gradients that may occur due to differences in temperature at different heights of a building space will cause discomfort, although it is generally accepted that the floor should be at the lowest temperature with the temperature gradient gently increasing toward the ceiling.

D. All of the above statements (i.e., A, B and C) are correct.

E. All of the above statements (i.e., A, B, C and D) are incorrect.

12. **Which (if any) of the following Indices of Thermal Stress are based on physical factors, as opposed to physiological strain.**

A. Wet Bulb Temperature.

B. Effective Temperature.

C. Predicted 4-Hour Sweat Rate.

D. All of the above statements (i.e., A, B and C) are correct.

E. All of the above statements (i.e., A, B, C and D) are incorrect.

13. **The approximate just acceptable limits of Dry Bulb Temperature for hot-dry (X°F) and hot-humid (Y°F) conditions are known to be, respectively:**

A. X = 73 and Y = 73.

B. X = 90 and Y = 95.

C. X = 95 and Y = 90.

D. X = 88 and Y = 82.

E. All of the above statements (i.e., A, B, C and D) are incorrect.

14. **Which (if any) of the following statements are <u>incorrect?</u>**

A. As muscular activity increases so does the metabolic rate, which produces heat. For a sedentary office worker this heat production is less than 700 BTU/hour.

B. From a qualitative and subjective viewpoint a ***comfortable*** thermal environment should be as cool as possible, have adequate air movement, and have a relative humidity between 70% and 30%.

C. Local thermal effects that are generally desirable include a ceiling temperature that is significantly higher than the floor temperature.

D. All of the above statements (i.e., A, B and C) are correct.

E. All of the above statements (i.e., A, B, C and D) are incorrect.