V. MEASUREMENT OF HEAT STRESS

The Occupational Safety and Health Administration (OSHA) defined heat stress as the aggregate of environmental and physical factors that constitute the total heat load imposed on the body [7]. The environmental factors of heat stress are air temperature and movement, water vapor pressure, and radiant heat. Physical work contributes to total heat stress of the job by producing metabolic heat in the body in proportion to the work intensity. The amount, thermal characteristics, and type of clothing worn also affect the amount of heat stress by altering the rate of heat exchange between the skin and the air [7].

Assessment of heat stress may be conducted by measuring the climatic and physical factors of the environment and then evaluating their effects on the human body by using an appropriate heat-stress index. This chapter presents information on (1) measurement of environmental factors, (2) prediction of climatic factors from National Weather Service data, and (3) measurement of metabolic heat.

A. Environmental Factors

The environmental factors which are of concern in industrial heat stress are (1) dry bulb (air) temperature, (2) humidity or more precisely water vapor pressure, (3) air velocity, (4) radiation (solar and infrared), and (5) microwave radiation.

1. Dry Bulb (Air) Temperature

The dry bulb temperature (t_a) is the simplest to measure of the climatic factors. It is the temperature of the ambient air as measured with a thermometer; therefore. Temperature units proposed by the International Standards Organization (ISO) are degrees Celsius (or Centigrade) C=(°F-32)x5/9 and degrees Kelvin °K=°C+273.

The primary types of thermometers used for measuring dry bulb temperature are (a) liquid-in-glass thermometers, (b) thermocouples, and (c) resistance thermometers (thermistor). These thermometers are basically different in the nature, properties, characteristics, and materials of the sensing element.

General precautions which must be considered in using any thermometer are as follows [81]:

- The temperature to be measured must be within the measuring range of the thermometer.
- The time allowed for measurement must be greater than the time required for thermometer stabilization.
- The sensing element must be in contact with or as close as possible to the area of thermal interest.

- Under radiant conditions (i.e., in sunlight or where the temperature of the surrounding surfaces is different from the air temperature), the sensing element should be shielded.

Each type of these thermometers has advantages, disadvantages, and fields of application as shown in Table V-1.

a. Liquid-in-Glass Thermometers

Although a thermometer is any instrument for measuring temperature, this term is commonly identified with the liquid-in-glass thermometer which is the simplest, most familiar, and the most widely used thermometer.

Mercury and alcohol are the more commonly used liquids. Mercury-in-glass thermometers are preferred under hot conditions, while alcohol-in-glass thermometers are preferred under cold conditions since the freezing point of mercury is -40°C (-40°F) and that of alcohol is -114°C (-173.6°F).

Thermometers used for measuring dry bulb temperature must be total immersion types. These thermometers are calibrated by total immersion in a thermostatically controlled medium, and their calibration scale depends on the coefficients of expansion of both the glass and the liquid. Only thermometers with the graduations marked on the stem should be used.

TABLE V-1.--Advantages, disadvantages and limitations, and fields of application for different types of temperature measuring instruments

	Liquid-in-glass thermometers	Thermocouples	Resistance thermometers
Advantages	1. Simplest thermometers to use 2. Most readily available in various temperature ranges and with various degrees of accuracy 3. The least expensive of the temperature instruments 4. Compact, self-contained, and direct reading device	1. Adaptability to remote or continuous recording 2. Equilibrium time is almost instantaneous 3. Temperatures may be obtained within thin materials and narrow spaces 4. Less affected by radiation 5. High accuracy (0.1°C) can be obtained	1. Simple to use with minimum training 2. Output signal may be recorded 3. Variety of probes are available for different applications 4. Thermistors respond quickly to changing temperatures 5. Less affected by radiation 6. Calibration procedure
Disadvantages and Limitations	1. Fragile 2. Affected by radiation 3. Long stabilization time (at least 5 minutes) 4. Unsuitable for remote use	1. Require expensive measuring device 2. Require reference junction 3. Some kinds are subject to oxidation	1. High cost and hard to repair 2. Thermistor probes may require individual calibration before use 3. May require frequent calibration 4. Unreliable above 510°C
Fields of Application	1. Measuring range is from -200 to 540°C 2. Industrial-type are available for permanent installation 3. Measuring temperatures of gases and liquid by contact 4. Partial immersion thermometers are used for wet bulb and globe temperature measurements	1. Measuring range is from -190 to 1650°C 2. Used for measuring physiologic and surface temperatures 3. Remote measurement and recording 4. For measuring high temperatures	1. Measuring range is from -240 to 980°C 2. Remote measurement and recording 3. Frequently encountered in permanently installed temperature measurement or control systems 4. Calibration problems over range where it may be used

Adapted from Reference 81.

b. **Thermocouples**

A thermocouple consists of two wires of different metals connected together at both ends by soldering, welding, or merely twisting to form a pair of junctions. One junction is kept at a constant reference temperature, e.g., usually at 0°C (32°F) by immersing the junction in an ice bath. The second junction is exposed to the measured temperature. Due to the difference in electrochemical properties of the two metals, an electromotive force (emf) or voltage is created whose potential is a function of the temperature difference between the two junctions. By using a millivoltmeter or a potentiometer to measure the existing emf or the induced electric current, respectively, the temperature of the second junction can be determined from an appropriate calibration table or curve. Copper and constantan are the metals most commonly used to form the thermocouple.

c. **Resistance Thermometers**

A resistance thermometer or thermistor utilizes a metal wire (i.e., a resistor) as its sensing element; the resistance of the sensing element increases as the temperature increases. By measuring the resistance of the sensor element using a Wheatstone bridge and/or a galvanometer, the measured temperature can be determined from an appropriate calibration table or curve, or in some cases the thermistors are calibrated to give a direct temperature reading.

2. **Humidity**

Humidity, the amount of water vapor within a given space, is commonly measured as the relative humidity (rh), i.e., the percentage of moisture in the air relative to the amount it could hold if saturated at the same temperature. Humidity is important as a temperature-dependent expression of the actual water vapor pressure which is the key climatic factor affecting heat exchange between the body and the environment by evaporation. The higher the water vapor pressure, the lower will be the evaporative heat loss.

A hygrometer or psychrometer is an instrument which measures humidity; however, the term is commonly used for those instruments which yield a direct reading of relative humidity. Hygrometers utilizing hair or other organic material are rugged, simple, and inexpensive instruments; however, they have low sensitivity, especially at temperatures above 50°C (122°F) and an rh below 20%.

a. **Water Vapor Pressure**

Vapor pressure (p_a) is the pressure at which a vapor can accumulate above its liquid if the vapor is kept in confinement, and the temperature is held constant. SI units for water vapor pressure are millimeters of mercury (mmHg). For calculating heat loss by evaporation of sweat, the ambient water vapor pressure must be used. The lower the ambient water vapor pressure, the higher will be the rate of evaporative heat loss.

Water vapor pressure is most commonly determined from a psychrometric chart. The psychrometric chart is the graphical representation for the relationships among the dry bulb temperature (t_a), wet bulb temperature (t_{wb}), dew point temperature (t_{dp}), relative humidity (rh), and vapor pressure (p_a). By knowing any two of these five climatic factors, the other three can be obtained from the psychrometric chart.

b. Natural Wet Bulb Temperature

The natural wet bulb temperature (t_{nwb}) is the temperature measured by a thermometer which has its sensor covered by a wetted cotton wick and which is exposed only to the natural prevailing air movement.

In measuring t_{nwb} a liquid-in-glass partial immersion thermometer, which is calibrated by immersing only its bulb in a thermostatically controlled medium, should be used. If a total immersion thermometer is used, the measurements must be corrected by applying a correction factor [82]. Accurate measurements of t_{nwb} require using a clean wick, distilled water, and proper shielding to prevent radiant heat gain. A thermocouple, thermistor, or resistance thermometer may be used in place of a liquid-in-glass thermometer.

c. Psychrometric Wet Bulb Temperature

The psychrometric wet bulb temperature (t_{wb}) is obtained when the wetted wick covering the sensor is exposed to a high forced air movement. The t_{wb} is commonly measured with a psychrometer which consists of two mercury-in-glass thermometers mounted alongside of each other on the frame of the psychrometer. One thermometer is used to measure the t_{wb} by covering its bulb with a clean cotton wick wetted with water, and the second measures the dry bulb temperature (t_a). The air movement is obtained manually with a sling psychrometer or mechanically with a motor-driven psychrometer.

The sling psychrometer is usually whirled by a handle, which is jointed to the frame, for a period of approximately 1 minute. A motor-driven psychrometer uses a battery or spring-operated fan to pull air across the wick. When no temperature change occurs between two repeated readings, measurement of t_{wb} is taken. Psychrometers are simple, more precise, and faster responding than hygrometers; however, they cannot be used under low temperatures near or below the freezing point of water (humidity is usually 100% and water vapor pressure is about 3 mmHg).

d. **Dew Point Temperature**

Dew point temperature (t_{dp}) is the temperature at which the condensation of water vapor in air begins for a given state of humidity and pressure as the vapor temperature is reduced. The dew point hygrometer measures the dew point temperature by means of cooling a highly polished surface exposed to the atmosphere and observing the temperature at which condensation starts. Dew point hygrometers are more precise than other hygrometers or psychrometers and are useful in laboratory measurements; however, they are more expensive and less rugged than the other humidity measuring instruments and generally require an electric power source.

3. Air Velocity

Wind, whether generated by body movements or air movement (V_a), is the rate in feet per minute (fpm) or meters per second (m/sec) at which the air moves and is important in heat exchange between the human body and the environment, because of its role in convective and evaporative heat transfer.

Wind velocity is measured with an anemometer. The two major types are (a) vane anemometers (swinging and rotating) and (b) thermoanemometers. Table V-2 summarizes the advantages, disadvantages, and fields of application for these types of anemometers. It should be mentioned that accurate determinations of wind velocity contour maps in a work area are very difficult to make, because of the large variability in air movement both with time and within space. In this case, the thermoanemometers are quite reliable and are sensitive to 0.05 m/sec (10 fpm) but not very sensitive to wind direction.

TABLE V-2.--Advantages, disadvantages, and fields of application for different air velocity measuring instruments

	Vane anemometers (swing and cup)	Thermoanemometers
Advantages	1. Light and suitable for field use 2. Accurate when properly calibrated 3. Direct readout integrated over time 4. Relatively inexpensive 5. Small	1. Convenient and practical for low velocities 2. Can measure turbulent airflow 3. Light and suitable for field use
Disadvantages	1. Measure only directional air velocity 2. Easily damaged from handling, vibration, and dust 3. Relatively insensitive for use below 1 m/sec 4. It is necessary to average visually the needle movements to obtain average velocity (does not apply to rotating) 5. Require simultaneous measurement of time	1. Need properly charged battery or a power supply 2. The sensing elements are fragile 3. Some types of thermal anemometers are not portable 4. Fluctuating needle movement requires visual averaging for velocity estimate
Fields of Application	1. Measuring range is from 0.5 m/sec to 150 m/sec 2. For indoors and ducts 3. More suitable for use in mine shafts and tunnels 4. Used outside in standard Weather Service set up	1. Measuring range is from 0.03 to 300 m/sec 2. For low and very high velocities measurements 3. For directional and turbulent measurements 4. For permanent stations

Adapted from Reference 81.

If an anemometer is not available for accurate air velocity measurement, air velocity can be estimated as follows [81]:

	v_a m/sec	v_a fpm
• No sensation of air movement (e.g., closed room without any air source)	$v_a<0.2$	39
• Sensing light breezes (e.g., slight perception of presence of air movement)	$0.2 \leq v_a \leq 1.0$	39-197
• Sensing moderate breezes (e.g., few meters away from a fan; definite perception of air movement; air causing tousling of hair and movement of paper)	$1.0<v_a \leq 1.5$	197-235
• Sensing heavy breezes (e.g., located close proximity to a fan; air causing marked movement of clothing)	$v_a>1.5$	>235

a. Vane Anemometers (swing and cup)

The two major types of vane anemometers are the rotating vane and the deflecting or swinging vane anemometers. The propeller or rotating vane anemometer consists of a light, rotating wind-driven wheel enclosed in a ring. It indicates, using recording dials, the number of revolutions of the wheel or the linear distance in meters or feet. In order to determine the wind velocity, a stopwatch must be used to record the elapsed time. The newer models have a digital readout. The swinging anemometer consists of a vane enclosed in a case which has an inlet and an outlet air opening. The vane is placed in the pathway of the air, and the movement of the air causes the vane to deflect. This deflection can be translated to a direct readout of the wind velocity by means of a gear train. Rotating vane anemometers are more accurate than swinging vane anemometers.

Another type of rotating anemometer consists of three or four hemispherical cups mounted radially from a vertical shaft. Wind from any direction causes the cups to rotate the shaft and wind speed is determined from the shaft speed [83].

b. Thermoanemometers

Air velocity is determined with thermoanemometers by measuring the cooling effect of air movement on a heated element, using one of two techniques to bring the resistance or the electromotive force (emf) (voltage) of a hot wire or a thermocouple to a specified value, measure the current required to maintain this value, and then determine the wind velocity from a calibration chart; or heat the thermometer (usually by applying an electric current) and then determine the air velocity from a direct reading or a calibration chart relating air velocity to the wire resistance or to the emf for the hot-wire anemometer and the heated-thermocouple anemometers, respectively.

4. Radiation

Radiant heat sources can be classified as artificial (i.e., infrared radiation in such industries as iron and steel industry, the glass industry, foundries, etc.) or natural (i.e., solar radiation).

Instruments which are used for measuring occupational radiation (black globe thermometers or radiometers) have different characteristics from pyrheliometers or pyranometers which are used to measure solar radiation. However, the black globe thermometer is the most commonly used instrument for measuring the thermal load of solar and infrared radiation on man.

a. Artificial (Occupational) Radiation

(1) Black Globe Thermometers

In 1932, Vernon developed the black globe thermometer to measure radiant heat. The thermometer consists of a 15-centimeter (6-inch) hollow copper sphere (a globe) painted a matte black to absorb the incident infrared radiation (0.95 emissivity) and a sensor (thermistor, thermocouple, or mercury-in-glass partial immersion thermometer) with its sensing element placed in the center of the globe. The Vernon globe thermometer is the most commonly used device for evaluating occupational radiant heat, and it is recommended by NIOSH for measuring the black globe temperature (t_g)[9]; it is sometimes called the standard 6-inch black globe.

Black globe thermometers exchange heat with the environment by radiation and convection. The temperature stabilizes when the heat exchange by radiation is equivalent to the heat exchange by convection. Both the thermometer stabilization time and the conversion of globe temperature to mean radiant temperature are functions of the globe size [84]. The standard 6-inch globe requires a period of 15 to 20 minutes to stabilize; whereas small black globe thermometers of 4.2 centimeters (1.65-inch) diameter, which are commercially available, require about 5 minutes to stabilize [85].

The t_g is used to calculate the Mean Radiant Temperature (MRT). The MRT is defined as the temperature of a "black enclosure of uniform wall temperature which would provide the same radiant heat loss or gain as the nonuniform radiant environment being measured." The MRT for a standard 6-inch black globe can be determined from the following equation:

$$MRT=t_g+(1.8\ V_a\ ^{0.5})(t_g-t_a)$$

where:

MRT = Mean Radiant Temperature (°C)
t_g= black globe temperature (°C)
t_a= air temperature (°C)
V_a= air velocity (m/sec)

(2) Radiometers

A radiometer is an instrument for measuring infrared radiation. Some radiometers, e.g., infrared pyrometers, utilize the measured radiant energy to indicate the surface temperature of the radiant source. Surface temperatures ranging from -30° to 3000°C can be measured with an infrared pyrometer.

The net radiometer consists of a thermopile with the sensitive elements exposed on the two opposite faces of a blackened disc. It has been used to measure the radiant energy balance of human subjects [86]. A variety of radiometers has been used to measure radiant flux [87]. Radiometers are not, however, commonly used in occupational radiant heat measurements. They are used in laboratories or for measuring surface temperature.

b. Natural (Solar) Radiation

Solar radiation can be classified as direct, diffuse, or reflected. Direct solar radiation comes from the solid angle of the sun's disc. Diffuse solar radiation (sky radiation) is the scattered and reflected solar radiation coming from the whole hemisphere after shading the solid angle of the sun's disc. Reflected solar radiation is the solar radiation reflected from the ground or water. The total solar heat load is the sum of the direct, diffuse, and reflected solar radiation as modified by clothing worn and position of the body relative to the solar radiation [88].

(1) Pyrheliometers

Direct solar radiation is measured with a pyrheliometer. A pyrheliometer consists of a tube which can be directed at the sun's disc and a thermal sensor. Generally, a pyrheliometer with a thermopile as sensor and a view angle of 5.7° is recommended [89,90]. Two different pyrheliometers are widely used: the Angstrom compensation pyrheliometer and the Smithsonian silver disc pyrheliometer, each of which uses a slightly different scale factor.

(2) Pyranometers

Diffuse and total solar radiations can be measured with a pyranometer. For measuring diffuse radiation the pyranometer is fitted with a disc or a shading ring to prevent direct solar radiation from reaching the sensor. The receiver usually takes a hemispherical dome shape to provide a 180° view angle for total sun and sky radiation. It is used in an inverted position to measure reflected radiation. The thermal sensor may be a thermopile, a silicon cell, or a bimetallic strip. Pyranometers can be used for measuring solar or other radiation between 0.35 and 2.5 micrometers (μm) which includes the ultraviolet, visible, and infrared range. Additional descriptions of solar radiation measurement can be found elsewhere [89,91,92].

5. Microwaves

Microwaves comprise the band in the electromagnetic spectrum with wavelength ranging from 1 to 100 centimeter and frequency from 0.3 to 300 gigahertz (GHz). Microwaves have been used basically for heating and/or communications in a variety of applications and provide a broad base for human exposure [93].

Most investigators agree that "high-power density" of microwaves can result in pathophysiologic manifestations of a thermal nature. Some reports have suggested that "lower-power density" microwave energy can affect neural and immunologic function in animals and man [94]. Since 1973, a large volume of literature on the biologic effects of microwave radiation has become available [95]. The principal acute hazard from microwave radiation is thermal damage to the skin and heating of the underlying tissues [90,96,97].

In numerous investigations of animals and humans, cataracts attributed to microwave exposure have been reported [94]. Exposure to microwaves may result in direct or indirect effects on the cardiovascular system. Other biologic effects have also been reported [98,99], and these effects are more pronounced under hot environments [90].

Microwave detectors can be divided into two categories: thermal detectors and electrical detectors. Thermal detectors utilize the principles of temperature changes in a thermal sensor as a result of exposure to microwaves. Electrical detectors, however, rectify the microwave signal into direct current which may be applied to a meter calibrated to indicate power. Thermal detectors are generally preferred over electrical detectors [90].

The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLV®) for occupational exposure to microwave energy have been established [2]. These TLVs are based on the frequency and the power density of the microwave. At the frequency range of 10 kilohertz (kHz) to 300 gigahertz (GHz) for continuous exposure with total exposure time limited to an 8-hour workday, the power density level should not exceed 10 to 100 milliwatts per square centimeter (mW/cm^2) as the frequency increases from 10 kHz to 300 GHz. Under conditions of moderate to severe heat stress, the recommended values may need to be reduced.

B. Prediction of Climatic Factors from the National Weather Service Data

The National Weather Service provides a set of daily environmental measurements which can be a useful supplement to the climatic factors measured at a worksite. The National Weather Service data include daily observations at 3-hour intervals for air temperature (t_a), wet bulb temperature (t_{wb}), dew point temperature (t_{dp}), relative humidity (rh), and wind velocity (V_a), sky cover, ceiling, and visibility. A summary of daily environmental measurements includes t_a (maximum, minimum, average, and departure from normal), average t_{dp} type, precipitation, atmospheric pressure (average at station and sea levels), wind velocity (direction and speed), extent of sunshine and sky cover. These data, where available, can be used for approximate assessment of the worksite environmental heat load for outdoor jobs or for some indoor jobs where air conditioning is not in use. Atmospheric pressure data can also be used for both indoor and outdoor jobs. National Weather Service data have also been used in studies of mortality due to heat-aggravated illness resulting from heat waves in the United States [60,61,100].

Continuous monitoring of the environmental factors at the worksite provides information on the level of heat stress at the time the measurements are made. Such data are useful for developing engineering heat-stress controls. However, in order to have established work practices in place when needed, it is desirable to predict the anticipated level of heat stress for a day or more in advance. A methodology has been developed based on the psychrometric wet bulb for calculating the wet bulb globe temperature (WBGT) at the worksite from the National Weather Service meteorologic data. The data upon which the method is based were derived from simultaneous measurements of the thermal environment in 15 representative worksites, outside the worksites, and from the closest National Weather Service station. The empirical relationships between the inside and outside data were established. From these empirical relationships, it is possible to predict worksite WBGT, effective temperature (ET), or corrected effective temperature (CET) values from weather forecasts or local meteorologic measurements. To apply the predictions model, it is first necessary to perform a short environmental study at each worksite to establish the differences in inside and outside values and to determine the regression constants which are unique for each workplace, perhaps because of the differences in actual worksite air motion as compared to the constant high air motion associated with the use of the ventilated wet bulb thermometer [101].

C. Metabolic Heat

The total heat load imposed on the human body is the aggregate of environmental and physical work factors. The energy cost of an activity as measured by the metabolic heat (M) is a major element in the heat-exchange balance between the human body and the environment. The metabolic heat value can be measured or estimated. The energy cost of an activity is made up of two parts: the energy expended in doing the work and the energy transformed into heat. On the average, muscles may reach 20% efficiency in performing heavy physical work. However, unless external physical work is produced, the body heat load is approximately equal to the total metabolic energy turnover. For practical purposes M is equated with total energy turnover.

1. Measurements of Metabolic Heat

a. Measurement of Metabolic Heat by Direct Calorimetry

To determine the worker's heat production by direct calorimetry, the subject is placed in a calorimeter, an enclosed chamber surrounded by circulating water; the increase in the temperature of the circulating water is used to determine the amount of heat liberated from the human body. The direct procedure has limited practical use in occupational heat-stress studies, because the procedure is difficult and time consuming and the equipment and chambers are expensive [102].

b. Measurements of Metabolic Heat by Indirect Calorimetry

Primary methods of measurements of metabolic heat by indirect calorimetry are based on measuring oxygen consumption. Indirect calorimetry utilizes the closed circuit procedure or the open circuit procedure. Another even more indirect procedure for measuring metabolic heat is based on the linear relationship between heart rate and oxygen consumption. The linearity, however, usually holds only at submaximal heart rates, because on approaching the maximum, the pulse rate begins to level off while the oxygen intake continues to rise. The linearity also holds only on an individual basis because of the wide interindividual differences in the responses [103,104].

(1) Closed Circuit

In the closed circuit procedure the subject inhales from a spirometer, and the expired air returns to the spirometer after passing through carbon dioxide and water vapor absorbents. The depletion in the amount of oxygen in the spirometer represents the oxygen consumed by the subject. Each liter of oxygen consumed results in the production of approximately 4.8 kcal of metabolic heat. The development of computerized techniques, however, has revised the classical procedures so that equipment and the evaluation can be automatically controlled by a computer which results in prompt, precise, and simultaneous measurement of the significant variables [105].

(2) Open Circuit

In the open circuit procedure the worker breathes atmospheric air, and then the exhaled air is collected in a large container, i.e., a Douglas bag or meteorological balloon. The volume of the expired air can be accurately measured with a calibrated gasometer. The concentration of oxygen in the expired air can be measured by chemical or electronic methods. The oxygen and carbon dioxide in the atmospheric air usually averages 20.90% and 0.03%, respectively, or they can be measured so that the amount of oxygen consumed, and consequently the metabolic heat production for the performed activities, can be determined. Each liter of oxygen consumed represents 4.8 kcal of metabolism.

Another open circuit procedure, the Max Planck respiration gasometer, eliminates the need for an expired air collection bag and a calibrated gasometer [105]. The subject breathes atmospheric air and exhales into the gasometer where the volume and temperature of the expired air are immediately measured. An aliquot sample of the expired air is collected in a rubber bladder for later analysis for oxygen and carbon dioxide concentrations. Both the Douglas bag and the respiration gasometer are portable and thus appropriate for collecting expired air of workers at different industrial or laboratory sites [105].

2. Estimation of Metabolic Heat

The procedures for direct or indirect measurement of metabolic heat are limited to relatively short duration activities and require equipment for collecting and measuring the volume of the expired air and for measuring the oxygen and carbon dioxide concentrations. On the other hand, metabolic heat estimates, using tables of energy expenditure or task analysis, although less accurate and reproducible, can be applied for short and long duration activities and require no special equipment. However, the accuracy of the estimates made by a trained observer may vary by about $\pm$ 10-15%. A training program consisting of supervised practice in using the tables of energy expenditure in an industrial situation will usually result in an increased accuracy of the estimates of metabolic heat production [106,107].

a. Tables of Energy Expenditures

Estimates of metabolic heat for use in assessing muscular work load and human heat regulation are commonly obtained from tabulated descriptions of energy cost for typical work tasks and activities [108,109]. Errors in estimating metabolic rate from energy expenditure tables are reported to be as high as 30% [110].

The International Organization for Standardization (ISO) [110] recommends that the metabolic rate could be estimated by adding values of the following groups: (1) basal metabolic rate, (2) metabolic rate for body position or body motion, (3) metabolic rate for type of work, and (4) metabolic rate related to work speed. The basal metabolic rate averages 44 and 41 W/m^2 for the "standard" man and woman, respectively. Metabolic rate values for body position and body motion, type of work, and those related to work speed are given [110].

b. Task Analysis

In order to evaluate the average energy requirements over an extended period of time for industrial tasks including both the work and rest activities, it is necessary to divide the task into its basic activities and subactivities. The metabolic heat of each activity or subactivity is then measured or estimated and a time-weighted average for the energy required for the task can be obtained.

It is common in such analyses to estimate the metabolic rate for the different activities by utilizing tabulated energy values from tables which specify incremental metabolic heat resulting from the movement of different body parts, i.e., arm work, leg work, standing, and walking [2]. The metabolic heat of the activity can then be estimated by summing the component M values based on the actual body movements. The task analysis procedure recommended by ACGIH is summarized in Table V-3.

TABLE V-3.--Estimating energy cost of work by task analysis

A. Body position and movement	kcal/min*
Sitting	0.3
Standing	0.6
Walking	2.0-3.0
Walking uphill	add 0.8 per meter rise

B. Type of work	Average kcal/min	Range kcal/min
Hand work		
light	0.4	0.2-1.2
heavy	0.9	
Work one arm		
light	1.0	0.7-2.5
heavy	1.8	
Work both arms		
light	1.5	1.0-3.5
heavy	2.5	
Work whole body		
light	3.5	2.5-9.0
moderate	5.0	
heavy	7.0	
very heavy	9.0	

C. Basal metabolism	1.0

D. Sample calculation**	Average kcal/min
Assembling work with heavy hand tools	
1. Standing	0.6
2. Two-arm work	3.5
3. Basal metabolism	1.0
Total	5.1 kcal/min

* For standard worker of 70 kg body weight (154 lbs.) and 1.8 m^2 body surface (19.4 ft^2).

**Example of measuring metabolic heat production of a worker when performing initial screening.

Adapted from References 2,108,111,112.