Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments

Revised Criteria 2013

DEPARTMENT OF HEALTH AND HUMAN SERVICES

Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Foreword

[To be finalized.]

Executive Summary

The National Institute for Occupational Safety and Health (NIOSH) has evaluated the scientific data on heat stress and hot environments, and updated the Criteria for a Recommended Standard: Occupational Exposure to Hot Environments [NIOSH 1986a]. This document was last updated in 1986, and in recent years, including during the Deepwater Horizon oil spill response of 2010, questions were raised regarding the need for revision to reflect recent research and findings. This revision includes additional information relating to the physiological changes that result from heat stress; updated information from relevant studies, such as those on caffeine usage; evidence to redefine heat stroke and associated symptoms; and updated information on physical monitoring and personal protective equipment and clothing that can be used to control heat stress.

Workers who are exposed to extreme heat or work in hot environments may be at risk for heat stress. Exposure to extreme heat can result in occupational illnesses caused by heat stress, including heat stroke, heat exhaustion, heat cramps, or heat rashes. Heat can also increase the risk of injuries in workers as it may result in sweaty palms, fogged-up safety glasses, and dizziness. Other heat injuries, such as burns, may occur as a result of accidental contact with hot surfaces or steam. Workers at risk of heat stress include outdoor workers and workers in hot environments, such as firefighters, bakery workers, farmers, construction workers, miners, boiler room workers, factory workers, and others.

In 2011, NIOSH published with the Occupational Safety and Health Administration (OSHA) a co-branded heat illness-related infosheet. Through this combined effort, many recommendations were updated, including recommended water consumption. In addition, factors that increase risk and symptoms of heat-related illnesses were more thoroughly defined.

Chapters on basic knowledge of heat balance and heat exchange largely remained unchanged, although clothing insulation factors have been updated to reflect current International Organization for Standardization (ISO) recommendations. Additional information on the biological effects of heat has become available in recent studies, specifically increasing the understanding of the central nervous system, circulatory regulation, the sweating mechanism, water and electrolyte balance, and dietary factors. New knowledge has been established about risk factors that can increase a worker’s risk of heat-related illness. Those over the age of 60 are at additional risk for suffering from heat disorders [Kenny et al. 2010]. Additional studies have examined sex-related differences regarding sweat-induced electrolyte loss and whole-body sweat response, as well as how pregnancy affects heat stress tolerance [Meyer et al. 1992; Navy Environmental Health Center 2007; Gagnon and Kenny 2011]. As obesity and the increasingly overweight portions of the population in the United States continue to increase, this is now a major health concern in workers. Heat disorders among the obese and overweight occur more frequently than in lean individuals [Henschel 1967; Chung and Pin 1996; Kenny et al. 2010]. Another factor affecting heat-related illness is drug usage, including alcohol, prescription drugs and caffeine. Caffeine usage has long been argued against, as it has a diuretic effect and may reduce fluid volume leading to cardiovascular strain during heat exposure [Serafin 1996]. However, more recent studies have found that the effect of caffeine on heat tolerance may be far less significant than previously suspected [Roti et al. 2006; Armstrong et al. 2007a; Ely et al. 2011].

The definition of heat stroke has also changed in recent years. Heat stroke is now classified either as classical heat stroke or, more commonly in industrial settings, exertional heat stroke. Characteristics of the individual (e.g., age, health status), the type of activity in which they were involved (e.g., sedentary versus strenuous exertion) and the symptoms (e.g., sweating versus dry skin) vary between these two classifications [DOD 2003]. Re-education is needed in the workplace; particularly, in regards to symptoms, as many workers have incorrectly been taught that, as long as they were still sweating, they were not in danger of heat stroke.

Measurements of heat stress are largely the same, although additional information is added on bimetallic thermometers and the psychrometric chart. The psychrometric chart is a useful graphical representation of the relationships among dry bulb temperature, wet bulb temperature, relative humidity, vapor pressure and dew point temperature. These charts are especially valuable for assessing the indoor thermal environment.

Heat stress can be reduced by modifying one of more of the following factors: metabolic heat production or heat exchange by convection, radiation or evaporation. In a controlled environment, these last three can be modified through engineering controls, including increasing ventilation, bringing in cooler outside air, reducing the hot temperature of a radiant heat source or shielding the worker, and utilizing air conditioning equipment. Heat stress can also be administratively controlled through limiting the exposure time or temperature (e.g., work/rest schedules), reducing metabolic heat load and enhancing heat tolerance (e.g., acclimatization). While most healthy workers will be able to acclimatize over a period of time, some workers may be heat intolerant. Heat intolerance may be related to many factors; however, a heat tolerance test may be used to evaluate an individual's tolerance, especially after an episode of heat exhaustion or exertional heat stroke [Moran et al. 2007].

Health and safety training is important for employers to provide to workers before they begin working in a hot environment. This training should include information about the recognition of heat-related illness symptoms, proper hydration (e.g., drink 8 oz. of water or other fluids every 15-20 minutes), the care and use of heat-protective clothing and equipment, the effects of various factors affecting heat tolerance (e.g., drugs, alcohol, obesity, etc.), the importance of acclimatization, the importance of reporting symptoms and appropriate first aid. Supervisors also should be provided with appropriate training about how to monitor weather reports and weather advisories. Additional preventive strategies against heat stress include establishing a Heat-Alert program and providing auxiliary body cooling and protective clothing (e.g., water-cooled garments, air-cooled garments, cooling vests, and wetted overgarments).

The NIOSH Recommended Alert Limit (RAL) and Recommended Exposure Limit (REL) were evaluated. It was determined that the current RAL for unacclimatized workers and REL for acclimatized workers are still protective. No new data were identified to use as the basis for an updated REL and RAL. The RAL and REL were developed with the intent to protect most healthy workers exposed to environmental and metabolic heat below the appropriate NIOSH RAL/REL from developing adverse health effects. In addition, no worker should be exposed to environmental and metabolic heat loads exceeding the Ceiling Limits without adequate heat-protective clothing and equipment. The WBGT-based threshold values for acclimatized workers are similar to those of OSHA, the American Conference of Governmental Industrial Hygienists (ACGIH), the American Industrial Hygiene Association (AIHA), and the International Organization for Standardization (ISO).

While many new research developments have occurred since the last revision of this document, the need for additional research continues. Two newer areas of research that will likely continue to grow include the effects of climate change on outdoor workers and how heat stress affects toxic response to chemicals. It is unclear whether and to what extent global climate change may impact known hazards of heat exposures for outdoor workers with regard to increased severity, prevalence and distribution [Schulte and Chun 2009]. In relation to toxicology, heat exposure can affect the absorption of chemicals into the body. Most of what is known on this subject comes from animal studies, so a better understanding of the mechanisms and role of ambient environment involved in humans is still needed [Gordon 2003; Gordon and Leon 2005]. With changes in the climate, the need for this better understanding will become increasingly important [Leon 2008].

In addition to the updated research, NIOSH has included additional resources for worker and employer training within the criteria document. Information about the use of urine color charts, including a chart and additional information, is included in Appendix B. The National Weather Service Heat Index is also included (Appendix C), along with the OSHA-modified corresponding worksite protective measures and associated risk levels.

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Glossary

Acclimatization: The physiological changes which occur in response to a succession of days of exposure to environmental heat stress that reduce the strain caused by the heat stress of the environment.

Area, DuBois (A_{Du}): Total nude body surface area in square meters (m^2) calculated from the DeBois formula based on body weight (kg) and height (m).

Area, Effective Radiating (A_r): Surface area of the body in square meters (m^2) that exchanges radiant energy with a radiant source.

Area, Solar Radiation (A_s): Surface area of the body in square meters (m^2) that is projected normal to the sun.

Area, Wetted (A_w): Square meters (m^2) of skin area covered by sweat.

Body Heat Balance: Steady state equilibrium between body heat production and heat loss to the environment.

Body Heat Balance Equation: Mathematical expression of relation between heat gain and heat loss expressed as (H=M±C±R-E)

Body Heat Storage (S): The change in heat content (either + or -) of the body.

Circadian Rhythm: Synchronized rhythmic biological phenomena which occurs on approximately a 24-hour cycle.

clo: A unit expression of the insulation value of clothing. clo=5.55 expressed as kcal/m^2/hºC.

Convective Heat Transfer (C): The net heat exchange by convection between an individual and the environment.

Convective Heat Transfer Coefficient (h_c): The rate of heat transfer between the body surface and the ambient air per square meters (m^2) skin surface expressed as kcal, Btu, or W.

Deep Core Body Temperature: The temperature of the deep internal structures of the body (e.g., heart, viscera, or hypothalamus) as opposed to the skin. The core body temperature varies with the individual, time of day, and with fever or exertion. The average core body temperature is 37°C (98.6°F).

Evaporative Heat Loss (-E): Body heat loss by evaporation of water (sweat) from the skin expressed as kcal, Btu, or W.

Evaporative Heat Transfer (E): Rate of heat loss by evaporation of water from the skin or gain from condensation of water on the skin expressed as kcal, Btu, or W.

Evaporative Heat Transfer Coefficient (h_e): The rate of heat exchange by evaporation between the body surface and the ambient air as a function of the vapor pressure difference between the two and air velocity.

Heat Capacity: Mass times specific heat of a body.

Heat Content of Body: Body mass times average specific heat and absolute mean body temperature.

Heat Cramp: A heat-related illness characterized by spastic contractions of the voluntary muscles (mainly arms, hands, legs, and feet) usually associated with restricted salt intake and profuse sweating without significant body dehydration.

Heat Exhaustion: A heat-related illness characterized by muscular weakness, distress, nausea, vomiting, dizziness, pale clammy skin, and fainting; usually associated with lack of heat acclimatization and physical fitness, low health status, and an inadequate water intake.

Heat Strain: The physiological response to the heat load experienced by a person, which attempts to increase heat loss from the body in order to maintain a stable body temperature.

Heat Stress: The net heat load to which a person may be exposed from the combined contributions of metabolic heat, environmental factors, and clothing requirements which may result in an increase in heat storage in the body.

Heat Stroke: An acute medical emergency arising during exposure to heat from an excessive rise in body temperature and failure of the temperature regulating mechanism. It is characterized by a sudden and sustained loss of consciousness preceded by vertigo, nausea, headache, cerebral dysfunction, bizarre behavior, and body temperatures usually in excess of 41.1ºC (106ºF).

Heat Syncope: Collapse and/or loss of consciousness during heat exposure without an increase in body temperature or cessation of sweating, similar to vasovagal fainting except heat induced.

Humidity, Relative (Ø or rh): The ratio of the water vapor present in the ambient air to the water vapor present in saturated air at the same temperature and pressure.

Hyperpyrexia: A body core temperature exceeding 40ºC (104ºF).

Hyperthermia: A condition where the core temperature of an individual is higher than one standard deviation above the mean for the species.

Insensible Perspiration: Water that passes through the skin by diffusion.

Maximum Oxygen Consumption (VO_2max): The maximum amount of oxygen that can be utilized by the body.

Metabolic Rate (MR): Chemical energy transfer into free energy per unit time.

Metabolism (M): Transformation of chemical energy into energy which is used for performing work and producing heat.

Prescriptive Zone: That range of environmental heat stress below which the physiologic strain (heart rate and body temperature) is independent of the level of environmental heat stress.

Pressure, Atmospheric (P_a): Pressure exerted by the weight of the air which is 760 mmHg at sea level and decreases with altitude.

Pressure, Water Vapor (P_a): The pressure exerted by the water vapor in the air.

Radiant Heat Exchange (R): Heat exchange by radiation between two radiant surfaces of different temperatures.

Radiative Heat Transfer Coefficient (h_r): Rate of heat transfer between two black surfaces per unit temperature difference.

Standard Man: A representative human with a body weight of 70 kg (154 lb.) and a body surface area of 1.8 m^2 (19.4 ft^2).

Sweating, Thermal: Response of the sweat glands to thermal stimuli.

Temperature, Ambient ($\bar{t}_a$): The temperature of the air surrounding a body. Also called *air temperature* or *dry bulb temperature*.

Temperature, Ambient, Mean ($\bar{t}_a$): The mean value of several dry bulb temperature readings taken at various locations or at various times.

Temperature, Core (t_{cr}): Temperature of the tissues and organs of the body. Also called *Deep Body Temperature*.

Temperature, Dew-point (t_{dp}): The temperature at which the water vapor in the air first starts to condense.

Temperature, Effective (ET): Index for estimating the effect of temperature, humidity, and air movement on the subjective sensation of warmth.

Temperature, Globe (t_g): The temperature inside a blackened, hollow, thin copper globe measured by a thermometer whose sensing element is in the center of the sphere.

Temperature, Mean Body ($\bar{t}_b$): The mean value of temperature readings taken at several sites within the body and on the skin surface. It can be approximated from skin and core temperatures.

Temperature, Radiant (t_r): The point temperature of the surface of a material or object.

Temperature, Mean Radiant ($\bar{t}_r$): The mean surface temperature of the material and objects totally surrounding the individual.

Temperature, Rectal (t_{re}): Temperature measured 10 centimeters (cm) in the rectal canal.

Temperature, Mean Skin ($\bar{t}_{sk}$): The mean of temperatures taken at several locations on the skin weighted for skin area.

Temperature, Skin (t_{sk}): Temperature measured by placing the sensing element on the skin.

Temperature, Oral (t_{or}): Temperature measured by placing the sensing element under the tongue for a period of 3 to 5 minutes.

Temperature, Tympanic (t_{ty}): Temperature measured by placing the sensing element in the ear canal close to the tympanic membrane.

Temperature Regulation: The maintenance of body temperature within a restricted range under conditions of positive heat loads (environmental and metabolic) by physiologic and behavioral mechanisms.

Temperature, Operative (t_o): The temperature of a uniform black enclosure within which an individual would exchange heat by convection and radiation at the same rate as in a nonuniform environment being evaluated.

Temperature, Psychrometric Wet Bulb (t_{wb}): The lowest temperature to which the ambient air can be cooled by evaporation of water from the wet temperature sensing element with forced air movement.

Temperature, Natural Wet Bulb (t_{nwb}): The wet bulb temperature under conditions of the prevailing air movement.

Thermal Insulation, Clothing (I_{cl}): The insulation value of a clothing ensemble.

Thermal Insulation, Effective (I_{cl}+I_a): The insulation value of the clothing plus the still air layer.

Thermal Strain: The sum of physiologic responses of the individual to thermal stress.

Thermal Stress: The sum of the environmental and metabolic heat load imposed on the individual.

Wettedness, Skin (w): The amount of skin that is wet with sweat.

Wettedness, Percent of Skin (Aw/SWA_{Du} x 100): The percent of the total body skin surface that is covered with sweat.

Symbols

Symbol	Term	Units
A_b	Body surface area	m^2
A_{Du}	Body surface area, DuBois	m^2
A_r	Skin area exposed to radiation	m^2
A_w	Wetted area of skin	m^2
Btu	British thermal units	Btu/h
C	Heat exchange by convection	W, kcal/h; Btu/h
CO	Cardiac output of blood per minute	l/m
E_{max}	Maximum water vapor uptake by the air at prevailing meteorological conditions	kg/h
E_{req}	Amount of sweat that must be evaporated to maintain body heat balance	kg/h
F_{cl}	Reduction factor for loss of convective heat exchange due to clothing	dimensionless
H	Body heat content	kcal, Btu, w w
h_c	Convection heat transfer coefficient	$Wm^{-2}/°C^{-1}$; $kcal/h^{-1}/m^{2°}C^{-1}$; $Btu/h^{-1}/ft^{-2°}F^{-1}$
h_e	Evaporative heat transfer coefficient	$Wm^{-2}/°C^{-1}$; $kcal/h^{-1}/m^{2°}C^{-1}$; $Btu/h^{-1}/ft^{-2°}F^{-1}$
HR	Heart rate	bpm
h_r	Radiative heat transfer coefficient	$Wm^{-2}/°C^{-1}$; $kcal/h^{-1}/m^{2°}C^{-1}$; $Btu/h^{-1}/ft^{-2°}F^{-1}$
h_{r+c}	Radiative + convective heat transfer coefficient	$Wm^{-2}/°C^{-1}$; $kcal/h^{-1}/m^{2°}C^{-1}$;

		$Btu/h^{-1}/ft^{-2o}F^{-1}$
I_a	Thermal insulation of still air layer	clo
I_{cl}	Thermal insulation of clothing layer	clo
i_m	Moisture permeability index of clothing	dimensionless
i_m/clo	Permeability index-insulation ratio	dimensionless
K	Heat exchanged by conduction	W, kcal/h, Btu/h
kcal	Kilocalories	kcal/h
Met	Unit of metabolism, 1 met = 50 $kcal/m^2/h$	met
mmHg	Pressure in millimeters of mercury	mmHg
ms^{-1}	Meters per second	m/sec
P_a	Water vapor pressure of ambient air	mmHg, kP_a
P_{sk}	Water vapor pressure of wetted skin	mmHg, kP_a
$p_{sk,s}$	Water vapor pressure at skin temperature	mmHg, kP_a
rh	Relative humidity	percent
R	Heat exchange by radiation	$Wm^{-2}/^oC^{-1}$; $kcal/h^{-1}/m^{2o}C^{-1}$; $Btu/h^{-1}/ft^{-2o}F^{-1}$
S	Sweat produced	l, g, kg
SR	Sweat produced per unit time	g/min, g/h, kg/min, kg/h
SV	Stroke volume, or amount of blood pumped by the heart per beat	ml
SWA	Area of skin wet with sweat	m^2
%SWA	SWA/A_{Du} x 100 = % of body surface wet with sweat	percent
T	Absolute temperature (t + 273)	ºK, TR

T_a	Ambient air dry bulb temperature	ºC, ºF
t_{adb}	Ambient dry bulb temperature adjusted for solar radiation	ºC, ºF
t_{cr}	Body core temperature	ºC, ºF
T_{dp}	Dew point temperature	ºC, ºF
T_g	Black globe temperature	ºC, ºF
T_{nwb}	Natural wet bulb temperature	ºC, ºF
t_o	Operative temperature	ºC, ºF
t_r	Radiant temperature	ºC, ºF
$\bar{t}_r$	Mean radiant temperature	ºC, ºF
t_{re}	Rectal temperature	ºC, ºF
t_{sk}	Skin temperature	ºC, ºF
$\bar{t}_{sk}$	Mean skin temperature	ºC, ºF
T_{wb}	Psychrometric wet bulb temperature	ºC, ºF
t_{wg}	Wet globe temperature	ºC, ºF
V_a	Air velocity	ms, fpm
$\dot{V}$ $\dot{V}$ O_2max	Maximum aerobic capacity	mL/min, l/h
μ	Mechanical efficiency of work	%, percent
ω	Skin wettedness	dimensionless
σ	Stefan-Bolzmann constant	$Wm^{-2}K^4$
ε	Emittance coefficient	dimensionless

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Education and Information Division

Thomas Lentz, Ph.D.

Kathleen MacMahon, D.V.M.

Ralph Zumwalde

Lauralynn Taylor McKernan, Ph.D.

HeeKyoung Chun, Ph.D.

Barbara Dames

Sherry Fendinger

Division of Surveillance, Hazard Evaluations and Field Studies

Melody Kawamoto, M.D., M.S.

Mark Methner, Ph.D.

Division of Safety Research

Larry Jackson, Ph.D.

Emergency Preparedness and Response Office

Joseph Little, M.S.P.H.

Health Effects Lab Division

Dan Sharp, M.D., Ph.D.

Western States Office

Yvonne Boudreau, M.D., M.S.P.H.

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1. Recommendations for an Occupational Standard for Workers Exposed to Heat and Hot Environments

The National Institute for Occupational Safety and Health (NIOSH) recommends that worker exposure to heat stress in the workplace be controlled by complying with all sections of the standard found in this document. This recommended standard is expected to prevent or greatly reduce the risk of adverse health effects to exposed workers. Heat-related occupational illnesses, injuries, and reduced productivity occur in situations of heat stress when the total heat load (environmental plus metabolic) exceeds the capacities of the body to maintain normal body functions without excessive strain. The reduction of adverse health effects can be accomplished by the proper application of engineering and work practice controls, worker training and acclimatization, measurements and assessment of heat stress, medical supervision, and proper use of heat-protective clothing and equipment.

In this criteria document, total heat stress is considered to be the sum of heat generated in the body (metabolic heat) plus the heat gained from the environment (environmental heat) minus the heat lost from the body to the environment. The bodily response to total heat stress is called the heat strain. Many of the bodily responses to heat exposure are desirable and beneficial (i.e., sweating). However, at some amount of heat stress, the worker's compensatory mechanisms will no longer be capable of maintaining body temperature at the level required for normal body functions. As a result, the risk of heat-related illnesses, injuries, and accidents substantially increases. The level of heat stress at which excessive heat strain will result depends on the heat-tolerance capabilities of the worker. However, even though there is a wide range of heat tolerance between workers, each worker has an upper limit for heat stress beyond which the resulting heat strain can cause the worker to become a heat fatality. In most workers, appropriate repeated exposure to elevated heat stress causes a series of physiologic adaptations called acclimatization, whereby the body becomes more efficient in coping with the heat stress. Such an acclimatized worker can tolerate a greater heat stress before a harmful level of heat strain occurs.

The occurrence of heat-related illnesses among a group of workers in a hot environment, or the recurrence of such illnesses in individual workers, represents "sentinel health events" (SHEs) which indicate that heat control measures, medical screening, or environmental monitoring measures may not be adequate [Rutstein et al. 1983]. One or more occurrences of heat-related illness in a particular worker indicate the need for medical inquiry about the possibility of temporary or permanent loss of the worker's ability to tolerate heat stress. The recommendations in this document are intended to establish the permissible limits of total heat stress so that the risk of incurring heat-related illnesses and disorders in workers is reduced.

Almost all healthy workers, who are not acclimatized to working in hot environments and who are exposed to combinations of environmental and metabolic heat less than the appropriate NIOSH Recommended Alert Limits (RALs) given in Figure 8.1, would be expected to tolerate total heat without substantially increasing their risk of incurring acute adverse health effects. Almost all healthy workers, who are heat-acclimatized to working in hot environments and who are exposed to combinations of environmental and metabolic heat less than the appropriate NIOSH Recommended Exposure Limits (RELs) given in Figure 8.2, would be expected to be capable of tolerating the total heat without incurring adverse effects. The estimates of both environmental and metabolic heat are expressed as 1-hour time-weighted averages (TWAs) as described by American Conference of Governmental Industrial Hygienists (ACGIH) [ACGIH 2011].

At combinations of environmental and metabolic heat exceeding the Ceiling Limit (C) in Figures 8.1 and 8.2, no worker should be exposed without adequate heat-protective clothing and equipment. The Ceiling Limits (calculated using the heat balance equation [section 3.1]) were used to determine total heat loads where a worker could not achieve thermal balance, but might sustain up to a 1 degree Celsius (1°C) rise in body temperature in less than 15 minutes.

In this criteria document, healthy workers are defined as those who are not excluded from placement in hot environment jobs by the explicit criteria given in Chapters 4, 5, and 6. These exclusionary criteria are qualitative in that the epidemiologic parameters of sensitivity, specificity, and predictive power of the evaluation methods are not fully documented. However, the recommended exclusionary criteria represent the best judgment of NIOSH based on the best available data. This includes both absolute and relative exclusionary indicators related to age, stature, sex, percent body fat, medical and occupational history, specific chronic diseases or therapeutic regimens, and the results of medical tests.

The medical surveillance program should be designed and implemented to minimize the risk of the workers' health and safety being jeopardized by any heat hazards that may be present in the workplace (see Chapters 4, 5, and 6). The medical program should provide both preplacement medical examinations for those persons who are candidates for a hot job and periodic medical examinations for those workers who are currently working in hot jobs.

1.1 Workplace Limits and Surveillance

1.1.1 Recommended Limits

Unacclimatized workers

Total heat exposure to workers should be controlled so that unprotected healthy workers who are not acclimatized to working in hot environments are not exposed to combinations of metabolic and environmental heat greater than the applicable RALs given in Figure 8.1.

Acclimatized workers

Total heat exposure to workers should be controlled so that unprotected healthy workers who are acclimatized to working in hot environments are not exposed to combinations of metabolic and environmental heat greater than the applicable RELs given in Figure 8.2.

Effect of Clothing

The recommended limits given in Figures 8.1 and 8.2 are for healthy workers who are physically and medically fit for the level of activity required by their job and who are wearing the customary one layer work clothing ensemble consisting of not more than long-sleeved work shirts and trousers (or equivalent). The REL and RAL values given in Figures 8.1 and 8.2 may not provide adequate protection if workers wear clothing with lower air and vapor permeability or insulation values greater than those for the customary one layer work clothing ensemble discussed above. A discussion of these modifications to the REL and RAL is given in Section 3.3 Effects of Clothing on Heat Exchange.

Ceiling Limits

No worker shall be exposed to combinations of metabolic and environmental heat exceeding the applicable C of Figures 8.1 or 8.2 without being provided with and properly using appropriate and adequate heat-protective clothing and equipment.

1.1.2 Determination of Environmental Heat

Measurement methods

Environmental heat exposures should be assessed by the Wet Bulb Globe Thermometer (WBGT) method or equivalent techniques, such as Effective Temperature (ET), Corrected Effective Temperature (CET), or Wet Globe Temperature (WGT), that can be converted to WBGT values. The WBGT should be accepted as the standard method and its readings the standard against which all others are compared. When air- and vapor-impermeable protective clothing is worn, the dry bulb temperature (t_a) or the adjusted dry bulb temperature (t_{adb}) is a more appropriate measurement.

Measurement requirements

Environmental heat measurements should be made at or as close as feasible to the work area where the worker is exposed. When a worker is not continuously exposed in a single hot area, but moves between two or more areas with differing levels of environmental heat or when the environmental heat substantially varies at the single hot area, the environmental heat exposures should be measured at each area and during each period of constant heat levels where employees are exposed. Hourly TWA WBGTs should be calculated for the combination of jobs (tasks), including all scheduled and unscheduled rest periods.

Modifications of work conditions

Environmental heat measurements should be made at least hourly during the hottest portion of each workshift, during the hottest months of the year, and when a heat wave occurs or is predicted. If two such sequential measurements exceed the applicable RAL or REL, then work conditions should be modified by use of appropriate engineering controls, work practices, or other measures until two sequential measures are in compliance with the exposure limits of this recommended standard.

Initiation of measurements

A WBGT or an individual environmental factors profile should be established for each hot work area for both winter and summer seasons as a guide for determining when engineering controls and/or work practices or other control methods should be instituted. After the environmental profiles have been established, measurements should be made as described in this section during the time of year and days when the profile indicates that total heat exposures above the applicable RALs or RELs may be reasonably anticipated or when a heat wave has been forecast by the nearest National Weather Service station or other competent weather forecasting service.

1.1.3 Determination of Metabolic Heat

Metabolic heat screening estimates

For initial screening purposes, metabolic heat rates for each worker should be measured as to determine whether the total heat exposure exceeds the applicable RAL or REL.

Metabolic heat measurements

Whenever the combination of measured environmental heat (WBGT) and screening estimate of metabolic heat exceeds the applicable RAL or REL (Figures 8.1 and 8.2), the metabolic heat production should be measured using indirect calorimetry (see Chapter 6) or an equivalent method.

Metabolic heat rates should be expressed as kilocalories per hour (kcal/h), British thermal units (Btu) per hour, or watts (W) for a 1-hour TWA task basis that includes all activities engaged in during each period of analysis and all scheduled and nonscheduled rest periods (1 kcal/h = 3.97 Btu/h = 1.16 W).

EXAMPLE:

If the moderate work load task was performed by an acclimatized 70 kg (154 lb.) worker for the entire 60 minutes of each hour, the screening estimate for the 1-hour TWA metabolic heat would be about 300 kcal/h. Using the applicable Figure 8.2, a vertical line at 300 kcal/h would intersect the 60 min/h REL curve at a WBGT of 27.8°C (82°F). Then, if the measured WBGT exceeds 27.8°C, proceed to measure the worker's metabolic heat with the indirect open-circuit method or equivalent procedure.

If the 70-kg worker was unacclimatized, use of Figure 8.1 indicates that metabolic heat measurement of the worker would be required above a WBGT of 25°C (77°F).

1.1.4 Physiologic Monitoring

Physiologic monitoring may be used as an adjunct monitoring procedure to those estimates and measurements required in the preceding parts of this section. Heart rate, oral temperature, and body water loss can be assessed as measures of physiologic response to heat. More advanced methods and new tools are also available for physiologic monitoring (see Chapters 8.3 and 9.4).

1.2 Medical Screening

1.2.1 General

(1) The employer should institute a medical screening and surveillance program for all workers who are or may be exposed to heat stress above the RAL, whether they are acclimatized or not.

(2) The employer should assure that all medical examinations and procedures are performed by or under the direction of a licensed physician or other qualified healthcare provider.

(3) The employer should provide the required medical screening and surveillance without cost to the workers, without loss of pay, and at a reasonable time and place.

1.2.2 Preplacement Medical Examinations

For the purposes of the pre-placement medical examination, all workers should be considered to be unacclimatized to hot environments. At a minimum, the pre-placement medical examination of each prospective worker for a hot job should include:

> (1) A comprehensive work and medical history, with special emphasis on any medical records or information concerning any known or suspected previous heat illnesses or heat intolerance. The medical history should contain relevant information on the cardiovascular system, skin, liver, kidney, musculoskeletal, and the nervous and respiratory systems;

(2) A comprehensive physical examination that gives special attention to the cardiovascular system, skin, liver, kidney, musculoskeletal, and the nervous and respiratory systems;

(3) An assessment of the use of therapeutic drugs, over-the-counter medications, illicit drugs or social drugs (including alcohol), that may increase the risk of heat injury or illness (see Chapter 7);

(4) An assessment of obesity, that is defined as exceeding 25% of normal weight for males and exceeding 30% of normal weight for females, as based on age and body build;

(5) An assessment of the worker's ability to wear and use any protective clothing and equipment, especially respirators, that is or may be required to be worn or used; and

(6) Other factors and examination details included in Section 7.2.4 Pre-placement Physical Examination.

1.2.3 Periodic Medical Examinations

Periodic medical examinations should be made available at least annually to all workers who may be exposed at the worksite to heat stress exceeding the RAL. The employer should provide the examinations specified above including any other items the examining physician or other qualified healthcare provider considers relevant. If circumstances warrant (e.g., increase in job-related heat stress, changes in health status), the medical examination should be offered at shorter intervals at the discretion of the responsible physician or other qualified healthcare provider.

1.2.4 Emergency Medical Care

If the worker for any reason develops signs or symptoms of heat illness, the employer should provide appropriate emergency medical treatment.

1.2.5 Information to be provided to the Healthcare Provider

The employer should provide the following information to the examining physician or other qualified healthcare provider performing or responsible for the medical surveillance program:

(1) A copy of this recommended standard;

(2) A description of the affected worker's duties and activities as they relate to the worker's environmental and metabolic heat exposure;

(3) An estimate of the worker's potential exposure to workplace heat (both environmental and metabolic), including any available workplace measurements or estimates;

(4) A description of any protective equipment or clothing the worker uses or may be required to use; and

(5) Relevant information from previous medical examinations of the affected worker which is not readily available to the examining physician or other qualified healthcare provider.

1.2.6 Healthcare Provider's Written Opinion

The employer should obtain a written opinion from the responsible physician or other qualified healthcare provider which should include:

(1) The results of the medical examination and the tests performed;

(2) The detected material stress in the opinion of the physician or other qualified healthcare provider as to whether the worker has any medical conditions which would increase the risk of impairment of health from exposure to heat in the work environment;

(3) An estimate of the individual's tolerance to withstand hot working conditions;

(4) An opinion as to whether the worker can perform the work required by the job (i.e., physical fitness for the job);

(5) Any recommended limitations upon the worker's exposure to heat stress or upon the use of protective clothing or equipment; and

(6) A statement that the worker has been informed by the physician or other qualified healthcare provider of the results of the medical examination and any medical conditions which require further explanation or treatment.

1.3 Surveillance of Heat-related Sentinel Health Events

1.3.1 Definition

Surveillance of heat-related Sentinel Health Events (SHEs) is defined as the systematic collection and analysis of data concerning the occurrence and distribution of adverse health effects in defined populations at risk to heat injury or illness.

1.3.2 Requirements

In order to evaluate and improve prevention and control measures for heat- induced effects, which includes the identification of highly susceptible workers, data on the occurrence or recurrence in the same worker, and distribution in time, place, and person of heat-related adverse effects should be obtained and analyzed for each workplace.

1.4 Posting of Hazardous Areas

1.4.1 Dangerous Heat-Stress Areas

In work areas and at entrances to work areas or building enclosures where there is a reasonable likelihood of the combination(s) of environmental and metabolic heat exceeding the C, there should be posted readily visible warning signs containing information on the required protective clothing or equipment, hazardous effects of heat stress on human health, and information on emergency measures for heat injury or illness. This information should be arranged as follows:

DANGEROUS HEAT STRESS AREA
HEAT-STRESS PROTECTIVE CLOTHING OR EQUIPMENT REQUIRED
HARMFUL IF EXCESSIVE HEAT EXPOSURE OR WORK LOAD OCCUR
HEAT-RELATED FAINTING, HEAT RASH, HEAT CRAMP, HEAT EXHAUSTION, OR HEAT STROKE MAY OCCUR

1.4.2 Emergency Situations

In any area where there is a likelihood of heat stress emergency situations occurring, the warning signs required in this section should be supplemented with signs giving emergency and first aid instructions.

1.4.3 Additional Requirements for Warning Signs

All hazard warning signs should be printed in English and where appropriate in the predominant language of workers unable to read English. Workers unable to read the signs should be informed of the warning printed on the signs and the extent of the hazardous area(s). All warning signs should be kept clean and legible at all times.

1.5 Protective Clothing and Equipment

Engineering controls and safe work practices should be used to maintain worker exposure to heat stress at or below the applicable RAL or REL specified. In addition, protective clothing and equipment (e.g., water-cooled garments, air-cooled garments, ice-packet vests, wetted-overgarments, heat-reflective aprons or suits) should be provided by the employer to the workers when the total heat stress exceeds the C.

1.6 Worker Information and Training

1.6.1 Information Requirements

All new and current workers, who are unacclimatized to heat and work in areas where there is reasonable likelihood of heat injury or illness, should be kept informed, through continuing education programs, of:

(1) Heat stress hazards,

(2) Predisposing factors and relevant signs and symptoms of heat injury and illness,

(3) Potential health effects of excessive heat stress and first aid procedures,

(4) Proper precautions for work in heat stress areas,

(5) Worker responsibilities for following proper work practices and control procedures to help protect the health and provide for the safety of themselves and their fellow workers, including instructions to immediately report to the employer the development of signs or symptoms of heat stress overexposure,

(6) The effects of therapeutic drugs, over-the-counter medications, or social drugs (including alcohol), that may increase the risk of heat injury or illness by reducing heat tolerance (see Chapter 7),

(7) The purposes for and descriptions of the environmental and medical surveillance programs and of the advantages to the worker of participating in these surveillance programs, and

(8) If necessary, proper use of protective clothing and equipment.

1.6.2 Training Programs

(1) The employer should institute a continuing education program, conducted by persons qualified by experience or training in occupational safety and health, to ensure that all workers potentially exposed to heat stress have current knowledge of at least the information specified in this section. For each affected worker, the instructional program should include adequate verbal and/or written communication of the specified information. The employer should develop a written plan of the training program that includes a record of all instructional materials.

(2) The employer should inform all affected workers of the location of written training materials and should make these materials readily available, without cost to the affected workers.

1.6.3 Heat-Stress Safety Data Sheet

(1) The information specified in this section should be recorded on a heat-stress safety data sheet or on a form specified by the Occupational Safety and Health Administration (OSHA).

(2) In addition, the safety data sheet should contain:

(i) Emergency and first aid procedures, and

(ii) Notes to physician or other qualified healthcare provider regarding classification, medical aspects, and prevention of heat injury and illness. These notes should include information on the category and clinical features of each injury and illness, predisposing factors, underlying physiologic disturbance, treatment, and prevention procedures.

1.7 Control of Heat stress

1.7.1 General Requirements

(1) Where engineering and work practice controls are not sufficient to reduce exposures to or below the applicable RAL or REL, they should, nonetheless, be used to reduce exposures to the lowest level achievable by these controls and should be supplemented by the use of heat-protective clothing or equipment, and a heat-alert program should be implemented as specified in this section.

(2) The employer should establish and implement a written program to reduce exposures to or below the applicable RAL or REL by means of engineering and work practice controls.

1.7.2 Engineering Controls

(1) The type and extent of engineering controls required to bring the environmental heat below the applicable RAL or REL can be calculated using the basic heat exchange formulae (e.g., Chapters 4 and 5). When the environmental heat exceeds the applicable RAL or REL, the following control requirements should be used.

(a) When the air temperature exceeds the skin temperature, convective heat gain should be reduced by decreasing air temperature and/or decreasing the air velocity if it exceeds 1.5 meters per second (m/sec) (300 ft/min). When air temperature is lower than skin temperature, convective heat loss should be increased by increasing air velocity. The type, amount, and characteristics of clothing will influence heat exchange between the body and the environment.

(b) When the temperature of the surrounding solid objects exceeds skin temperature, radiative heat gain should be reduced by: placing shielding or barriers, which are radiant-reflecting or heat-absorbing, between the heat source and the worker; by isolating the source of radiant heat; or by modifying the hot process or operation.

(c) When necessary, evaporative heat loss should be increased by increasing air movement over the worker, by reducing the influx of moisture from steam leaks or from water on the workplace floors, or by reducing the water vapor content (humidity) of the air. The air and water vapor permeability of the clothing worn by the worker will influence the rate of heat exchange by evaporation.

1.7.3 Work and Hygienic Practices

(1) Work modifications and hygienic practices should be introduced to reduce both environmental and metabolic heat when engineering controls are not adequate or are not feasible. The most effective preventive work and hygienic practices for reducing heat stress include, but are not limited to the following parts of this section:

(a) Limiting the time the worker spends each day in the hot environment by decreasing exposure time in the hot environment and/or increasing recovery time spent in a cool environment;

(b) Reducing the metabolic demands of the job by such procedures as mechanization, use of special tools, or increase in the number of workers per task;

(c) Increasing heat tolerance by a heat acclimatization program and by increasing physical fitness;

(d) Training supervisors and workers to recognize early signs and symptoms of heat illnesses and to administer relevant first aid procedures;

(e) Implementing a buddy system in which workers are responsible for observing fellow workers for early signs and symptoms of heat intolerance such as weakness, unsteady gait, irritability, disorientation, changes in skin color, or general malaise; and

(f) Providing adequate amounts of cool, i.e., 10° to 15°C (50° to 59°F) potable water near the work area and encouraging all workers to drink a cup of water (about 150 to 200 mL (5 to 7 ounces) every 15 to 20 minutes. Individual, not communal, drinking cups should be provided.

1.7.4 Heat-Alert Program

A written Heat-Alert Program should be developed and implemented whenever the National Weather Service or other competent weather forecast service forecasts that a heat wave is likely to occur the following day or days. A heat wave is indicated when daily maximum temperature exceeds 35°C (95°F) or when the daily maximum temperature exceeds 32°C (90°F) and is 5°C (9°F) or more above the maximum reached on the preceding days. The details for a Heat-Alert Program are described in 5.3 Heat-Alert Program – Preventing Emergencies.

1.8 Recordkeeping

1.8.1 Environmental and Metabolic Heat Exposure Surveillance

(1) The employer should establish and maintain an accurate record of all measurements made to determine environmental and metabolic heat exposures to workers as required in this recommended standard.

(2) Where the employer has determined that no metabolic heat measurements are required as specified in this recommended standard, the employer should maintain a record of the screening estimates relied upon to reach the determination.

1.8.2 Medical Surveillance

The employer should establish and maintain an accurate record for each worker subject to medical surveillance as specified in this recommended standard.

1.8.3 Surveillance of Heat-related Sentinel Health Events

The employer should establish and maintain an accurate record of the data and analyses specified in this recommended standard.

1.8.4 Heat-related Illness Surveillance

The employer should establish and maintain an accurate record of any heat illness or injury and the environmental and work conditions at the time of the illness or injury.

1.8.5 Heat Stress Tolerance Augmentation

The employer should establish and maintain an accurate record of all heat stress tolerance augmentation for workers by heat acclimatization procedures and/or physical fitness enhancement.

1.8.6 Record Retention

In accordance with the requirements of 29 CFR 1910.20(d), the employer should retain records described by this recommended standard for at least the following periods:

(1) Thirty years for environmental monitoring records,

(2) Duration of employment plus 30 years for medical surveillance records,

(3) Thirty years for surveillance records for heat-related SHEs, and

(4) Thirty years for records of heat stress tolerance augmentation.

1.8.7 Availability of Records

(1) The employer should make worker environmental surveillance records available upon request for examination and copying to the subject worker or former worker or to anyone having the specific written consent of the subject worker or former worker in accordance with 29 CFR 1910.20.

(2) Any worker's medical surveillance records, surveillance records for heat-related SHEs, or records of heat stress tolerance augmentation that are required by this recommended standard should be provided upon request for examination and copying to the subject worker or former worker or to anyone having the specific written consent of the subject worker or former worker.

1.8.8 Transfer of Records

(1) The employer should comply with the requirements on the transfer of records set forth in the standard, Access to Medical Records, 29 CFR 1910.20(h).

2. Introduction

Criteria documents are developed by the National Institute for Occupational Safety and Health (NIOSH) in response to section 20(a) (3) of the Occupational Safety and Health Act of 1970. Through the Act, Congress charged NIOSH with recommending occupational safety and health standards and describing exposure limits that are safe for various periods of employment. These limits include, but are not limited to, the exposures at which no worker will suffer diminished health, functional capacity or life expectancy as a result of his or her work experience. By means of criteria documents, NIOSH communicates these recommended standards to regulatory agencies (including the Occupational Safety and Health Administration [OSHA]), health professionals in academic institutions, industry, organized labor, public interest groups and others in the occupational safety and health community, including the workers. Criteria documents contain a critical review of the scientific and technical information about the prevalence of hazards, the existence of safety and health risks and the adequacy of control methods.

A criteria document, Criteria for a Recommended Standard ....Occupational Exposure to Hot Environments [NIOSH 1972], was published in 1972. In 1986, NIOSH published a revised criteria document [NIOSH 1986a] and a companion pamphlet, “Working in Hot Environments, Revised 1986” [NIOSH 1986b]. These publications presented the NIOSH assessment of the potential safety and health hazards encountered in hot environments, regardless of the workplace, and recommended a standard to protect workers from those hazards.

Heat-related occupational illnesses and injuries occur in situations where the total heat load (environmental and metabolic) exceeds the capacities of the body to maintain homeostasis. In the 1986 documents, NIOSH recommended sliding scale limits based on environmental and metabolic heat loads. These recommendations were based on the relevant scientific data and industry experience at that time. This criteria document reflects the most recent NIOSH evaluation of the current scientific literature and research and supersedes the previous NIOSH documents. The current criteria document presents the updated criteria, techniques and procedures for the assessment, evaluation and control of occupational heat stress by engineering controls and preventive work practices. It also addresses the recognition, treatment and prevention of heat-related illnesses and injuries through provision of guidance for medical supervision, hygienic practices and training programs.

In this document, the recommended criteria were developed to ensure that adherence to them will (1) protect against the risk of heat-related illnesses and unsafe acts, (2) be achievable by techniques that are valid and reproducible and (3) be attainable using existing techniques. This recommended standard is also designed to prevent possible harmful effects from interactions between heat and toxic chemical and physical agents. The recommended environmental limits for various intensities of physical work, as indicated in Figures 8.1 and 8.2, are not upper tolerance limits for heat exposure for all workers but, rather, levels at which engineering controls, preventive work and hygienic practices, and administrative or other control procedures should be implemented in order to reduce the risk of heat-related illnesses, even in the least heat tolerant workers.

A 2008 Centers for Disease Control and Prevention (CDC) report identified 423 worker deaths among U.S. agricultural (16% in crop workers) and nonagricultural industries during 1992-2006. The heat-related average annual death rate for the crop workers was 0.39 per 100,000 workers, compared with 0.02 for all U.S. civilian workers [Luginbuhl et al. 2008]

In 2010, 4,190 injury and illness cases arising from exposure to environment heat among private industry and state and local government workers resulted in one or more days of lost work [Bureau of Labor Statistics 2011]. Eighty-six percent of the ill or injured workers were aged 16-54 years. In that same year, 40 workers died from exposure to environmental heat [Bureau of Labor Statistics 2010]. The largest number of workers (18) died in the construction industry; followed by 6 deaths in natural resources (includes agriculture) and mining; 6 deaths in professional and business services (includes waste management and remediation); and 3 deaths in manufacturing. Eighty percent of the deaths occurred among workers 25-54 years of age. Because of a lack of recognition of heat-related illness and the nature of reporting only illnesses involving days away from work, the actual number of occupational heat illnesses and deaths is not known. Additionally, estimates of the number of workers exposed to heat are not available.

A glossary of terms, symbols, abbreviations, and units of measurement used in this document is presented at the beginning of the document.

3. Heat Balance and Heat Exchange

An essential requirement for continued normal body function is that the deep body core temperature be maintained within the acceptable range of about 37°C (98.6°F) ± 1°C (1.8°F). Achieving this body temperature equilibrium requires a constant exchange of heat between the body and the environment. The rate and amount of the heat exchange are governed by the fundamental laws of thermodynamics of heat exchange between objects. The amount of heat that must be exchanged is a function of (1) the total heat produced by the body (metabolic heat), which may range from about 1 kcal per kilogram (kg) of body weight per hour (1.16 watts) at rest to 5 kcal/kg body weight/h (7 watts) for moderately hard industrial work; and (2) the heat gained, if any, from the environment. The rate of heat exchange with the environment is a function of air temperature and humidity, skin temperature, air velocity, evaporation of sweat, radiant temperature, and type, amount, and characteristics of the clothing worn. Respiratory heat loss is generally of minor consequence except during hard work in very dry environments.

3.1 Heat Balance Equation

The basic heat balance equation is:

$$\Delta S = (M - W) \pm C \pm R - E$$

where:

ΔS = change in body heat content

(M-W) = total metabolism - external work performed

C = convective heat exchange

R = radiative heat exchange

E = evaporative heat loss

To solve the equation, measurement of metabolic heat production, air temperature, air water-vapor pressure, wind velocity, and mean radiant temperature are required [Belding 1971; Ramsey 1975; Lind 1977; Grayson and Kuehn 1979; Goldman 1981; Nishi 1981; ISO 1982b; ACGIH 1985; DiBenedetto and Worobec 1985; Goldman 1985b, 1985a; Horvath 1985; Havenith 1999].

3.2 Modes of Heat Exchange

The major modes of heat exchange between humans and the environment are convection, radiation, and evaporation. Conduction, which is another potential way to exchange heat, plays a minor role in industrial heat stress, other than for brief periods of body contact with hot tools, equipment, floors, etc., which may cause burns; or for people working in water, or in supine positions [Havenith 1999]. The equations for calculating heat exchange by convection, radiation, and evaporation are available in Standard International (SI) units, metric units, and English units. In SI units, heat exchange is expressed in watts per square meter of body surface (W/m^2). The heat-exchange equations are available in both metric and English units for both the seminude individual and the worker wearing conventional long-sleeved work shirt and trousers. The values are expressed in kcal/h or British thermal units per hour (Btu/h) for the "standard worker" defined as one who weighs 70 kg (154 lbs.) and has a body surface area of 1.8 m^2 (19.4 ft^2). For workers who are smaller or larger than the standard worker, appropriate correction factors must be applied [Belding 1971]. The equations utilizing the SI units for heat exchange by C, R, and E are presented in Appendix A.

For these, as well as other versions of heat-balance equations, computer programs of different complexities have been developed. Some of them are commercially available.

3.2.1 Convection (C)

The rate of convective heat exchange between the skin of a person and the ambient air immediately surrounding the skin is a function of the difference in temperature between the ambient air (t_a) and the mean weighted skin temperature ($\bar{t}_{sk}$) and the rate of air movement over the skin (V_a). This relationship is stated algebraically for the standard worker wearing the customary one-layer work clothing ensemble as [Belding 1971]:

$$C = 7.0\ V_a^{\ 0.6}(t_a - \bar{t}_{sk})$$

where:

C = convective heat exchange, kcal/h

V_a = air velocity in meters per second (m/sec)

t_a = air temperature °C

$\bar{t}_{sk}$ = mean weighted skin temperature usually assumed to be 35°C (95°F)

when t_a >35°C, there will be a gain in body heat from the ambient air by convection;

when t_a <35°C, heat will be lost from the body to the ambient air by convection.

This basic convective heat-exchange equation in English units has been revised for the "standard worker" wearing the customary one-layer work clothing ensemble as:

$$C = 0.65\ V_a^{\ 0.6}(t_a - \bar{t}_{sk})$$

where:

C = convective heat exchange in Btu/h

V_a = air velocity in feet per minute (fpm)

t_a = air temperature °F

$\bar{t}_{sk}$ = mean weighted skin temperature usually assumed to be 95°F (35°C)

3.2.2 Radiation (R)

The radiant heat exchange is primarily a function of the temperature gradient between the mean radiant temperature of the surroundings ($\bar{t}_w$) and the mean weighted skin temperature ($\bar{t}_{sk}$). Radiant heat exchange is a function of the fourth power of the absolute temperature of the solid surroundings less the skin temperature $(T_w\text{-}T_{sk})^4$ but an acceptable approximation for the customary one-layer clothed individual is [Belding 1971]:

$$R = 6.6\ (\bar{t}_w - \bar{t}_{sk})$$

R = radiant heat exchange kcal/h

$\bar{t}_w$ = mean radiant temperature of the solid surrounding surface °C

$\bar{t}_{sk}$ = mean weighted skin temperature

For the customary one-layer clothed individual and English units, the equation becomes:

$$R = 15.0\ (\bar{t}_w - \bar{t}_{sk})$$

R = radiant heat exchange Btu/h

$\bar{t}_w$ = mean radiant temperature ºF

$\bar{t}_{sk}$ = mean weighted skin temperature

3.2.3 Evaporation (E)

The evaporation of water (sweat) from the skin surface results in a heat loss from the body. The maximum evaporative capacity (and heat loss) is a function of air motion (V_a) and the water vapor pressure difference between the ambient air (p_a) and the wetted skin at skin temperature

(p_{sk}). The equation for this relationship is for the customary one-layer clothed worker [Belding 1971]:

$$E = 14V_a^{0.6}(p_{sk} - p_a)$$

E = Evaporative heat loss kcal/h

V_a = air speed, m/sec

P_a = water vapor pressure of ambient air, mmHg

P_{sk} = vapor pressure of water on skin assumed to be 42 mmHg at a 35°C skin temperature

This translates in English units for the customary one-layer clothed worker into:

$$E = 2.4V_a^{0.6}(p_{sk} - p_a)$$

E = Evaporative heat loss Btu/h

V_a = air velocity, fpm

p_a = water vapor pressure air, mmHg

p_{sk} = water vapor pressure on the skin assumed to be 42 mmHg at a 95°F skin temperature

3.3 Effects of Clothing on Heat Exchange

Clothing serves as a barrier between the skin and the environment to protect against hazardous chemical, physical, and biologic agents. A clothing system (i.e., any matching garments worn suited to the requirements of the environment or job) will also alter the rate and amount of heat exchange between the skin and the ambient air by convection, radiation, and evaporation. When calculating heat exchange by each or all of these routes, it is, therefore, necessary to apply correction factors that reflect the type, amount, and characteristics of the clothing being worn when the clothing differs substantially (i.e., more than one-layer and/or greater air and vapor impermeability) from the customary one-layer work clothing. This clothing efficiency factor (F_{cl}) for dry heat exchange is nondimensional [Goldman 1978; McCullough et al. 1982; Vogt et al. 1982]. In general, the thicker and greater the air and vapor impermeability of the clothing barrier layer or layers, the greater is its interference with convective, radiant, and evaporative heat exchange.

Corrections of the REL and RAL to reflect the F_{cl} based on heat transfer calculation for a variety of environmental and metabolic heat loads and three clothing ensembles have been suggested [*Heat Stress Management Program for the Nuclear Power Industry - Interim Report* 1986]. The customary one-layer clothing ensemble was used as the basis for comparisons with the other clothing ensembles. When a two-layer clothing system is worn, the REL and RAL should be lowered by 2°C (3.8°F). When a partially air and/or vapor impermeable ensemble or heat reflective or protective aprons, leggings, gauntlets, etc. are worn, the REL and RAL should be lowered 4°C (7.2°F). These suggested corrections of the REL or RAL are professional judgments that have not been substantiated by controlled laboratory studies or long-term industrial experience.

In those workplaces where a vapor and air impermeable encapsulating ensemble (i.e, a protective overlayer used to limit or prevent exposure to toxins [e.g., HAZMAT] or radiant energy [e.g., firefighter bunker gear]; or safety helmets, respiratory protection, special boots, and gloves, etc.) must be worn, the WBGT is not the appropriate measurement of environmental heat stress. In these instances, the adjusted air temperature (t_{adb}) must be measured and used instead of the WBGT. Where the t_{adb} exceeds approximately 20°C (68°F), physiologic monitoring (oral temperature and/or pulse rate) is required. This physiologic monitoring must be conducted on a time schedule based upon metabolic heat production and t_{adb}. The suggested frequency of physiologic monitoring for moderate work varies from once every two hours at t_{adb} of 24°C (75°F) to every 15 minutes for moderate work at t_{adb} of 32°C (90°F) [NIOSH 1985].

3.3.1 Clothing Insulation and Non-evaporative Heat loss

Even without any clothing, there is a thin layer of still air (the boundary layer) trapped next to the skin. This external still air film acts as a layer of insulation against heat exchange between the skin and the ambient environment. Typically, without body or air motion, this air layer (l_a) provides about 0.8 clo units of insulation. One clo unit of clothing insulation is defined as allowing 5.55 kcal/m^2/h of heat exchange by radiation and convection (H_{R+C}) for each °C of temperature difference between the skin (at a mean skin temperature $\bar{t}_{sk}$) and adjusted dry bulb temperature $t_{adb} = (t_a + \bar{t}_r)/2$. For the "standard man" with 1.8 m^2 of surface area, the hourly heat exchange by radiation and convection (H_{R+C}) can be estimated as:

$$H_{R+C} = (10/\text{clo})\ (\bar{t}_{sk} - t_{adb})$$

Thus, the 0.8 clo still air layer limits the heat exchange by radiation and convection for the nude standard man to about 12.5 kcal/h (i.e., 10/0.8) for each °C of difference between skin temperature and air temperature. A resting individual in still air producing 90 kcal/h of metabolic heat will lose about 11 kcal/h (12%) by respiration and about the same by evaporation of the body water diffusing through the skin. The person will then have to begin to sweat and lose heat by evaporation to eliminate some of the remaining 68 kcal/h of metabolic heat if the t_{adb} is less than 5.5°C below t_{sk} [Goldman 1981].

The still air layer is reduced by increasing air motion, reaching a minimal value of approximately 0.2 clo at air speeds above 4.5 m/sec (890 fpm or 10 mph). At this wind speed, 68 kcal/h can be eliminated from the skin without sweating at an air temperature only 1.4°C below skin temperature, i.e., 68 / (10/0.2) = 1.36°C.

Studies of clothing materials over a number of years have led to the conclusion that the insulation provided by clothing is generally a linear function of its thickness. Differences in fibers or fabric weave, unless these directly affect the thickness or the vapor or air permeability of the fabric, have only very minor effects on insulation. The function of the fibers is to maintain a given thickness of still air in the fabric and block heat exchange. The fibers are more conductive than insulating; increasing fiber density (as when trying to fit two socks into a boot which has been sized to fit properly with one sock) can actually reduce the insulation provided [Goldman 1981].

The typical value for clothing insulation is 1.57 clo per centimeter of thickness (4 clo per inch) (see Table 3-1). It is difficult to extend this generalization to very thin fabric layers or to fabrics like underwear, which may simply occupy an existing still air layer of not more than 0.5 cm thickness. These thin layers show little contribution to the intrinsic insulation of the clothing, unless there is (a) "pumping action" of the clothing layers by body motion (circulation of air through and between layers of clothing due to body movement); (b) compression of the clothing by pressure from other clothing, by objects in contact with the body, or by external wind; or (c) penetration of some of the wind (as a function of the air permeability of the outer covering fabric) into the trapped air layer [ASHRAE 1981b; Goldman 1981; McCullough et al. 1982]. Table 3-1 presents a listing for the intrinsic insulation contributed by adding each of the listed items of typical clothing ensembles. The total intrinsic insulation is not the sum of the individual items, but 80% of their total insulation value; this allows for an average loss of 20% of the sum of the individual items to account for the compression of one layer on the next. This average 20% reduction is a rough approximation, which is highly dependent on such factors as nature of the fiber, the weave, the weight of the fabric, the use of foam or other nonfibrous layers, and the clothing fit and cut.

1 Table 3-1 Clo insulation values for typical clothing ensembles

Clothing ensemble	Clothing insulation (I_{cl})	
	Clo	M^2 °C W^{-1}
Underpants, coveralls, socks, shoes	0.70	0.11
Underpants, shirt, pants, socks, shoes	0.75	0.115
Underpants, shirt, coveralls, socks, shoes	0.80	0.125
Underpants, shirt, pants, light jacket, socks, shoes	0.85	0.135
Underpants, shirts, pants, smock, socks, shoes	0.90	0.14
Underpants, short-sleeve under shirt, shirt, pants, light jacket, socks, shoes	1.0	0.155
Underpants, short-sleeve under shirt, shirt, pants, coveralls, socks, shoes	1.1	0.17
Long underwear shirt and bottoms, heavy jacket, pants, socks, shoes	1.2	0.185
Underpants, short-sleeve under shirt, shirt, pants, light jacket, heavy jacket, socks, shoes	1.25	0.19
Underpants, short-sleeve under shirt, coveralls, heavy jacket and pants, shocks, shoes	1.40	0.22
Underpants, short-sleeve under shirt, pants, light jacket, heavy jacket and pants, socks, shoes	1.55	0.225
Underpants, short-sleeve under shirt, pants, light jacket, heavy quilted outer jacket and overalls, socks, shoes	1.85	0.285
Underpants, short-sleeve under shirt, pants, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	2.0	0.31
Long underwear shirt and bottoms, heavy jacket and pants, parka with heavy quilting, overalls with heavy quilting, socks, shoes, cap, gloves	2.55	0.395

2 Adapted from ISO [2007]

3 In summary, insulation is generally a function of the thickness of the clothing ensemble and this,
4 in turn, is usually a function of the number of clothing layers. Thus, each added layer of clothing,

if not compressed, will increase the total insulation. That is why most two-layer protective clothing ensembles exhibit quite similar insulation characteristics and most three-layer systems are comparable, regardless of some rather major differences in fiber or fabric type [Goldman 1981].

3.3.2 Clothing Permeability and Evaporative Heat Loss

Evaporative heat transfer through clothing tends to be affected linearly by the thickness of the ensemble. The moisture permeability index (i_m) is a dimensionless unit with a theoretical lower limit value of 0 for a vapor- and air-impermeable layer and an upper value of 1 if all the moisture that the ambient environment can take up (as a function of the ambient air vapor pressure and fabric permeability) can pass through the fabric. Since moisture vapor transfer is a diffusion process limited by the characteristic value for diffusion of moisture through still air, values of i_m approaching 1 should be found only with high wind and thin clothing. A typical i_m value for most clothing materials in still air is less than 0.5 (e.g., i_m will range from 0.45 to 0.48). Water repellent treatment, very tight weaves, and chemical protective impregnations can reduce the i_m value significantly. However, even impermeable layers seldom reduce the i_m value to zero since an internal evaporation-condensation cycle is set up between the skin surface and the inner surface of the impermeable layer, which effectively transfers some heat from the skin to the vapor barrier; this shunting, by passing heat across the intervening insulation layers, can be reflected as an i_m value of perhaps 0.08 even for a totally impermeable overgarment.

Very few fiber treatments have been found to improve the i_m index value of fabric layers; surfactants, which increase the number of free hydroxyl (OH) radicals on the fiber surface or which somehow improve wicking, appear to have improved the i_m value of a fabric. However, the ultimate evaporative heat transferred from the skin through the clothing and external air layers to the environment is not simply a function of the i_m, but is a function of the permeability index-insulation ratio (i_m/clo). The maximum evaporative heat exchange with the environment can be estimated for the H_{R+C} of a "standard man" with 1.8 m^2 of surface area, as:

$$HE_{max}=10i_m/clo \times 2.2(p_{sk}-p_a)$$

The constant 2.2 is the Lewis number; P_{sk} is the water vapor pressure of sweat (water) at skin temperature (t_{sk}); and P_a is the water vapor pressure of the ambient air at air temperature, t_a. Thus, the maximum evaporative transfer tends to be a linear, inverse function of insulation, if not further degraded by various protective treatments, which range from total impermeability to water repellent treatments [Goldman 1973, 1981, 1985a]. The Lewis number is derived the degree or percent of skin wetness (or moisture available for evaporation and, therefore, heat transfer) (ND), latent heat (L), and evaporative heat transfer (h_e).

3.3.3 Physiologic Problems of Clothing

The percent of sweat-wetted skin surface area ($\underline{w}$) that will be needed to eliminate the required amount of heat from the body by evaporation can be estimated simply as the ratio of the required evaporative cooling (E_{req}) and the maximum water vapor uptake capacity of the ambient air (E_{max}). A totally wetted skin = 100%.

$$\underline{w} = E_{req} / E_{max}$$

Some sweat-wetted skin is not uncomfortable; in fact, some sweating during exertion in heat increases comfort. As the extent of skin wetted with sweat approaches 20%, the sensation of discomfort begins to be noted. Discomfort is marked and performance decrements can appear when between 20% and 40% of the body surface is covered with sweat or moisture either from exercise or exposure to high enough environmental heat; they become increasingly noted as $\underline{w}$ approaches 60%. Sweat begins to be wasted, dripping rather than evaporating at 70%; physiologic strain becomes marked between 60% and 80% $\underline{w}$. Increases of $\underline{w}$ above 80% result in limited tolerance, even for physically fit, heat-acclimatized young people. The above arguments indicate that any protective work clothing will pose some limitations on tolerance since, with I_a plus I_{clo} rarely below 2.5 clo, their i_m/clo ratios are rarely above 0.20 [Goldman 1985b].

The physiologic problem with clothing, heat transfer, and exertion (work) can be estimated from equations which describe the competition for the blood pumped by the heart. The cardiac output (CO) is the stroke volume (SV) (or volume of blood pumped per beat) times heart rate (HR) in beats per minute (bpm) (CO = SV x HR). The cardiac output increases essentially linearly with increasing work; the rate limiting process for metabolism is the maximum rate of delivery of oxygen to the working muscle via the blood supply. It is expressed in liters per minute (L/min). In heat stress, this total blood supply must be divided between the working muscles and the skin where the heat exchange occurs.

SV rapidly reaches a constant value for a given intensity of work. Thus, the work intensity (i.e., the rate of oxygen delivered to the working muscles) is essentially indicated by HR; the individual worker's maximum HR limits the ability to continue work. Conditions that impair the return of blood from the peripheral circulation to fill the heart between beats will affect work capacity. The maximum achievable HR is a function of age and can be roughly estimated by the relationship: 220 bpm minus age in years [Hellon and Lind 1958; Drinkwater and Horvath 1979]. Given equivalent HR at rest (e.g., 60 bpm), a 20-year-old worker's HR has the capacity to increase by 140 bpm, i.e., (220-20)-60, while a 60-year-old worker can increase his HR only 100 bpm, i.e., (220-60)-60. Since the demands of a specific task will be roughly the same for 20- and 60-year-old individuals who weigh the same and do the same amount of physical work, the decline in maximum achievable HR with age increases both the perceived and the actual relative physiologic strain of work on the older worker.

The ability to transfer the heat produced by muscle activity from the core of the body to the skin is also a function of the CO. Blood passing through core body tissues is warmed by heat from metabolism during rest and work. The basic requirement is that skin temperature (t_{sk}) must be maintained at least 1°C (1.8°F) below deep body temperature (t_{re}) if blood that reaches the skin is to be cooled before returning to the body core. The heat transferred to the skin is limited, ultimately, by the CO and by the extent to which t_{sk} can be maintained below t_{re}.

A worker's t_{re} is a function of metabolic heat production (M) ($t_{re} = 36.7 + 0.004M$), as long as there are no restrictions on evaporative and convective heat loss by clothing, high ambient vapor pressures or very low air motion; e.g., at rest, if M = 105 watts, t_{re} is about 37.1°C (98.8°F). Normally, under the same conditions of unlimited evaporation, skin temperatures are below t_{re} by about 3.3°C + (0.006M); thus, at rest, when t_{re} is 37°C, the corresponding t_{sk} is about 33°C, i.e., 37 - (3.3 + 0.6). This 3°- 4°C difference between t_{re} and t_{sk} indicates that, at rest, each liter of blood flowing from the deep body to the skin can transfer approximately 4.6 watts or 4 kcal of heat to the skin. Since t_{re} increases and t_{sk} decreases due to the evaporation of sweat with increasing M, it normally becomes easier to eliminate body heat with increasing work, since the difference between t_{re} and t_{sk} increases by about 1°C (1.8°F) per 100 watts (86 kcal) of increase in M (i.e., t_{re} up 0.4°C (0.7ºF), and t_{sk} down 0.6°C (1.1°F) per 100 watts of M). Thus, at sustainable hard work (M=500 watts or 430 kcal/h), each liter of blood flowing from core to skin can transfer 9 kcal to the skin, which is 2.5 times that at rest [Goldman 1973, 1985a].

Work under a heat stress condition sets up a competition for CO, particularly as the blood vessels in the skin dilate to their maximum and less blood is returned to the central circulation. Gradually, less blood is available in the venous return to fully fill the heart between beats, causing the SV to decrease; therefore, HR must increase to maintain the same CO. For a fit, young workforce, the average work HR should be limited to about 110 bpm if an 8-hour workshift is to be completed; an average HR of 140 bpm for a maximum work time of 4 hours or less, and 160 bpm should not be maintained for more than 2 hours [Brouha 1960]. If the intensity of work results in a HR in excess of these values, the intensity of work should be reduced. Thus, heat added to the demands of work rapidly results in problems, even in a healthy, young workforce. These problems are amplified if circulating blood volume is reduced as a result of inadequate water intake to replace sweat losses, which can average one liter an hour over an 8-hour workshift (or by vomiting, diarrhea, or diuresis).

The crisis point, heat exhaustion and collapse, is a manifestation of inadequate blood supply to the brain; this occurs when CO becomes inadequate because of insufficient return of blood from the periphery to fill the heart for each beat or because of inadequate time between beats to fill the heart as HR approaches its maximum.

Unfortunately, clothing interferes with heat loss from the skin and skin temperature rises predictably with increased clothing. Because of the insulation-induced rise in t_{sk} and the resultant limited ability to dissipate heat that has been transferred from the core to the skin, core temperature (t_{re}) also rises when clothing is worn. Another type of interference with heat loss from the skin arises when sweat evaporation is required for body cooling (i.e., when M + HR + C > O), but is limited either by high ambient water vapor pressure, low wind, or a low clothing permeability index (i_m/clo).

As E_{req} approaches E_{max}, skin temperature increases dramatically and deep body temperature begins to increase rapidly. Deep body temperatures above 38.0°C (100.4°F) put workers at risk for heat-related illnesses. The risk of heat exhaustion collapse is about 25% at a deep body temperature of 39.2°C (102.6°F) associated with a skin temperature of 38°C (100.4°F) (i.e., t_{sk} converging toward t_{re} and approaching the 1°C (1.8°F) limiting difference where one liter of blood can transfer only 1 or 2 kcal to the skin). At a similarly elevated t_{sk} where t_{re} is 39.5°C (103.1°F), there is an even greater risk of heat exhaustion collapse, and as t_{re} approaches 40°C (104°F). With elevated skin temperatures, most individuals are in imminent danger of heat-related illness. Finally, t_{re} levels above 41°C (105.8°F) are associated with heat stroke, a life-threatening major medical emergency. The competition for CO is sorely exacerbated by dehydration (limited SV), by age (limited maximum HR), and by reduced physical fitness (compromised CO). These work-limiting and potentially serious deep body temperatures are reached more rapidly when combinations of these three factors are involved.

As indicated in the above statements, maximum work output may be seriously degraded by almost any protective clothing worn during either heavy work in moderately cool environments or low work intensities in hot conditions, because of the clothing interfering with heat elimination. The heat-stress problem is also likely to be increased with any two-layer protective ensembles or any effective single-layer vapor barrier system for protection against toxic products, unless some form of auxiliary cooling is provided [Goldman 1973, 1985a].

4. Biologic Effects of Heat

4.1 Physiologic Responses to Heat

4.1.1 The Central Nervous System

The central nervous system is responsible for the integrated organization of thermoregulation. The hypothalamus of the brain is considered to be the central nervous system structure which acts as the primary seat of control. Historically, in general terms, the anterior hypothalamus has been considered to function as an integrator and "thermostat" while the posterior hypothalamus provides a "set point" of the core or deep-body temperature and initiates the appropriate physiologic responses to keep the body temperature at the "set point" if the core temperature changes.

According to this model, the anterior hypothalamus is the area which receives the information from receptors sensitive to changes in temperature in the skin, muscle, stomach, other central nervous system tissues, and elsewhere. In addition, the anterior hypothalamus itself contains neurons which are responsive to changes in temperature of the arterial blood serving the region. The neurons responsible for the transmission of the temperature information use monoamines, among other neurotransmitters; this has been demonstrated in animals [Cooper et al. 1982]. These monoamine transmitters are important in the passage of appropriate information to the posterior hypothalamus. It is known that the "set point" in the posterior hypothalamus is regulated by ionic exchanges. However, the "set-point" hypothesis has generated considerable controversy [Greenleaf 1979]. The problem with the notion of a "set point" is that, (1) a neuroanatomical region controlling the "set point" has never been identified, and (2) the physiological responses to heat cannot be explained using the notion of a "set point". At present, it appears that the hypothalamic region does integrate neural traffic from thermoreceptors and integrate a physiological response to an increase in temperature. However, the current data suggest that the hypothalamus controls temperature within a so-called interthermal threshold (range of temperatures around a mean with which no physiological response occurs). The physiological responses only occur when the temperature moves beyond the "thresholds" to elicit either sweating or thermogenesis and the appropriate vasomotor response (i.e., vasoconstriction or vasodilation) [Mekjavic and Eiken 2006]. The ratio of sodium to calcium ions is also important in thermoregulation. The sodium ion concentration in the blood and other tissues can be readily altered by exercise and by exposure to heat.

When a train of neural traffic is activated from the anterior to the posterior hypothalamus, it is reasonable to suppose that once a "hot" pathway is activated, it will inhibit the function of the "cold" pathway and vice versa. However, there is a multiplicity of neural inputs at all levels in the central nervous system and many complicated neural "loops" undoubtedly exist.

Current research suggests that, instead of the historical notion of a “set point”, neural input into the hypothalamus is integrated into a response that can be described as “cross inhibitory”. In other words, when neural inputs from warm thermoreceptors in the skin are dominant, the integrated response results in an increase in sweating and cutaneous vasodilation, while simultaneously inhibiting thermogenesis and vice versa [Mekjavic and Eiken 2006]. Paradoxically, during exercise or exposure to elevated air temperatures , the core body temperature will increase and be regulated at a higher level in order to maintain an increase in heat loss by maintaining a thermal gradient between the core body temperature and the skin temperature for the transfer of heat to the environment [Taylor et al. 2008].

A question that must be addressed is the difference between a physiologically raised body temperature and a fever; it is considered that the "set-point" is elevated as determined by the posterior hypothalamus. At the onset of a fever, the body invokes heat-conservation mechanisms (such as shivering and cutaneous vasoconstriction) in order to raise the body temperature to its new regulated stable temperature [Cooper et al. 1982]. In contrast, during exercise in heat, which may result in an increase in body temperature, body temperature rises to a new stable level where it is regulated by the hypothalamus, and only heat-dissipation mechanisms are invoked. Once a fever is induced, the elevated body temperature appears to be normally controlled by the usual physiologic processes around its new and higher regulated level [Taylor et al. 2008].

4.1.2 Muscular Activity and Work Capacity

The muscles are by far the largest single group of tissues in the body, representing some 45% of the body weight. The bony skeleton, on which the muscles operate to generate their forces, represents a further 15% of the body weight. The bony skeleton is relatively inert in terms of metabolic heat production. Even at rest, the muscles produce about 20-25% of the body's total heat production [Rowell 1993]. The amount of metabolic heat produced at rest is quite similar for all individuals when it is expressed per unit of surface area or of lean or fat-free body weight. On the other hand, the heat produced by the muscles during work or exercise can be much higher and must be dissipated if a heat balance is to be maintained. The heat load from metabolism is, therefore, widely variable and it is during work in hot environments (which imposes its own heat load or restricts heat dissipation) that the greatest challenge to normal thermoregulation exists [Parsons 2003].

The proportion of maximal aerobic capacity ($\dot{V}O_2max$) needed to do a specific job is important for several reasons. First, the cardiovascular system must respond with an increased CO which, at levels of work of up to about 40% $\dot{V}O_2max$, is brought about by an increase in both SV and HR. When maximum SV is reached, additional increases in CO can be achieved solely by increased HR until maximal HR is reached [McArdle et al. 1996b; Taylor et al. 2008]. These changes in the cardiovascular response to exercise are responsible for providing sufficient blood flow to muscle to allow for the increase in muscular work [McArdle et al. 1996b]. Further complexities arise when high work intensities are sustained for long periods, particularly when work is carried out in hot surroundings [Åstrand et al. 2003]. Second, muscular activity is associated with an increase in muscle temperature, which then is associated with an increase in core temperature with attendant influences on the thermoregulatory controls. Third, at high levels of exercise, even in a temperate environment, the oxygen supply to the tissues may be insufficient to completely meet the oxygen needs of the working muscles [Taylor et al. 2008].

In warmer conditions, an adequate supply of oxygen to the tissues may become a problem even at moderate work intensities because of competition for blood distribution between the working muscle and the skin [Rowell 1993]. Because of the lack of oxygen, the working muscles must begin to draw on their anaerobic reserves, deriving energy from the oxidation of glycogen in the muscles [McArdle et al. 1996b]. That leads to the accumulation of lactic acid, which may be associated with the development of muscular fatigue. As the proportion of $\dot{V}O_2$max used increases further, anaerobic metabolism assumes a relatively greater proportion of the total muscular metabolism. An oxygen "debt" occurs when oxygen is required to metabolize the lactic acid that accumulates in the muscles. This "debt" must be repaid during the rest period. In hot environments, the recovery period is prolonged as the elimination of both the heat and the lactic acid stored in the body has to occur and water loss must be replenished. These occurrences may take 24 hours or longer [Cooper et al. 1982; Greenleaf and Harrison 1986].

It is well established that, in a wide range of cool to warm environments, 5°-29°C (41°-84.2°F), the deep body temperature rises during exercise to a similar equilibrium value in subjects working at the same proportion of $\dot{V}O_2$max [Lind 1976, 1977]. However, two individuals doing the same job and working at the same absolute load level who have widely different $\dot{V}O_2$max values will have quite different core temperatures. Studies have suggested that, in an industrial setting with a comfortably cool surrounding (i.e., absence of external heat stress), a work rate (metabolic rate) ranging from 30-40% $\dot{V}O_2$max will result in an increase in rectal temperature ranging from 37.4°C (99.3°F) – 37.7°C (99.9°F). Increasing the workload (metabolic rate) to 50% $\dot{V}O_2$max will increase the rectal temperature to 38°C (100.4°F). The increase in rectal (core) temperature is due primarily to the increase in metabolic heat generated by working muscle [Åstrand et al. 2003].

In addition to sex- and age-related variability, the inter-individual variability of $\dot{V}O_2$max is high; therefore, the range of $\dot{V}O_2$max to include 95 of every 100 individuals will be ±20% of the mean $\dot{V}O_2$max value. Differences in body weight (particularly the muscle mass) can account for about half that variability when $\dot{V}O_2$max is expressed as mL O_2/kg/min, but the source of the remaining variation has not been precisely identified. Age is associated with a reduction in $\dot{V}O_2$max after peaking at about 20 years of age, and falling in healthy individuals by nearly 10% each decade after age 30. The decrease in $\dot{V}O_2$max with age is less in individuals who have maintained a higher degree of physical fitness. Women have levels of $\dot{V}O_2max$ which average about 70% of that for men in the same age group, due to lower absolute muscle mass [Åstrand and Rodahl 1977; Åstrand et al. 2003]. There are many factors to consider with respect to the deep body temperature when the same job is done by both men and women of varying body weights, ages, and work capacities.

Other sources of variability when individuals work in hot environments are differences in circulatory system capacity, sweat production, and the ability to regulate electrolyte balance, each of which may be large.

Work capacity is reduced to a limited extent in hot surroundings if body temperature is elevated. That reduction becomes greater as the body temperature is increased. The $\dot{V}O_2max$ is not reduced by dehydration itself (except for severe dehydration) so that its reduction in hot environments seems to be principally a function of body temperature. Core temperature must be above 38°C (100.4°F) before a reduction is noticeable; however, a rectal temperature of about 39°C (102.2°F) may result in some reduction of $\dot{V}O_2max$.

The capacity for prolonged exercise of moderate intensity in hot environments is adversely affected by dehydration, which may be associated with a reduction of sweat production and a concomitant rise in rectal temperature and HR. If the total heat load and the sweat rate are high, it is increasingly more difficult to replace the water lost in the sweat (750-1,000 mL/h). The thirst mechanism is usually not strong enough to drive one to drink the large quantities of water needed to replace the water lost in the sweat [TBMed 2003]. Existing evidence supports the concept that, as the body temperature increases in a hot working environment, the endurance for physical work is decreased.

Heat stress may elicit mental effects, such as a decrease in cognitive performance, that may affect decision making and increase the risk of accidents and injury [O'Neal et al. 2010]. Impairment of cognitive performance would then, as the environmental heat stress increases, affect many of the psychomotor, vigilance, and other experimental psychological tasks that also show decrements in performance [Givoni and Rim 1962; Ramsey and Morrissey 1978; Hancock 1981, 1982; Marg 1983]. The decrement in performance may be at least partly related to increases in core temperature and dehydration. When the rectal temperature is raised to 38.5°-39.0°C (101.3°-102.2°F) and associated with heat exhaustion, there are many indications of disorganized central nervous system activity, including poor motor function, confusion, increased irritability, blurring of vision, and changes in personality, suggesting that cerebral anoxia (reduced oxygen supply to the brain) may be responsible [Macpherson 1960; Leithead and Lind 1964; Hancock 1982; McArdle et al. 2010; Morley et al. 2012].

4.1.3 Circulatory Regulation

The circulatory system is the transport mechanism responsible for delivering oxygen and nutrients to all tissues and for transporting unwanted metabolites and heat from the tissues. However, the heart cannot provide enough CO to meet both the peak needs of all of the body's organ systems and the need for dissipation of body heat. The autonomic nervous system and endocrine system control the allocation of blood flow among competing organ systems.

During exercise, there is widespread activation of the sympathetic nervous system resulting in circulatory vasoconstriction initially throughout the body, even in the cutaneous bed. The increase in blood supply to the active muscles is assured by the action of locally produced vasodilator substances which also inhibit (in the blood vessels supplying the active muscles) the increased sympathetic vasoconstrictor activity. In inactive vascular beds (i.e., networks of blood vessels), there is a progressive vasoconstriction with the severity of the exercise. This is particularly important in the large vascular bed in the digestive organs, where venoconstriction also permits the return of blood sequestered in its large venous bed, allowing up to one liter of blood to be added to the circulating volume [Rowell 1977; Rowell 1993].

If the need to dissipate heat arises, the autonomic nervous system reduces the vasoconstrictor tone of the cutaneous vascular bed, followed by "active" dilation, which occurs by a mechanism which is, at present, unclear. The sweating mechanism and an unknown critical factor that causes the importantly large dilation of the peripheral blood vessels in the skin are mutually responsible for humans' remarkable thermoregulatory capacity in the heat.

When individuals are exposed to continuous work at high proportions of VO_2max or to continuous work at lower intensities in hot surroundings, the cardiac filling pressure remains relatively constant, but the central venous blood volume decreases as the cutaneous vessels dilate. The SV falls gradually and the HR must increase to maintain the CO. The effective circulatory volume also decreases, partly due to dehydration, as water is lost in the sweat, and partly as the thermoregulatory system tries to maintain an adequate circulation to meet the needs of the exercising muscles as well as the circulation to the skin [Rowell 1977].

One of the most important roles of the cardiovascular system in thermoregulation is the circulation of warm blood from the body core to the skin for heat transfer to the environment. At rest and in the absence of heat, skin blood flow is approximately 200-500 ml/min and can increase up to 7-8 L/min under high heat stress. This range of skin blood flow is responsive to changes in body core temperature and is required to mobilize warm blood from the body core to the periphery for the purpose of heat transfer to the environment [Taylor et al. 2008]. However, the redistribution of blood to the cutaneous circulation results in a corresponding decrease in splanchnic, renal, and muscle blood flow. During exercise in the heat, blood is simultaneously required to supply oxygen to working muscle and to carry heat from the body core to the periphery (skin). However, muscle blood flow actually decreases under heat stress from approximately 2.4 ml/g/min down to 2.1 ml/g/min (-25%) due to cutaneous demands [Taylor et al. 2008]. This is readily accomplished in a well-hydrated individual under compensable heat stress [González-Alonzo et al. 2008; Taylor et al. 2008]. In the dehydrated individual working in the heat, increased core body temperature imposes stress on the cardiovascular system, as well as the thermoregulatory system in the hypothalamus [Taylor et al. 2008]. The mechanism of a redistribution of blood to muscle and the cutaneous circulation, under conditions of dehydration secondary to sweating, leads to an effective contraction of plasma volume [González-Alonzo et al. 2008]. A decrease in an effective plasma volume can result in an increase in heart rate and myocardial oxygen demand [Parsons 2003]. During heat stress at both rest and exercise, the HR, CO and SV all increase to a greater extent at a given workload than would normally be observed under thermo neutral conditions [Rowell 1993].

4.1.4 The Sweating Mechanism

In a hot environment, where heat transfer of radiation is no longer possible, the primary means for the transfer of heat to the environment in humans is evaporative heat loss through the vaporization of sweat. The sweat glands are found in abundance in the outer layers of the skin. They are stimulated by cholinergic sympathetic nerves and secrete a hypotonic watery solution onto the surface of the skin. Several other mechanisms for heat transfer to the environment include convection, conduction, and behavioral (e.g., leave the area, put on or take off clothes, drink water, modify environmental controls, etc.) [Taylor et al. 2008]. In addition, an ambient wet-bulb temperature (to account for humidity) of 35°C can result in a body fluid loss at rest (80 kcal/h) of 0.8-1.0 L/h through sweating. For every liter of water that evaporates, 2,436 kJ (580 kcal) are extracted from the body and transferred to the environment [McArdle et al. 1996a]. The enormous capacity for heat loss through evaporation is generally more than adequate to dissipate metabolic heat generated by a subject at rest (~315 kJ/h for a 75 kg person) and at high levels of activity. Mean sweat rate in endurance athletes ranges from 1.5-2.0 L/h, which translates into an evaporative heat loss capacity of 3,654-4,872 kJ (~11.6-15.5 times the amount of heat produced at rest) [Gisolfi 2000]. This is generally more than adequate to remove heat from the body even at extreme levels of metabolic heat production.

However, in environments with a high humidity, sweating continues (increasing the level of dehydration), but the evaporation of sweat is inhibited, heat transfer from the body is reduced and the internal body temperature increases. Thus, when the heat index is greater than 35°C and is largely due to high humidity, the evaporative heat loss is virtually nonexistent. Consequently, even if the ambient dry temperature is within a comfortable range (e.g., 23°C), the high humidity could result in an "apparent temperature" or heat index high enough to create heat stress to the worker that is great enough to present the possibility of heat illness or injury [Taylor et al. 2008].

People who are acclimatized to the heat can reach a peak water loss of 3 L/h through sweating and may lose up to 12 L/d during intense exercise in hot environments [McArdle et al. 1996a]. Thus, a major issue resulting from a high heat stress is the need for adequate re-hydration in order to replace the water lost to the environment from sweating and reduce the risk of hyperthermia. Sweating results in significant dehydration which leads to thermal and cardiovascular strain.

A rule of thumb is that a 0.45 kg (1.0 lb.) decrease in body weight represents a 450 mL (16 oz.) decrease in body water (mostly plasma volume) that needs to be replaced by consumption of water. Another source of body water loss is the respiratory tract [McArdle et al. 1996a]. Average water loss from the respiratory tract at rest is ~350 mL/d under mild conditions of heat and humidity. Respiratory water loss will also contribute to the dehydration of the worker. This fluid loss would be correspondingly greater with activity.

An important constituent of sweat is salt or sodium chloride. In most circumstances, a salt deficit does not readily occur because the normal American diet provides 4 g/d (174 mEq/d) [Food and Nutrition Board and Institute of Medicine 2005]. However, the salt content of sweat in unacclimatized individuals may range from 10-70 mEq/L sweat (0.23-1.62 g/L) [Montain and Cheuvront 2008], while for the acclimatized individual, sodium lost to sweat may be reduced to 23·mEq/L (.23 g/L), less than 50% of that of the unacclimatized individual. It is possible for a heat-unacclimatized individual who consumes a restricted salt diet to develop a negative salt balance. In theory, a prolonged negative salt balance with a large fluid intake could result in a need for moderate supplementation of dietary salt. If there is a continuing negative salt balance, acclimatization to heat is diminished. However, salt supplementation of the normal diet is rarely required, except possibly for heat-unacclimatized individuals during the first two or three days of heat exposure [Lind 1976; TBMed 2003]. By the end of the third day of heat exposure, a significant amount of heat acclimatization will have occurred, with a resulting decrease in salt loss in the sweat and urine and a decrease in salt requirement. In view of the high incidence of elevated blood pressure in the U.S. worker population and the relatively high salt content of the average U.S. diet, even in those who watch salt intake, recommending increased salt intake is probably not warranted. Salt tablets can irritate the stomach and should not be used [DOD 1980; TBMed 2003]. Heavier use of salt at meals has been suggested for the heat-unacclimatized individual during the first 2-3 days of heat exposure (if not on a restricted salt diet by order of a physician or other qualified healthcare provider) [TBMed 2003]. Sodium can also be replenished by consuming fluids containing approximately 20 mEq/L sodium (an amount found in many so-called “sports drinks”) [Montain and Cheuvront 2008]. Moreover, carefully induced heat acclimatization will reduce or eliminate the need for salt supplementation of the normal diet. Because potassium is lost in sweat, there can be a serious depletion of potassium when unacclimatized workers suddenly have to work hard in hot climates; marked depletion of potassium can lead to serious physiologic consequences, including the development of heat stroke [Leithead and Lind 1964]. A high table salt intake may increase potassium loss. However, potassium loss is usually not a problem, except for individuals taking diuretics, because potassium is present in most foods, particularly meats and fruits [Greenleaf and Harrison 1986]. Since some diuretics cause potassium loss, workers taking such medication while working in a hot environment may require special medical supervision.

4.1.4.1 Water and Electrolyte Balance and the Influence of Endocrines

It is imperative to replace the water lost in the sweat. It is not uncommon for workers to lose 6-8 liters of sweat during a working shift in hot industries. If the lost water is not replaced, there will be a progressive decrease of body water with a shrinkage not only of the extracellular space and interstitial and plasma volumes, but also of water in the cells. There is clear evidence that the amount of sweat production depends on the state of hydration [Leithead and Lind 1964; Henschel 1971; Greenleaf and Harrison 1986] so that progressive dehydration results in a lower sweat production and a corresponding increase in body temperature, which is a dangerous situation.

Water lost in sweat in high quantities is often difficult to replace completely as the day's work proceeds and it is not uncommon for individuals to register a water deficit of 2-3% or greater of their body weight. During exercise in either cool or hot environments, a correlation has been reported between the elevation of rectal temperature and the percentage of water deficit in excess of 3% of body weight [Kerslake 1972]. Because the normal thirst mechanism is not sensitive enough to ensure a sufficient water intake [Greenleaf and Harrison 1986; TBMed 2003], every effort should be made to encourage individuals to drink water or other fluids (e.g., sports drinks). The fluid should be as palatable as possible at 10°-15°C or 50°-60°F. Small quantities taken at frequent intervals, i.e., about 8 ounces every 15-20 minutes, is a more effective regimen for practical fluid replacement than the intake of large amounts of fluid once an hour. Communal drinking containers may not work as well as individual bottles. Individuals are seldom aware of just how much sweat they produce or how much water is needed to replace that lost in the sweat; 1 L/h is not an uncommon rate of water loss. A general rule of thumb for those exercising in the heat for 1-2 hours is to drink plain, cool water. As discussed elsewhere in this document, sweat is hypotonic to the plasma and one does not lose a significant amount of sodium in the first hour or two of exercise [McArdle et al. 1996b]. Therefore, one does not require fluids containing electrolytes for this exposure. However, during prolonged sweating lasting several hours, it is advisable to consume a “sports” drink that contains balanced electrolytes to replace those lost during sweating as long as the concentration of electrolytes/carbohydrates does not exceed 8% by volume. Exceeding the 8% limit will slow absorption of fluids from the GI tract [Parsons 2003]. Since thirst is a poor indicator of hydration status, fluids should be consumed at regular intervals to replace water lost from sweating [McArdle et al. 1996b].

Two hormones are important in thermoregulation; the antidiuretic hormone (ADH) and aldosterone. A variety of stimuli encourages the synthesis and release of those hormones, such as changes in plasma volume, plasma concentration of sodium chloride, etc. ADH is released by the pituitary gland, which has direct neural connections with the hypothalamus but may receive neural input from other sources. Its function is to reduce water loss by the kidney, but it has no effect on the water loss through sweat glands. Body water, including the plasma volume in the vascular compartment (i.e., the amount of blood that can be found at any given instance inside the blood vessels in a vascular bed of a specific tissue), is also controlled by the renin-angiotensin-aldosterone system (RAAS). Changes in fluid volume or electrolyte (sodium) concentration will activate the RAAS to conserve fluids and electrolytes at the level of the kidney and sweat glands through the action of aldosterone [Jackson 2006]. The control of fluid (especially plasma) volume is also important in the maintenance of blood pressure and organ perfusion. Another product of the RAAS is angiotensin II, which is a powerful vasoconstrictor that helps maintain blood pressure and overall cardiovascular function in the presence of significant fluid loss from the vascular compartment, as well as being a significant stimulator of the release of aldosterone from the adrenal glands [Williams et al. 2003].

4.1.4.2 Dietary Factors

A well-balanced diet in temperate environments should also suffice for hot climates. A very high protein diet might increase the obligatory urine output for nitrogen removal and increase water intake requirements [Greenleaf 1979; Greenleaf and Harrison 1986]. The importance of water and salt balance has been emphasized above and the possibility that it might be desirable to supplement the diet with potassium has also been considered. In some countries where the normal diet is low or deficient in Vitamin C, supplementation may enhance heat acclimatization and thermoregulatory function [Strydom et al. 1976]. It is important to note that supplemental sodium may be abused in the interest of increasing fluid retention. However, studies have shown that an excess of dietary sodium may actually decrease plasma volume, even with a controlled fluid intake. Therefore, supplemental dietary sodium must be used judiciously to prevent further dehydration and electrolyte depletion of the worker [McArdle et al. 1996a; Williams et al. 2003].

4.1.5 Acclimatization to Heat

When workers are unexpectedly exposed to hot work environments, they readily show signs of distress and discomfort, e.g., develop increased core temperatures and heart rates; complain of headache or nausea; and suffer other symptoms of heat-related illnesses[Leithead and Lind 1964; WHO 1969; Kerslake 1972; Wyndham 1973; Knochel 1974; Hancock 1982; Spaul and Greenleaf 1984; TBMed 2003]. On repeated exposure to a hot environment, there is a marked adaptation in which the principal physiologic benefit appears to result from an increased sweating efficiency (earlier onset, greater sweat production, and lower electrolyte concentration) and a concomitant stabilization of the circulation, such that, after daily heat exposure for 7-14 days, the individuals perform the work with a much lower core temperature and HR and a higher sweat rate (i.e., a reduced thermoregulatory strain) and with none of the distressing symptoms that were experienced initially [Moseley 1994; Armstrong and Stoppani 2002; TBMed 2003; Navy Environmental Health Center 2007; Casa et al. 2009; ACGIH 2011]. During that period, there is a rapid expansion of plasma volume, so that, even though there is a hemoconcentration throughout the exposure to heat, the plasma volume at the end of the heat exposure in the acclimatized state is often equal to or greater than the value before the first day of heat exposure.

Acclimatization to heat is an unsurpassed example of physiologic adaptation which is well demonstrated in laboratory experiments and field experience [Lind and Bass 1963; WHO 1969]. However, acclimatization does not necessarily mean that the individuals can work above the Prescriptive Zone (see Glossary) as effectively as below it [Lind 1977].

Full heat acclimatization occurs with relatively brief daily exposures to working in the heat. It does not require exposure to heat at work and rest for the entire 24 hours; in fact, such excessive exposures may be deleterious because it is hard for individuals without heat acclimatization experience to replace all of the water lost in sweat. The minimum exposure time for achieving heat acclimatization is at least two hours per day which may be broken into one hour exposures [TBMed 2003]. Some daily period of relief from exposure to heat, in air-conditioned surroundings, is beneficial to the well-being of the individuals if, for no other reason, than that they find it hard to rest effectively in hot surroundings [Kerslake 1972]. It is important to note that resting in an air-conditioned environment will not affect acclimatization [OSHA-NIOSH 2011]. The level of acclimatization is relative to the initial level of individual physical fitness and the total heat stress experienced by the individual [TBMed 2003]. Thus, a worker who does only light work indoors in a hot climate will not achieve the level of acclimatization needed to work outdoors with the additional heat load from the sun or to do harder physical work in the same hot environment indoors. Increased aerobic fitness confers at least partial acclimatization to the heat because of the increased metabolic heat production that occurs during exercise and physically fit individuals have a reduced incidence of heat injury or illness during exposure to hot environments [Tipton et al. 2008].

Failure to replace the water lost in sweat will slow or even prevent the development of the physiologic adaptations described. It is important to understand that heat acclimatization increases the sweating rate, therefore workers will have an increased water requirement during this time [TBMed 2003; Navy Environmental Health Center 2007]. In spite of the fact that acclimatization will be reasonably well maintained for a few days of no heat exposure, absence from work in the heat for a week or more results in a significant loss in beneficial adaptations. However, heat acclimatization can usually be regained in two to three days upon return to a hot job [Lind and Bass 1963; Wyndham 1973]. Heat acclimatization appears to be better maintained by individuals who are physically fit [Pandolf et al. 1977].

The total sweat production increases with acclimatization and sweating begins at a lower skin temperature [TBMed 2003]. Cutaneous circulation and circulatory conductance decreases with acclimatization, reflecting the reduction in the proportion of CO that must be allocated for thermoregulation because of the more efficient sweating mechanism. Also during acclimatization cardiovascular stability is improved, heart rate is lowered, stroke volume is increased, and myocardial compliance is improved [TBMed 2003]. It is clear, however, that during exercise in heat, the production of aldosterone is increased to conserve salt from both the kidney and the sweat glands, while an increase in antidiuretic hormone (ADH) conserves the amount of water lost through the kidneys. The increase in the levels of aldosterone results in a lower concentration of sodium in the sweat and, thus, serves to limit sodium and fluid loss from the plasma during exercise in the heat [Taylor et al. 2008].

It is obvious from the foregoing description that sudden seasonal shifts and sudden increases in environmental temperature may result in thermoregulatory difficulties for exposed workers. At such times, cases of heat–related illnesses may occur, even for acclimatized workers, if the outside environment becomes very hot.

Acclimatization to work in hot, humid environments provides adaptive benefits which also apply in hot, desert environments, and vice versa; the qualifying factor appears to be the total heat load experienced by the individual [TBMed 2003]. For a summary on acclimatization see Table 4-1.

Table 4-1: Acclimatization in workers

Topics	Acclimatization Information
Disadvantages of Being Unacclimatized	• Readily show signs of heat stress when exposed to hot environments. • Difficulty replacing all of the water lost in sweat. • Failure to replace the water lost will slow or prevent acclimatization.
Advantages of Being Acclimatization	• Increased sweating efficiency (earlier onset of sweating, greater sweat production, and reduced electrolyte loss in sweat). • Stabilization of the circulation. • Work is performed with lower core temperature and heart rate. • Increased skin blood flow at a given core temperature.
Acclimatization Plan	• Gradually increase exposure time in hot environmental conditions over a 7-14 day period. • For new workers, the schedule should be no more than 20% exposure on day 1 and a no more than 20% increase on each additional day. • For workers who have had previous experience with the job, the acclimatization regimen should be no more than a 50% exposure on day 1, 60% on day 2, 80% on day 3, and 100% on day 4.
Level of Acclimatization	• Relative to the initial level of physical fitness and the total heat stress experienced by the individual.
Maintaining Acclimatization	• Can be maintained for a few days of non-heat exposure. • Absence from work in the heat for a week or more results in a significant loss in the beneficial adaptations leading to an increase likelihood of acute dehydration, illness, or fatigue.

- Can be regained in 2-3 days upon return to a hot job.
- Appears to be better maintained by those who are physically fit.
- Seasonal shifts in temperatures may result in difficulties.
- Working in hot, humid environments provides adaptive benefits which also apply in hot, desert environments, and vice versa.
- Air conditioning will not affect acclimatization.

Adapted from [Moseley 1994; Armstrong and Stoppani 2002; TBMed 2003; Casa et al. 2009; ACGIH 2011; OSHA-NIOSH 2011].

4.1.6 Other Related Factors

There are many factors that can increase a worker's risk of heat-related illness. Some of the factors are environmental, such as direct sun exposure, and high temperatures and humidity. Indoor radiant heat sources, like ovens and furnaces also can increase the amount of heat in the environment. Other factors may be related to characteristics of each individual worker or an individual's current status of health at the time of exposure to heat stress in a hot environment. Heat-related illness factors are presented in Figure 4.1.

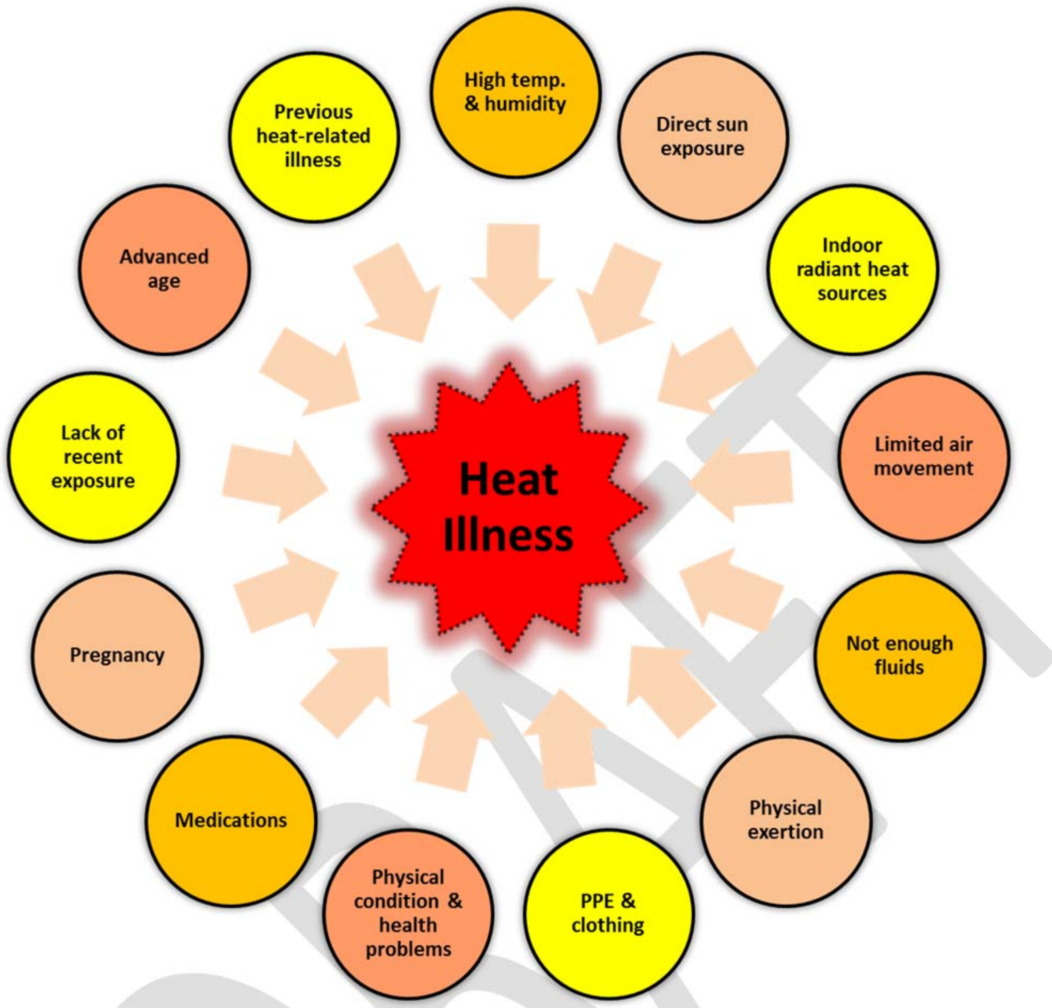

Figure 4.1 Examples of some of the risk factors of heat-related illness

4.1.6.1 Age

The aging process results in a more sluggish response of the sweat glands, which leads to a less effective control of body temperature. Aging also results in an increased level of skin blood flow associated with exposure to heat. The cause of this remains undetermined, but implies an impaired thermoregulatory mechanism, possibly related to a reduced efficiency of the sympathetic nervous system [Hellon and Lind 1958; Lind 1977; Drinkwater and Horvath 1979]. For women, it has been found that the skin temperature increases with age in moderate and high heat loads, but not in low heat loads [Hellon and Lind 1958; Drinkwater and Horvath 1979]. When two groups of male coal miners of average age 47 and 27 years, respectively, worked in several comfortable or cool environments, they showed little difference in their responses to heat near the REL with light work, but in hotter environments, the older men showed a substantially greater thermoregulatory strain than their younger counterparts; the older men also had lower aerobic work capacities [Lind et al. 1970]. In analyzing the distribution of five years' accumulation of data on heat stroke in South African gold mines, Strydom [1971] found a marked increase in heat stroke with increasing age of the workers. Thus, men over 40 years of age represented less than 10% of the mining population, but they accounted for 50% of the fatal and 25% of the nonfatal cases of heat stroke. The incidence of cases per 100,000 workers was 10 or more times greater for men over 40 years than for men under 25 years of age. In all the experimental and epidemiologic studies described above, the workers had been medically examined and were considered free of disease. Total body water decreases with age, which may be a factor in the observed higher incidence of fatal and nonfatal heat stroke in the older group.

As mentioned previously, older people are more susceptible to the effects of heat and, after the age of 60, this population represents a significant fraction of those suffering from heat disorders [Kenny et al. 2010]. The age-related susceptibility to heat is multifactorial and may be related to decreases in sweating, cutaneous blood flow, changes in cardiovascular function and decreases in overall fitness[Kenney et al. 1990; Minson et al. 1998; Inoue et al. 1999]. Decreased sweating, which would result in a compromise of the most effective form of heat exchange in humans, may be due to changes in the amount of sweat produced, rather than changes in the number of sweat glands [Inbar et al. 2004]. Thus, while acclimatization to heat can occur in the elderly, the rate of acclimatization is reduced [Armstrong and Kenney 1993; Inoue et al. 1999].

4.1.6.2 Sex

Purely on the basis of a lower aerobic capacity, the average woman, similar to a small man, is at a disadvantage when she has to perform the same job as the average-sized man. While all aspects of heat tolerance in women have not been fully examined, their thermoregulatory capacities have been. When they work at similar proportions of their $V0_2$max, the women perform either similarly or only slightly less well than men [Drinkwater et al. 1976; Avellini et al. 1980a; Avellini et al. 1980b; Frye and Kamon 1981].

A study examining sweat electrolyte loss during exercise in the heat found that sweat concentrations of Na^+ and Cl^- in men were higher than women [Meyer et al. 1992]. The study was unable to explain why there appeared to be a difference between the sexes, although sweating rate and the effects of hormonal variations may play a part.

A recent study investigated whether there was an effect of sex on whole-body sudometer (a device to measure total sweat loss from the individual) activity during exercise in the heat [Gagnon and Kenny 2011]. Gagnon and Kenny found that females have a lower whole-body sweat response during exercise in the heat, which resulted in a greater increase in body temperature. The study concludes that the “results were not due to differences in physical characteristics, as both sexes were matched for body mass and surface area.”

According to Nunneley [1978], there seemed to be little change in thermoregulatory capacities at different times during women's menstrual cycles. However, pregnancy, as it progresses, decreases tolerance of heat stress [Navy Environmental Health Center 2007]. The fetus acts as a source of metabolic heat and also increases the weight of the mother.

4.1.6.3 Body Fat

It is well established that obesity predisposes individuals to heat disorders [Leithead and Lind 1964]. In fact, heat disorders occur 3.5 times more frequently in the obese than in the lean individual [Henschel 1967; Chung and Pin 1996; Kenny et al. 2010]. The acquisition of fat means that additional weight must be carried, thereby calling for a greater expenditure of energy to perform a given task and use of a greater proportion of the VO_2max on an overall per weight basis. However, there is no difference in VO_2max between obese and lean subjects if measured on an oxygen consumption per lean body weight basis [Vroman et al. 1983]. In addition, the body surface to body weight ratio in the obese individual (m to kg) becomes less favorable for heat dissipation. Probably more important is the lower physical fitness and decreased maximum work capacity and cardiovascular capacity frequently associated with obesity. The increased layer of subcutaneous fat provides an insulation barrier between the skin and the deep-lying tissues. The fat layer theoretically would reduce the direct transfer of heat from the muscles to the skin [Wells and Buskirk 1971].

The limited number of studies in the area of heat stress and obesity has shown that obese individuals have a lower forearm blood flow during exercise in the heat, which is thought to reduce the cutaneous exchange of heat with the environment [Vroman et al. 1983; Kenny et al. 2010]. The reason is not completely clear, but may be due to changes in sympathetic control over the vasculature or reduced stroke volume that regulate the relative blood flow to muscle (to perform work) and the blood flow to the cutaneous vasculature for the purpose of heat exchange. Some evidence also exists that obese individuals suffer from asymptomatic small fiber neuropathies, which lower thermal sensitivity [Herman et al. 2007].

It has also been proposed that the increase in thermal load in the obese is due simply to the reduced specific heat capacity of adipose tissue, which contains a lower amount of water per gram, compared to lean mass. Thus, for a given thermal load, the obese individual will store thermal energy at a greater rate than the lean individual, resulting in a greater average tissue temperature [Henschel 1967; Kenny et al. 2010].

Finally, the extra weight carried by the obese individual results in an increase in metabolic energy for any given task, compared to the lean individual. The increase in metabolic energy produced in the form of muscular work results in an increase in body temperature that must be exchanged compared to the lean individual performing the same task in the same environment [Bar-Or et al. 1969; Kenny et al. 2010]. From all the above, it is apparent that obesity places the individual at a significantly higher risk of suffering a heat-related illness at any given workload or environmental temperature compared to the lean individual.

4.1.6.4 Drugs

(1) Alcohol

Alcohol has been commonly associated with the occurrence of heat stroke [Leithead and Lind 1964]. It is a drug which interferes with central and peripheral nervous function and is associated with dehydration by suppressing ADH production. The ingestion of alcohol prior to or during work in the heat should not be permitted because it reduces heat tolerance and increases the risk of heat-related illnesses.

(2) Therapeutic Drugs

Many drugs prescribed for therapeutic purposes can interfere with thermoregulation [Khagali and Hayes 1983]. Some of these drugs are anticholinergic in nature or involve inhibition of monoamine oxidative reactions, but almost any drug that affects central nervous system activity, cardiovascular reserve, or body hydration could potentially affect heat tolerance. Thus, a worker who requires therapeutic medications should be under the supervision of a physician or other qualified healthcare provider who understands the potential ramifications of drugs on heat tolerance. In such instances, a worker taking therapeutic medications who is exposed only intermittently or occasionally to a hot environment should seek the guidance of a physician or other qualified healthcare provider.

Table 4-2: Drugs implicated in intolerance to heat

Drug or drug class	**Proposed mechanism of action**
Anticholinergics	Impaired sweating
Antihistamines	Impaired sweating
Phenothiazines (Thorazine®, Stelazine®, Trilafon®)	Impaired sweating, (possibly) disturbed hypothalamic temperature regulation
Tricyclic antidepressants (imipramine, amitriptyline)	Impaired sweating, increased motor activity and heat production
Amphetamines, cocaine, “Ecstasy”	Increased psychomotor activity, activated vascular endothelium
Ergogenic stimulants (ephedrine/ephedra)	Increased heat production
Lithium	Nephrogenic diabetes insipidus and water loss

Diuretics	Salt depletion and dehydration
Antihypertensives (atenolol, carvedilol)	Reduced skin blood flow and reduced blood pressure
Ethanol	Diuresis, possible effects on intestinal permeability
Barbiturates	Reduced blood pressure
Antispasmodics	Impaired sweating
Haloperidol	Tachycardia, altered central temperature regulation, and hyponatremia

Adapted from Heat Stress Control and Heat Casualty Management [DOD 2003].

(3) Social Drugs (e.g., caffeine)

It is hard to separate drugs used therapeutically from those used socially. Nevertheless, there are many drugs other than alcohol which are used on social occasions and have been implicated in cases of heat disorder, sometimes leading to death [Khagali and Hayes 1983]. Caffeine may be considered a socially accepted drug found in common beverages and foods (coffee, tea, soft drinks, energy drinks, cocoa, chocolate) and in some over-the-counter analgesics that are consumed worldwide to enhance alertness, reduce fatigue, enhance athletic performance, augment the effects of mild analgesics and for simple enjoyment [Undem 2006; Taylor et al. 2008]. Coffee (one of the most widely consumed beverages in the world), which contains caffeine, has a diuretic effect and should not be considered for replacing volume lost to sweating. Moreover, coffee is generally consumed as a hot beverage; in this respect, it has the potential to exacerbate heat stress. In the past, the common position was to say that caffeine is a mild diuretic and may contribute to heat stress by reducing fluid volume and resulting in cardiovascular strain during exposure to the heat [Serafin 1996]. However, recent studies present evidence that caffeine may have less effect on heat tolerance than previously suspected [Roti et al. 2006; Armstrong et al. 2007a; Ely et al. 2011].

Armstrong et al. [2007a] propose that caffeine consumption does not result in water-electrolyte imbalances and does not reduce exercise-heat tolerance. The study also suggests that "caffeinated fluids contribute to the daily human water requirement in a manner that is similar to pure water." Ely et al. [2011] had similar findings in that a caffeine dose of 9 mg/kg did not substantially alter heat balance during work in a hot environment. Caffeine appeared not to interfere with dry heat gains or evaporative heat losses and, according to this study, caffeine levels of 9 mg/kg or less could be considered safe in hot, dry environments. Roti et al. [2006] concluded that there was no evidence that dehydration or impaired thermoregulation resulted from chronic caffeine ingestion prior to or during exercise in the heat.

While these studies present evidence that caffeine usage may be potentially harmless and acceptable for those exerting themselves in a hot environment, water is still the most optimal, hydrating beverage for a worker to drink before, during, and after work. Further research is needed on the effects of large doses of caffeine consumed at one time and the differences between modes of caffeine delivery (i.e., capsules, various beverages, and solid food) [Armstrong et al. 2007a]. Caffeine containing fluids are now marketed to the public as "energy drinks". The "energy drinks" contain higher than normal doses of caffeine and have been used extensively among competitive athletes prior to participation in athletic events [Burke 2008]. The problem is that the toxic dose of caffeine is about 500 mg (about 2 energy drinks). Other than the diuretic effects of caffeine, this dose is capable of inducing cardiac arrhythmias [Undem 2006] which could be potentiated by heat stress (i.e., as a result of already existing cardiovascular strain). It seems that there would be a tendency to drink several "energy drinks" just to alleviate thirst, thus inadvertently overdosing on caffeine.

4.1.6.5 Non-heat Disorders

It has long been recognized that individuals suffering from degenerative diseases of the cardiovascular system and other diseases, such as diabetes or simple malnutrition, are in extra jeopardy when they are exposed to heat and when a stress is imposed on the cardiovascular system. The outcome is readily seen during sudden or prolonged heat waves in urban areas where there is a sudden increase in mortality, especially among older individuals who supposedly have age-related reduced physiologic reserves [Leithead and Lind 1964; Henschel et al. 1969; Ellis 1972; Kilbourne et al. 1982]. In prolonged heat waves, the mortality is higher in the early phase of the heat wave [Henschel et al. 1969; Ellis 1972]. While acclimatization may play a part in the decrease in mortality during the latter part of a prolonged heat wave, the increased death rate in the early days of a heat wave may reflect an "accelerated mortality," with the most vulnerable more likely to succumb at that time rather than more gradually as a result of degenerative diseases.

4.1.6.6 Individual Variation

In all experimental studies of the responses of humans to hot environmental conditions, a wide variation in responses has been observed. These variations are seen not only between different individuals, but also, to some extent, in the same individual exposed to high environmental stress on different occasions. Such variations are not totally understood. It has been shown [Wyndham 1973] that the influence of body size and its relationship to aerobic capacity in tolerance to heat could account for about half of the variability, leaving the remainder to be accounted for. Possibly, changes in hydration and salt balance might be responsible for some of the remaining variability [Buskirk and Bass 1980]. However, the degree of variability in tolerance to hot environments remains an unexplained problem.

4.1.7 Heat-Related Illnesses and Work

The incidence of occupational heat-related illness in the U.S. is not documented by an existing occupational injury and illness surveillance system. According to BLS data from 2010, 4,190 illness and injury cases from exposure to environmental heat occurred among private industry and state and local workers resulting in one or more days of lost work [Bureau of Labor Statistics 2011]; however, BLS does not report all nonfatal illnesses or deaths. In that same year, 40 workers died from exposure to environmental heat. Eighteen of these workers died in the construction industry; 6 workers died in natural resources (includes agriculture) and mining; 6 died in professional and business services (includes waste management and remediation); and 3 died in manufacturing.

In the following sections, various worksites that may have heat exposure are reported as short summarizations and case studies. The first set are summarized from NIOSH Health Hazard Evaluation (HHE) Reports and address heat exposure in an aluminum smelter potroom, an automobile parts manufacturing facility, a glass bottle manufacturer, and a national park. Additional case studies are summarized from Fatality Assessment and Control Evaluation (FACE) reports and a Morbidity and Mortality Weekly Report (MMWR) which address cases of heat exposure in a landscaper, a migrant worker in agriculture, a construction laborer, and a wildland fire fighter.

4.1.7.1 Health Hazard Evaluation (HHE) Reports

Aluminum Smelter Potrooms

HETA 2006-0307-3139

NIOSH assessed employee exposure to heat while working in the potrooms at an aluminum smelter [NIOSH 2006a]. In the smelting process, alumina is reduced to nearly pure aluminum at an operating temperature of approximately 1,800°F. Employees were interviewed, and completed questionnaires about their medical history, work history, and symptoms experienced during the shift on which they were monitored. Monitoring included core body temperature and heart rate. In addition urine specific gravity and blood electrolytes were measured before and after shifts. WBGTs were monitored in several locations insides the potrooms, and outdoor weather conditions were monitored.

The mean outdoor temperature for the 5 days of evaluation was 78°F. The WGBT measurements ranged from 83°F to 120°F, with dry bulb air temperatures reaching 134°F and radiant temperatures reaching 188°F. High radiant heat means that the employees were absorbing rather than radiating heat, unless proper shielding was provided. Metabolic rates of employees were estimated to be light to moderate (115-360 watts). Except for the crane operator, portions of all tasks were found to exceed the NIOSH ceiling and ACGIH TLV for working in a hot environment. Common symptoms reported during shifts included racing heartbeat or palpitations, headache, muscle cramps, and lightheadedness or dizziness. Postshift blood bicarbonate, blood urea nitrogen (BUN), creatinine, and urine specific gravity increased significantly. Volume depletion was suggested by the significant decrease over the shift of the BUN to creatinine ratio and potassium level. Excessive sweating may cause volume depletion. Many of the participants were found to not be sufficiently hydrated. In addition, several participating workers had evidence of acute kidney injury which may have been a result of or affected by volume depletion rhabdomyolysis caused by excess heat stress exposure or extreme physical activity.

The NIOSH HHE made the following recommendations for managers and employees:

Managers

- Reduce the physical demands on employees working in the potrooms.
- Require the use of heat reflective personal protective equipment.
- Install cooling recovery areas in the potrooms.
- Do not use outdoor air to cool employees when it is over 95°F outside.
- Follow the heat stress management program.
- Stop 8-hour overtime shifts during extremely hot weather.

Employees

- Use reflective personal protective equipment.
- Use the cooling recovery areas when on breaks.
- Take time to work safely.

Automobile Parts Manufacturing Facility
HETA 2003-0268-3065

The painting department of an automobile parts manufacturing facility was assessed in part for employees subjected to high heat [NIOSH 2003a]. WBGT monitors were placed in the loading and unloading area among the workers and in the cafeteria (for comparison) for the entire work shift. Heat strain was measured on six workers over two days, through the use of wireless core body temperature monitoring devices that are swallowed. In addition, heart rate and skin temperature were monitored using other devices. Pre- and post-shift body weights were measured on both days to determine degree of dehydration.

Four of the six participating workers exceeded the ACGIH core body temperature's lower limit (100.4°F) six times, and one worker exceeded its upper limit (101.3°F) once. Of the 13 measures over two days, taken in participating workers, nine showed signs of dehydration (post-weight was less than pre-weight). Three of these measures met or exceeded the 1.5% guideline for adequate hydration. The dry bulb temperatures ranged from 80.5°F to 86.2°F for the loading and unloading areas, and 70.2°F to 70.7°F for the cafeteria. Inadequate ventilation was suspected by the steadily increasing temperature in the loading and unloading areas.

The NIOSH HHE made the following recommendations for managers:

- Allow workers to rest during the rest portion of the work/rest regiment, and not assign any duties during this time.
- Position fans above workstations, not directly in front of the workers.
- Hire a consultant familiar with ventilation in hot processes to reduce heat.

Glass Bottle Manufacturer

HETA 2003-0311-3052

A manufacturer of glass containers for the beer, spirit, juice, and tea industries was assessed by NIOSH as there was concern regarding heat-related illnesses among employees exposed to hot working environments in the hot end of the plant, including the forming department [NIOSH 2003b]. In this department, raw materials are melted together in a furnace at temperatures of 2,300°F to 2,800°F. The manufacturer uses various controls such as, fans that supply cooler air from the basement, evaporative cooling fans, sports drinks, two 25-minute worker rest breaks (plus additional breaks at management's discretion), and a review of heat safety during safety meetings and through displayed posters. WBGT measurements were collected in the forming department, metabolic rates of workers were estimated, and employees were interviewed.

The highest WBGT reading was 87.2°F, with a dry bulb temperature of 87.0°F, and a globe temperature of 115.7°F. These results indicated that most surfaces in the department were at an elevated temperature and acted as radiant heat sources. The nearby break room's WBGT was 70.3°F, with a dry bulb temperature of 75.5°F. NIOSH guidelines were used to estimate the metabolic heat produced by the workers (186 kcal/hr) resulting in a light workload rate. WBGTs and metabolic rates were then compared to those listed in the NIOSH RELs and ACGIH TLVs, and both recommended a continuous work schedule in similar environments. Eighteen workers were interviewed, with two having experienced heat-related symptoms on a hot day a few months earlier (i.e. heart racing, lack of sweating, persistent headache). Other employees mentioned symptoms in previous years, including those related to heat exhaustion, cramping, and nausea. Some employees mentioned that new employees typically start work in June and are not given enough time to acclimatize, resulting in some quitting. In addition, employees noted that the fans were useful (particularly the evaporative coolers), however they were not well maintained and some were not functional.

The NIOSH HHE made the following recommendations for managers:

- Place the fans that supply cooler air from the basement and the evaporative cooling fans on a preventative maintenance schedule to ensure they are operational throughout the summer months.
- Develop a heat acclimatization program to decrease the risk of heat-related illnesses.
- Develop continuing education programs to ensure that all employees potentially exposed to hot environments and physically demanding job activities stay current on heat stress and heat stress prevention information.
- Monitor environmental heat exposures during the hottest months using a WBGT monitor at, or as close as possible to, the area where the workers are exposed.
- Establish criteria for the declaration of a heat alert.
- Develop a heat-related illness surveillance program, which includes establishing and maintaining accurate records of any heat-related disorder events and noting the environmental and work conditions at the time of disorder.
- Ensure that employees stay hydrated and do not lose more than 1.5% body weight during their shift.
- Create a buddy system so that employees can monitor each other for symptoms of heat disorders.
- Allow employees to take unscheduled breaks if they report feeling weak, nauseated, excessively fatigued, confused, and/or irritable during hot temperatures.

National Park

HETA 99-0321-2873

Management requested NIOSH assess park rangers' exposure to high temperatures while patrolling and hiking into and out of the Grand Canyon. Summer temperatures of the inner canyon range from 80-110°F, and have been recorded at 120°F and above [NIOSH 1999]. WBGTs measurements were collected and individual metabolic rates were estimated. Heat strain was assessed using wireless core body temperature monitoring devices that were swallowed. Other devices recorded heart rate, gross motor activity, skin temperature, and ear temperature. A medical evaluation included a questionnaire and a dehydration assessment that was determined using pre- and post-activity body weights. In addition, changes in blood chemistry were examined.

Individual metabolic rates ranged from 300 kcal/hr to over 500 kcal/hr. The inner-canyon WBGTs averaged 83°F, with a one-day peak of 98°F. Therefore most trail crew and park rangers were exposed to excessive heat stress. All participants had small to moderate rises in core body temperature, and the median percent body weight loss was 1.5%, with one employee showing a loss of 6 lbs. (3.0% of body weight). Of the eight employees interviewed, all reported at least one incident in which they had suffered a heat-related symptom. Dehydration was viewed as the most common problem, and often occurred during the hikes to and from the rim, and during victim rescues. Employees are given 6 days of leave after about 8 days of work, which means acclimatization is lost and full acclimatization may not be reached.

The NIOSH HHE made the following recommendations for managers and employees:

Managers

- Decrease the work load of those hiking out by using mules or helicopter transportation.
- Create a heat stress program that will:
  - assess employees for medical fitness;
  - allow them time to acclimatize;
  - train employees to know the dangers of and protect themselves from working in extreme heat;
  - encourage employees to report heat stress symptoms or signs;
  - keep systematic records of employee reports of heat-related illnesses;
  - teach employees to monitor their own and others' heat stress and strain signs.
- Install outdoor showers and/or use ice vests to prevent employee heat stress and strain.

Employees

- Take more time to complete hard work, such as hiking out, by taking longer breaks more often.
- Wait to do hard work until it is cooler.
- Soak your body and clothes in the shower or the creek during hot weather before you leave the station for rescues or patrol.
- Learn to monitor yourselves and co-workers for heat stress, and heed warning signs of heat stress by taking breaks and rehydrating when needed.
- Take care of personal needs before those of victims for safer, more effective rescues.
- Report and record any heat-related illnesses and other concerns.

4.1.7.2 Case Studies

Landscaping Case Study
FACE Report 02MI7501

A 30-year-old male landscape mowing assistant collapsed and died of heat stroke after a day of caring for residential lawns [NIOSH 2002]. Two hours before his death he had complained of feeling light-headed and short of breath, but he refused assistance offered to him by his partner. The worker was on medication that had a warning about exposure to extreme heat, and this could have possibly interfered with body temperature regulation. The landscape worker had been wearing two pairs of work pants on the day he died, but his partner did not notice any profuse sweating or flushed or extremely dry skin. Upon collapse, the victim was treated by EMS personnel at the site and then transported to the hospital. There he was pronounced dead, with an internal temperature of 107.6 °F. On the day of the incident, the maximum air temperature was 81°F.

The following employer recommendations were made after the incident:

- Employers should ensure that supervisors/managers monitor workers during periods of high heat stress.
- Identify workers with risk factors that would predispose them to heat-related illnesses.
- Train employees regarding heat stress, heat strain, and heat-related illnesses.
- Ensure all employees are able to recognize the signs and symptoms of heat-related illnesses in themselves and in others.
- Stress the importance of drinking nonalcoholic beverages before, during, and after working in hot conditions.
- Periodically remind workers of the signs of heat-related illness and encourage them to drink copious amounts of water during hot conditions.

Migrant Farm Worker Case Studies

MMWR

A male Hispanic worker aged 56 died of heat stroke after working for 3 days hand-harvesting ripe tobacco leaves on a North Carolina farm [CDC 2008]. On the third day, the man started working at 6:00 a.m. and took a short mid-morning break and a 90-minute lunch break. Mid-afternoon, a supervisor observed the man working slowly and reportedly instructed him to rest, but the man continued working. An hour later, the man appeared confused and coworkers carried him to the shade and tried to get him to drink water. The man was taken by ambulance to an emergency department, where his core temperature was recorded as 108°F and, despite treatment, he died. On the day of the incident, the local temperature was approximately 93°F with 44% relative humidity and clear skies. The heat index (a measurement of how hot it feels when both actual temperature and relative humidity are considered) for the day was in the range of 86–112°F.

In an additional similar case study, a male Hispanic migrant worker aged 44 died of heat stroke while working in another North Carolina tobacco farm [NIOSH 2006b]. The worker had been working in the fields for about the last week of July. On August 1, the heat index was between 100°F and 110°F. Around 3 p.m. the worker complained to the crew leader that he was not feeling well. He drank some water and was driven to the workers' housing and left alone. He was found unconscious approximately 45 minutes later. Emergency medical personnel responded within 5 minutes and the worker was taken to the hospital and pronounced dead. His core body temperature was recorded at 108°F.

The following employer recommendations were made after the incident:

- Agricultural employers should develop, implement, and enforce a comprehensive safety and health program which includes standard operating procedures for prevention of heat-related illnesses.
- Train supervisors and employees on how to prevent, recognize, and treat heat illness, using a language and literacy level that workers can understand.
- Establish a hydration program which provides adequate potable water (or other appropriate hydrating fluid) for each employee and which encourages workers to drink at regular intervals.
- Monitor environmental conditions and develop work/rest schedules to accommodate high heat and humidity.
- Provide an appropriate acclimatization program for new workers to a hot environment, workers who have not been on the job for a period of time, and experienced workers during a rapid change in excessively hot weather.
- Provide prompt medical attention to workers who show signs of heat-related illness.

Construction Case Study

FACE Report 03KY053

A 41-year-old male construction laborer was sawing boards to make concrete forms that were to be part of an addition to a factory [NIOSH 2004]. At 5 p.m. the worker collapsed in the parking lot on the way to his vehicle. He was found 30 minutes later by a factory employee who then returned to the factory and reported the situation to a supervisor. The receptionist was instructed to call emergency medical services while the supervisor administered emergency care to the collapsed worker. The worker's body temperature was recorded as 107°F by the EMS and as 108°F when admitted to the hospital. The worker died the next day from heat stroke.

The following recommendations were made after the incident:

- Employers should train supervisors and employees to recognize symptoms of heat exhaustion/stroke when working in high heat index and/or humid conditions.
- To avoid dehydration and heat exhaustion/stroke, employees should be given frequent breaks and be provided drinking water and other hydrating drinks when working in humid or hot conditions.
- Work hours should be adjusted to accommodate environmental work conditions such as high heat index and/or high humidity.

Fire Fighter Case Study
FACE Report 97CA01001

During the construction of a fire line during a small, wildland fire, a 21-year-old fire fighter died from heat stroke, another was overcome by heat stroke and survived, and two others suffered heat exhaustion [NIOSH 1997]. The crew had initially started their day by exercising 1 to 1.5 hours as part of their physical training regimen. The 21-year-old had been sick with a suspected viral or bacterial infection in days prior. After physical training, the crew practiced constructing a fire line for about one hour. At 11:45 a.m., the crew arrived at the actual fire that had been reported and constructed a fire line as a precaution in an area with no fire. Crews carried canteens and could drink when desired. Around 1:45 p.m., the crew took a 15 minute break and drank water or Gatorade. At 2 p.m. they resumed the fire line, and 15 minutes later one member fell from heat exhaustion and broke his shoulder. He was administered first aid and transported to the hospital. Prior to this, a member of another crew suffered heat exhaustion, was treated by paramedics and was returned to his base of operation. Around 2:30 p.m., the 21-year-old moved off the line as though he was going to relieve himself. However, 5 minutes later he was found on the ground thrashing. The crew leader found that he was semi-conscious and suffering from heat stroke. His clothing was removed, water was dumped on his skin, and chemical cold packs were applied to his body. At 2:50 p.m. paramedics arrived and continued to administer aid. At 3 p.m. another crew member experienced symptoms of heat stroke. An ambulance transported the 21-year-old to the hospital at 3:20 p.m.; however he died early the following morning. The maximum measured temperature during the incident was 98°F.

The following recommendations were made after the incident:

- Fire agencies should require supervisors to regularly medically monitor fire fighters, using generally accepted techniques, during periods of high heat stress.
- Fire agencies should assure fire fighter workloads are appropriate for their level of acclimatization.
- Fire agencies should assure fire fighter workloads are appropriate for ambient weather conditions and clothing.

4.2 Acute Heat Disorders

A variety of heat disorders can be distinguished clinically when individuals are exposed to excessive heat [Minard and Copman 1963; Leithead and Lind 1964; Minard 1973; Lind 1977; Dinman and Horvath 1984; Springer 1985]. These disorders range from simple postural heat syncope (fainting) to the complexities of heat stroke. The heat disorders are interrelated and seldom occur as discrete entities. A common feature in all the heat-related disorders (except simple postural heat syncope) is some degree of elevated body temperature, which may be complicated by deficits of body water. The prognosis depends on the absolute level of the elevated body temperature, the promptness of treatment to lower the body temperature, and the extent of deficiency or imbalance of fluids or electrolytes. A summary of classification, clinical features, prevention, and first-aid treatment of heat-related illnesses is presented in Table 4-3.

Table 4-3: Classification, medical aspects, and first aid of heat-related illness

Signs and symptoms	Examples of predisposing factors	Underlying physiologic disturbance	First aid
1. Temperature Regulation			
Heat stroke • Hot, dry skin or profuse sweating • Confusion • Loss of consciousness • Seizures • Very high body temperature • Fatal if treatment delayed	• Sustained exertion in heat • Obesity and lack of physical fitness • Recent alcohol intake • Dehydration • Individual susceptibility • Chronic cardiovascular disease	• Failure of thermoregulation (lack of sweating) leading to loss of evaporative cooling and an uncontrolled accelerating rise in temperature.	• A medical emergency: Call 911 for emergency medical care. • Someone should stay with worker until emergency medical services arrive. • Move the worker to a shaded, cool area and remove outer clothing (including socks and shoes). • Wet the worker's skin, place cold wet compresses or ice on head, face, neck, armpits, and groin; or soak their clothing with cool water. • Circulate the air around the worker to speed cooling.
2. Circulatory Hypostasis			
Heat Syncope Fainting, dizziness, or light-headedness during prolonged standing or suddenly rising from a sitting or lying position	• Dehydration • Lack of acclimatization	• Pooling of blood in dilated vessels of skin and lower parts of body	• Move the worker to a shaded, cool area to sit or lie down. • Encourage the worker to slowly drink water, clear juice, or a carbohydrate-electrolyte replacement liquid (e.g., sports

			drinks).
3. Water and/or Salt Depletion			
Heat Exhaustion • Headache • Nausea • Dizziness • Weakness • Irritability • Thirst • Heavy sweating • Elevated body temperature • Decreased urine output	• Sustained exertion in heat • Lack of acclimatization • Failure to replace water lost in sweat	• Dehydration • Depletion of circulating blood volume • Circulatory strain from competing demands for blood flow to skin and to active muscles	• Take workers to a clinic or emergency room for medical evaluation and treatment. • If medical care is unavailable, call 911. • Someone should stay with worker until emergency medical services arrive. • Move the worker to a shaded, cool area and remove outer clothing (including socks and shoes). • Encourage the worker to frequently drink water, clear juice, or a carbohydrate-electrolyte replacement liquid (e.g., sports drinks). • Wet the worker's skin, place cold wet compresses or ice on head, face, or neck.
Heat Cramps • Muscle cramps, pain, or spasms in the abdomen, arms, or legs	• Heavy sweating during hot work • Drinking large volumes of water without replacing salt loss	• Loss of electrolytes in sweat • Water intake dilutes electrolytes • Water enters muscles, causing spasm	• Encourage the worker to drink water and have a snack, and/or carbohydrate-electrolyte replacement liquid (e.g., sports drinks) every 15 to 20 minutes. • Avoid salt tablets.

			• Get medical help if the worker has heart problems, is on a low sodium diet, or if cramps do not subside within one hour.
4. Skin Eruptions			
Heat Rash (miliaria rubra: "prickly heat") • Looks like red cluster of pimples or small blisters that usually appears on the neck, upper chest, groin, under the breasts, and in elbow creases	• Unrelieved exposure to humid heat with skin continuously wet with unevaporated sweat	• Plugging of sweat gland ducts with retention of sweat and inflammatory reaction	• When possible, a cooler, less humid work environment is best treatment. • Keep rash area dry. • Powder may be applied to increase comfort. • Ointments and creams should not be used.
Anhidrotic Heat Exhaustion (miliaria profunda) • Extensive areas of skin which do not sweat on heat exposure, but present gooseflesh appearance, which subsides with cool environments • Associated with incapacitation in heat	• Weeks or months of constant exposure to climatic heat with previous history of extensive heat rash and sunburn	• Skin trauma (heat rash; sunburn) causes sweat retention deep in skin, reduced evaporative cooling causes heat intolerance	• No effective treatment, recovery of sweating occurs gradually on return to cooler climate

5. Behavioral Disorders			
Transient Heat Fatigue • Impaired performance of skilled sensorimotor, mental, or vigilance tasks, in heat	• Performance decrement greater in unacclimatized and unskilled worker	• Discomfort and physiologic strain	• First aid is not indicated unless accompanied by other heat-related illness. • Acclimatizing the worker over a period of time will lessen the severity.

Adapted from [Minard 1973; TBMed 2003; OSHA-NIOSH 2011].

4.2.1 Heat stroke

Heat stroke can be described as either classical or exertional. Classical heat stroke includes: (1) a major disruption of central nervous system function (unconsciousness or convulsions); (2) a lack of sweating; and (3) a rectal temperature in excess of 41°C (105.8°F) [Minard and Copman 1963; Leithead and Lind 1964; Shibolet et al. 1976; Khagali and Hayes 1983]. The 41°C rectal temperature is an arbitrary value for hyperpyrexia because observations are made only after the admission of patients to hospitals, which may occur from about 30 minutes to several hours after the event. Exertional heat stroke occurs in physically active individuals who will often continue sweating [TBMed 2003; Armstrong et al. 2007b; Navy Environmental Health Center 2007]. With exertional heat stroke, there is often acute rhabdomyolysis (the rapid breakdown of skeletal muscle) with resulting renal failure [TBMed 2003]. The risk of renal failure is about 25% for those suffering from exertional heat stroke [Navy Environmental Health Center 2007]. For additional comparisons between classical and exertional heat stroke see Table 4-4. The metabolic and environmental heat loads which give rise to heat stroke are highly variable and are often difficult or impossible to accurately reconstruct. Medical outcomes from one patient to another may vary, depending on the caregiver's knowledge, understanding, skill and available facilities.

Heat stroke is a medical emergency and rapidly cooling the affected worker is imperative. Placing the affected worker in a shady area, removing outer clothing and wetting or applying ice to the head, neck, armpits, and groin areas, and increasing air movement to enhance evaporative cooling are all important activities to perform while waiting for professional healthcare personnel. Frequently, by the time a worker is admitted to a hospital, the disorder has progressed to a multisystem emergency affecting virtually all tissues and organs [Dukes-Dobos 1981]. In the typical clinical presentation, the central nervous system is disorganized and there is commonly evidence of fragility of small blood vessels, possibly coupled with the loss of integrity of cellular membranes in many tissues. The blood-clotting mechanism is often severely disturbed, as are liver and kidney functions. It is not clear, however, whether these events are present at the onset of the disorder, or whether they develop over time. Postmortem evaluation indicates there are few tissues which escape pathological involvement. Early recognition of the disorder or its impending onset, associated with appropriate treatment, considerably reduces the death rate and the extent of organ and tissue involvement [TBMed 2003; Navy Environmental Health Center 2007]. An ill worker should not be sent home or be left unattended without a specific order from a physician or other qualified healthcare provider.

1 Table 4-4: Comparison of classical and exertional heat stroke

Patient characteristics	Classical	Exertional
Age	Young children or elderly	15-45 years
Health	Chronic illness common	Usually healthy
Prevailing weather	Frequent in prolonged heat waves	Variable
Drug use	Diuretics, antidepressants, anticholinergics, phenothiazines	Usually none, sometimes ergogenic stimulants or cocaine
Activity	Sedentary	Strenuous exercise
Sweating	Usually absent	Often present
History of febrile illness	Unusual	Common
Acid-base disturbances	Respiratory alkalosis	Lactic acidosis
Acute renal failure	Fairly rare	Common
Rhabdomyolysis	Seldom severe	Common, may be severe
Hyperuricemia	Modest	Marked
Creatinine: blood urea nitrogen ratio	1:10	Elevated
CK, aldolase	Mildly elevated	Markedly elevated
Hyperkalemia	Usually absent	Often present
Hypocalcemia	Uncommon	Common
DIC	Mild	May be marked
Hypoglycemia	Uncommon	Common

2 Adapted from Heat Stress Control and Heat Casualty Management [DOD 2003].

4.2.2 Heat Exhaustion

Heat exhaustion is often considered a precursor to the more serious heat stroke. This disorder has been encountered frequently in experimental assessment of heat tolerance. Characteristically, it is sometimes, but not always, accompanied by a slightly elevated body temperature (38°-39°C or 100.4º-102.2ºF). The symptoms of headache, nausea, vertigo, weakness, thirst, heavy sweating, irritability, and a decreased urine output are common to both heat exhaustion and the early stage of heat stroke. There is wide variation in the ability to tolerate an increased body temperature; some individuals cannot tolerate rectal temperatures of 38°-39°C and others continue to perform well at even higher rectal temperatures [Joy and Goldman 1968].

Failure to replace water may predispose the individual to one or more of the heat disorders and may complicate an already complex situation; cases of heat exhaustion can be precipitated by dehydration. It is unlikely that there is only one cause of heat exhaustion without some influence from another. Data suggest that cases of heat exhaustion can be expected to occur some 10 times more frequently than cases of heat stroke [Khagali and Hayes 1983].

4.2.3 Heat Cramps

Heat cramps are not uncommon in individuals who work hard in the heat. They are attributable to a continued loss of salt in the sweat, accompanied by a copious intake of water without appropriate replacement of salt. Other electrolytes, such as magnesium, calcium, and potassium, may also be involved. Cramps often occur in the muscles principally used during work and can be readily alleviated by rest, the ingestion of water and the correction of any body fluid electrolyte imbalance. Salt tablets should not be taken. Salt losses are best replaced by the ingestion of normal salted foods or fluids over many hours [TBMed 2003].

4.2.4 Heat Syncope

Heat syncope (fainting) usually occurs with prolonged standing or sudden rising from a sitting or supine position. There is a temporary circulatory failure due to the pooling of blood in the peripheral veins, resulting in a decrease in diastolic filling of the heart [TBMed 2003]. Symptoms of heat syncope include light-headedness, dizziness, and fainting. Factors that may contribute to heat syncope include dehydration and lack of acclimatization. Workers who have fainted will usually recover rapidly if they sit or lay down; however, complete recovery of stable blood pressure and HR may take an hour or two [TBMed 2003].

4.2.5 Heat Rashes

The most common heat rash is prickly heat (miliaria rubra), which appears as red papules, usually in areas where clothing is restrictive, and gives rise to a prickling sensation, particularly as sweating increases. It occurs in skin that is persistently wetted by unevaporated sweat, apparently because the keratinous layers of the skin absorb water, swell, and mechanically obstruct the sweat ducts [Pandolf et al. 1980b, 1980a; DiBenedetto and Worobec 1985]. If untreated, the papules may become infected and develop secondary staphylococcal infections [TBMed 2003]. Another skin disorder (miliaria crystallina) appears with the onset of sweating in skin previously injured at the surface, commonly in sunburned areas. The damage prevents the escape of sweat and results in the formation of small to large watery vesicles which rapidly subside once sweating stops; the problem ceases to exist once the damaged skin is sloughed.

Miliaria profunda occurs when the blockage of sweat ducts is below the skin surface. This rash also occurs following a sunburn injury, but has been reported to occur without clear evidence of previous skin injury. Discrete and pale elevations of the skin, resembling gooseflesh, are present.

In most cases, these rashes disappear when the individuals are returned to cool environments. It seems likely that none of the rashes occur (or if they do, certainly with greatly diminished frequency) when a substantial part of the day is spent in cool and/or dry areas so that the skin surface can dry.

Although these heat rashes are not dangerous in themselves, each can result in anhidrotic patchy areas which adversely affect evaporative heat loss and thermoregulation. Wet and/or damaged skin could also absorb toxic chemicals more readily than dry, unbroken skin. In experimentally induced miliaria rubra, sweating capacity recovers within 3-4 weeks [Pandolf et al. 1980b, 1980a].

4.3 Chronic Heat Disorders

Some long-term effects from heat stress (based on historical, epidemiologic and experimental evidence) have been suggested. Severe heat-related illness may cause permanent damage to a person's organs, such as the heart, kidneys, and liver, which may result in a chronic disorder. Dukes-Dobos reviewed evidence and proposed a three-category classification of possible heat-related chronic health effects [Dukes-Dobos 1981]. The three categories are Type I - those related to acute heat-related illnesses, such as reduced heat tolerance or reduced sweating capacity following heat stroke; Type II - not clear clinical entities, but are similar to general stress reactions; and Type III - which includes anhidrotic heat exhaustion, tropical neurasthenia and increased incidence of kidney stones. The primary references cited in the review are suggestive of some possible chronic heat effects.

Another study compared a cohort of U.S. Army personnel hospitalized for heat-related illness with those that had appendicitis. Heat-related illness cases were shown to have a 40% increased risk of all-cause mortality compared to the appendicitis patients [Wallace et al. 2007]. Further, it was found that males with heat-related illness were at an increased rate of death from cardiovascular disease and ischemic heart disease, compared to the appendicitis cases.

More studies are needed to increase our understanding of long-term effects of heat-related illness. How severe the illness and how long the exposures were are just two of possibly many factors that may have an effect on a worker's chronic condition.

5. Measurement of Heat Stress

Heat stress is the net heat load to which a worker may be exposed from the combined contributions of metabolic heat, environmental factors, and clothing requirements which may result in an increase in heat storage in the body. The heat load experienced by the worker provokes a physiological response (heat strain) which attempts to increase heat loss from the body in order to maintain a stable body temperature. This is not always successful and, when unsuccessful, may result in heat injury and death. The environmental factors of heat stress are temperature and movement of air, water vapor pressure, and radiant heat. Physical work contributes to total heat stress of a job by producing metabolic heat in the body in proportion to the work intensity. The amount, thermal characteristics, and type of clothing worn also contribute by altering the rate of heat exchange between the skin and the air [OSHA 1999].

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.

5.1 Environmental Factors

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

5.1.1 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 measured with a thermometer. Temperature units are in degrees Celsius (or Centigrade) [C = (ºF-32) x 5/9]. 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 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 [Ramsey and Beshir 2003]:

- 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.

5.1.1.1 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. Advantages of these thermometers are that they are simple to use; however, they may be fragile and can be affected by radiation.

5.1.1.2 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. Thermocouples are less affected by radiation, are highly accurate, have a fast response and may be used for remote measurements.

5.1.1.3 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. Thermistors are also less sensitive to radiation, but probes may require individual calibration.

5.1.1.4 Bimetallic Thermometers

Bimetallic thermometers are composed of two strips of different metals connected to each other at one end. They operate based on each metal's coefficient of expansion; when the strips are heated or cooled, they change length by a differing amount, which produces a movement in an indicator calibrated to temperature. These thermometers are frequently used in thermostats and appliances.

5.1.2 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 RH below 20%.

5.1.2.1 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. International System of Units (SI) units for water vapor pressure are in 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.

5.1.2.2 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 [Benedict 1977]. 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.

5.1.2.3 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 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 one 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 temperatures near or below the freezing point of water (humidity is usually 100% and water vapor pressure is about 3 mmHg).

5.1.2.4 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 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.

5.1.3 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 vane anemometers (swinging and rotating) and thermoanemometers. It should be mentioned that accurate determinations of wind velocity contour maps in a work area are very difficult because of the large variability in air movement with time and within space. In this case, the thermoanemometers are quite reliable and are sensitive to 0.05 m/sec (10 fpm), but are not very sensitive to wind direction.

If an anemometer is not available for accurate air velocity measurement, air velocity can be estimated as follows [Ramsey and Beshir 2003]:

	V_am/sec	**$V_a$fpm**
No sensation of air movement (e.g., closed room V_a without any air source)	$V_a < 0.2$	39
Sensing light breezes (e.g., slight perception of presence of air movement)	$0.2 < V_a < 1.0$	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)	$1.0 < V_a < 1.5$	197-235
Sensing heavy breezes (e.g., located close proximity to a fan; air causing marked movement of clothing)	$V_a > 1.5$	> 235

5.1.3.1 Vane Anemometers (swing and cup)

The two major types of vane anemometers are the propeller (or 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 the number of revolutions of the wheel or the linear distance in meters or feet. 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 [ASHRAE 1981a]. 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.

5.1.3.2 Thermoanemometers

Air velocity is determined with thermoanemometers by measuring the cooling effect of air movement on a heated element. Two types of thermoanemometers include hot-wire anemometers, which use resistance thermometers, and heated thermocouple anemometers. Two measurement techniques are used: (1) Bring the resistance (voltage) of a hot-wire anemometer or the electromotive force (emf) of a heated thermocouple to a specified value, measure the current required to maintain this value and then determine the wind velocity from a calibration chart; or (2) Heat the thermometer (usually by applying a specific electric current) and then determine the air velocity from a direct reading or a calibration chart relating air velocity to the wire resistance of the hot-wire anemometer or to the emf of the heated thermocouple anemometer.

5.1.4 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.

5.1.4.1 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) [NIOSH 1972]; 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 [Kuehn 1973]. 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 five minutes to stabilize [Kuehn and Machattie 1975].

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 non-uniform 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 (ºC)

T_g = black globe temperature (ºC)

T_a = air temperature (ºC)

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 [Cena et al. 1981]. A variety of radiometers has been used to measure radiant flux [Gagge 1970]. Radiometers are not, however, commonly used in occupational radiant heat measurements. They are used in laboratories or for measuring surface temperature.

5.1.4.2 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 direct, diffuse, and reflected solar radiation as modified by clothing worn and position of the body relative to the solar radiation [Roller and Goldman 1967].

(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 5.7º is recommended [Allen et al. 1976; Garg 1982]. 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 [Duffie and Beckman 1980; Garg 1982; Chang and Ge 1983].

5.1.5 Psychrometric Chart

The psychrometric chart is a graphical representation of the relationships among dry bulb temperature, wet bulb temperature, relative humidity, vapor pressure and dew point temperature. If any two of these variables are known, any of the others can be determined from the psychrometric chart. Figure 5.1 depicts a standard psychrometric chart [ISO 1993]. Note that when relative humidity equals 100%, dry bulb, wet bulb, and dew point temperature are equal. Psychrometric charts are valuable tools for assessing the thermal environment indoors where there is negligible solar or radiant heat exposure.

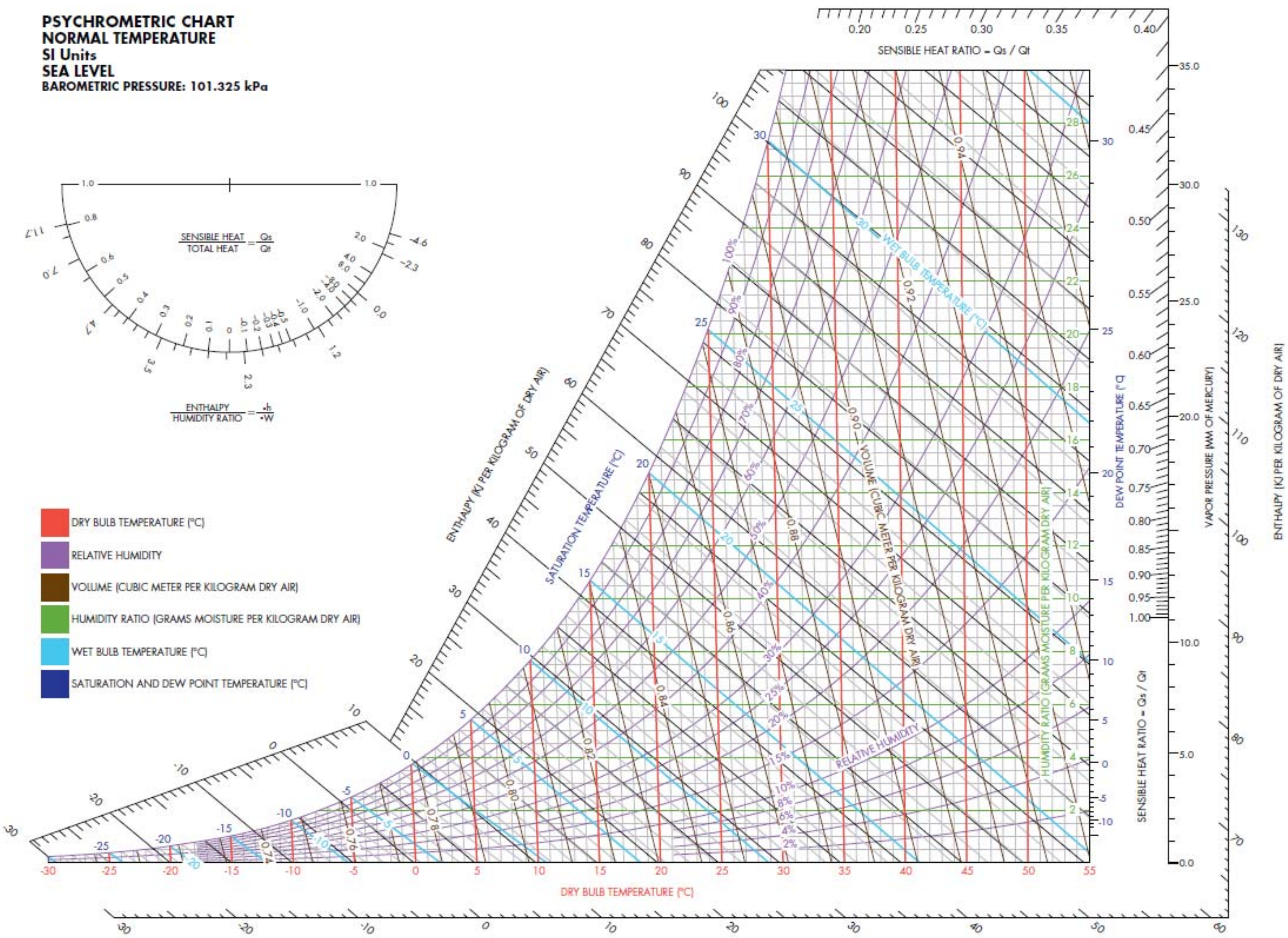

Figure 5.1 The Psychrometric Chart

Adapted from ISO [1993] and Coolerado [2012].

5.2 Prediction of Climatic Factors from the National Weather Service Data

The National Oceanic and Atmospheric Administration's National Weather Service provides daily environmental measurements, which can be a useful supplement to the climatic factors measured at a worksite. The National Weather Service data include timely observations for air temperature, humidity, wind speed, dew point, and visibility. These data 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. In addition, the National Weather Service may issue specific advisories during extreme heat based on the heat index. The heat index incorporates temperature with relative humidity to estimate the "feels like" temperature [Golden et al. 2008]. A recent study found that 86% of heat injuries were associated with a heat index range of 90°F to 104°F [Armed Forces Health Surveillance 2011]. For additional information on the heat index, see Appendix C.

National Weather Service data have also been used in studies of mortality due to heat-related illness resulting from heat waves in the U.S. [Semenza et al. 1996; Curriero et al. 2002; Knowlton et al. 2007; Golden et al. 2008]. However attributing heat waves and extreme heat events (EHE) the related health impacts can be a difficult task. Heat waves are often referred to as silent killers because unlike with other natural disasters such as hurricanes, they do not leave an obvious trail of destruction [Luber and McGeehin 2008]. Despite this, heat waves and EHEs are responsible for more deaths in the U.S. than hurricanes, lightening, tornadoes, floods, and earthquakes combined [Centers for Disease Control and Prevention 2009]. Heat-related illnesses and deaths estimates due to a heat wave are often misclassified, unrecognized, or not reported at all [Luber and McGeehin 2008].

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 heat-stress engineering 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 for the employer or safety and health professional 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 [Mutchler et al. 1976].

5.3 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 M 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.

5.3.1 Measurements of Metabolic Heat

5.3.1.1 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 [Banister and Brown 1968].

5.3.1.2 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 either the closed circuit or the open circuit procedure. An even more indirect procedure for measuring metabolic heat is based on the linear relationship between HR and oxygen consumption. The linearity, however, usually holds only at submaximal HRs 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 [Karpovich and Sinning 1971; Berger 1982].

(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 [Stegman 1981].

(2) Open Circuit

In the open circuit procedure, the worker breathes atmospheric air and 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 atmospheric air usually averages 20.90% and 0.03%, respectively, or they can be measured so that the amount of oxygen consumed and 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 [Stegman 1981]. 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 [Stegman 1981].

5.3.2 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. Alternatively, although they are less accurate and reproducible, metabolic heat estimates using tables of energy expenditure or task analysis 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 ± 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 [AIHA 1971; Garg et al. 1978].

5.3.2.1 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 [Smith and Ramsey 1980; ACGIH 2011]. Errors in estimating metabolic rate from energy expenditure tables are reported to be as high as 30% [ISO 1990]. The International

Organization for Standardization (ISO) [1990] recommends that the metabolic rate could be estimated by adding the following values: (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 (i.e., body surface area of 1.67 m^2) and woman (i.e., body surface area of 1.94 m^2), respectively. Metabolic rate values for body position and body motion, type of work, and those related to work speed are provided [ISO 1990].

5.3.2.2 Task Analysis

In order to evaluate the average energy requirements over an extended period of time for industrial tasks, including both work and rest activities, it is necessary to divide the task into its basic activities and sub activities. The metabolic heat of each activity or sub activity 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 (see Table 5-1) which specify incremental metabolic heat resulting from the movement of different body parts (e.g., arm work, leg work, standing, and walking) [McArdle et al. 1996b]. The metabolic heat of the activity can then be estimated by summing the component M values based on the actual body movements.

Table 5-1: Comparison of WBGT threshold values for acclimatized workers

Work Load	ACGIH	AIHA	OSHA	ISO	NIOSH
Resting		32.2°C 100 kcal/hr (117 watts)		33°C ≤ 100 kcal/hr (117 watts)	
Light	30°C 100-200 kcal/hr (117-233 watts)	30°C 200 kcal/hr (233 watts)	30.0°C[A], 32.2°C[B] < 200 kcal/hr (233 watts)	30°C 100-201 kcal/hr (117-234 watts)	30°C < 200 kcal/hr (233 watts)
Moderate	26.7°C 201-350 kcal/hr (234-407 watts)	26.7°C 300 kcal/hr (349 watts)	27.8°C[A], 30.6°C[B] 201-300 kcal/hr (234-349 watts)	28°C 201-310 kcal/hr (234-360 watts)	28°C 201-300 kcal/hr (234-349 watts)
Heavy			26.1°C[A], 28.9°C[B] > 301 kcal/hr (350 watts)	25°C[A], 26°C[B] 310-403 kcal/hr (360-468 watts)	26°C 301-400 kcal/hr (350-465 watts)
Very Heavy	25°C 350-500 kcal/hr (407-581 watts)			23°C[A], 25°C[B] > 403 kcal/hr (468 watts)	25°C 401-500 kcal/hr (466-580 watts)

[A] Low velocity

[B] High velocity

Adapted from AIHA [2003].

6. Control of Heat Stress

From a review of the heat balance equation [H = (M - W) ± C ± R - E] described in section 3.1, total heat stress can be reduced only by modifying one or more of the following factors: metabolic heat production, heat exchange by convection, heat exchange by radiation, or heat exchange by evaporation. Environmental heat load (C, R, and E) can be modified by engineering controls (e.g., ventilation, air conditioning, screening, insulation, and modification of process or operation) and protective clothing and equipment; whereas, metabolic heat production can be modified by work practices and application of labor-reducing devices. Each of these alternative control strategies will be discussed separately. Actions that can be taken to control heat stress and strain are listed in Table 6-1 [Belding 1973].

Table 6-1: Checklist for controlling heat stress and strain

Item		Actions for consideration
I.	Controls	
	Body heat production of task (M)	• reduce physical demands of the work; powered assistance for heavy tasks
	Radiative load (R)	• interpose line-of-sight barrier; furnace wall insulation, metallic reflecting screen, heat reflective clothing, cover exposed parts of body
	Convective load (C)	• if air temperature is above 35ºC (95ºF); reduce air temperature, reduce air speed across skin, wear clothing • if air temperature is below 35ºC (95ºF); increase air speed across skin and reduce clothing
	Maximum evaporative cooling by sweating (E_{max})	• increase by decreasing humidity and/or increasing air speed • reduce clothing
II.	Work Practices	• shorten duration of each exposure; more frequent short exposures better than fewer long exposures • schedule very hot jobs in cooler parts of

		day when possible
	Exposure limit	• self-limiting, based on formal training of workers and supervisors on signs and symptoms of overstrain
	Recovery	• air-conditioned space nearby
III.	Personal Protection (R, C, and E_{max})	• cooled air, cooled fluid, or ice cooled conditioned clothing • reflective clothing or aprons
IV.	Other Considerations	• determine by medical evaluation, primarily of cardiovascular status • careful break-in of unacclimatized workers • water intake at frequent intervals to prevent dehydration (1 cup every 15-20 minutes) • fatigue or mild illness not related to the job may temporarily contraindicate exposure (e.g., low grade infection, diarrhea, sleepless night, alcohol ingestion)
V.	Heat Wave	• introduce heat alert program

Adapted from Belding [1973] and OSHA-NIOSH [2011].

6.1 Engineering Controls

The environmental factors that can be modified by engineering procedures are those involved in convective, radiative, and evaporative heat exchange.

6.1.1. Convective Heat Control

As discussed earlier, the environmental variables concerned with convective heat exchange between the worker and the ambient environment are dry bulb air temperature (t_a) and the speed of air movement (V_a). When air temperature is higher than the mean skin temperature (t_{sk} of 35°C or 95°F), heat is gained by convection. The rate of heat gain is dependent on temperature differential (t_a - t_{sk}) and air velocity (V_a), where t_a is below t_{sk}, heat is lost from the body; the rate of loss is dependent on t_a - t_{sk} and air velocity.

Engineering approaches to enhancing convective heat exchange are limited to modifying air temperature and air movement. When t_a is less than $t_{sk,}$ increasing air movement across the skin by increasing either general or local ventilation will increase the rate of body heat loss. When t_a exceeds t_{sk} (convective heat gain), t_a should be reduced by bringing in cooler outside air or by evaporative or refrigerative cooling of the air. In addition, as long as t_a exceeds $\bar{t}_{sk,}$ air speed should be reduced to levels which will still permit sweat to evaporate freely, but will reduce convective heat gain (see Table 6-1). The effect of air speed on convective heat exchange is a 0.6 root function of air speed. Spot cooling (t_a less than $\bar{t}_{sk}$) of the individual worker can be an effective approach to controlling convective heat exchange, especially in large workshops where the cost of cooling the entire space would be prohibitive. However, spot coolers or blowers may interfere with the ventilating systems required to control toxic chemical agents.

6.1.2 Radiant Heat Control

Radiant heat exchange between the worker and hot equipment, processes, and walls that surround the worker is a fourth power function of the difference between skin temperature ($\bar{t}_{sk}$) and the temperature of hot objects that "see" the worker (t_r). Obviously, the only engineering approach to controlling radiant heat gain is to reduce t_r or to shield the worker from the radiant heat source.

To reduce t_r would require (1) lowering the process temperature, which is usually not compatible with the temperature requirements of the manufacturing processes; (2) relocating, insulating, or cooling the heat source; (3) placing line-of-sight radiant reflective shielding between the heat source and the worker; or (4) changing the emissivity of the hot surface by coating the material. Of the alternatives, radiant reflective shielding is generally the easiest to install and the least expensive. Radiant reflective shielding can reduce the radiant heat load by as much as 80-85%. Some ingenuity may be required in placing the shielding so that it doesn't interfere with the worker performing the work. Remotely operated tongs, metal chain screens or air or hydraulically activated doors, which are opened only as needed, are some of the approaches.

6.1.3 Evaporative Heat Control

Heat is lost from the body when sweat evaporates from the skin surface. The rate and amount of evaporation is a function of the speed of air movement over the skin and the difference between the water vapor pressure of the air (p_a) at ambient temperature and the water vapor pressure of the wetted skin, assuming a skin temperature of 34°-35ºC (93.2°-95ºF). At any air-to-skin vapor pressure gradient, the evaporation increases as a 0.6 root function of increased air movement. Evaporative heat loss at low air velocities can be greatly increased by improving ventilation (increasing air velocity). At high air velocities (2.5 m/sec or 500 fpm), an additional increase will be ineffective, except when the clothing worn interferes with air movement over the skin.

Engineering control of evaporative cooling can therefore assume two forms: (1) increase air movement or (2) decrease ambient water vapor pressure. Of these, increased air movement by the use of fans or blowers is often the simplest and usually the cheapest approach to increasing the rate of evaporative heat loss. Ambient water vapor pressure reduction usually requires air-conditioning equipment (cooling compressors). In some cases, the installation of air conditioning, particularly spot air conditioning, may be less expensive than the installation of increased ventilation because of the lower airflow involved. The vapor pressure of the worksite air is usually at least equal to that of the outside ambient air, except when all incoming and recirculated air is humidity controlled by absorbing or condensing the moisture from the air (i.e., by air conditioning). In addition to the ambient air as a source of water vapor, water vapor may be added from the manufacturing processes as steam, leaks from steam valves and steam lines, and evaporation of water from wet floors. Eliminating these additional sources of water vapor can help reduce the overall vapor pressure in the air and thereby increase evaporative heat loss by facilitating the rate of evaporation of sweat from the skin [Dasler 1977].

6.2 Work and Hygienic Practices and Administrative Controls

The job risk factors for occupational heat stress are thermal environment, work demands, and clothing requirements. These are reflected in occupational exposure limits (OELs) traditionally based on wet bulb globe temperature (WBGT), such as NIOSH RELs and ACGIH threshold limit values (TLVs), and in ISO 7243. Many workers spend some part of their working day in a hot environment where the temperature is above the OELs. Strategies to reduce the effects of heat in the workplace include engineering controls, administrative controls, and personal protective equipment.

In some situations, it may be technologically impossible or impractical to completely control heat stress by the application of engineering controls; the level of environmental heat stress may be unpredictable and variable (as in seasonal heat waves), and exposure time may vary with the task and with unforeseen critical events. When engineering controls of the heat stress are not practical or sufficient, other solutions must be sought to keep the worker’s total heat stress level within limits that will not be associated with an increased risk of heat-related illnesses.

The application of preventive practices frequently can be an alternative or complementary approach to engineering techniques for controlling heat stress. Preventive practices are mainly of five types: (1) limiting or modifying the duration of exposure time; (2) reducing the metabolic component of the total heat load; (3) enhancing the heat tolerance of the workers by heat acclimatization, physical conditioning, etc.; (4) training the workers in safety and health procedures for work in hot environments; and (5) medical screening of workers to eliminate individuals with low heat tolerance and/or low physical fitness.

6.2.1 Limiting Exposure Time and/or Temperature

There are several ways to control the daily length of time and temperature to which a worker is exposed in heat stress conditions [OSHA-NIOSH 2011].

- When possible, schedule hot jobs for the cooler part of the day (early morning, late afternoon, or night shift).
- Schedule routine maintenance and repair work in hot areas for the cooler seasons of the year.
- Alter the work/rest schedule to permit more rest time (See Table 6-2 and 6-3 below).
- Provide cool areas for rest and recovery.
- Add extra personnel to reduce exposure time for each member of the crew.
- Permit work interruption when a worker feels extreme heat discomfort.
- Increase water intake of workers on the job.
- Adjust schedule, when possible, so that hot operations are not performed at the same time and place as other operations that require the presence of workers, e.g., maintenance and cleanup while tapping a furnace.

Table 6-2: Work/Rest schedules for workers wearing normal work clothing[A]

Adjusted temperature (°F)[B]	Light work (minutes worked/rest)	Moderate work (minutes worked/rest)	Heavy work (minutes worked/rest)
90	Normal	Normal	Normal
91	Normal	Normal	Normal
92	Normal	Normal	Normal
93	Normal	Normal	Normal
94	Normal	Normal	Normal
95	Normal	Normal	45/15
96	Normal	Normal	45/15
97	Normal	Normal	40/20
98	Normal	Normal	35/25
99	Normal	Normal	35/25
100	Normal	45/15	30/30
101	Normal	40/20	30/30
102	Normal	35/25	25/35
103	Normal	30/30	20/40
104	Normal	30/30	20/40
105	Normal	25/35	15/45
106	45/15	20/40	Caution [C]
107	40/20	15/45	Caution [C]
108	35/25	Caution [C]	Caution [C]
109	30/30	Caution [C]	Caution [C]
110	15/45	Caution [C]	Caution [C]
111	Caution[C]	Caution [C]	Caution [C]
112	Caution [C]	Caution [C]	Caution [C]

[A] Assumes workers and conditions are: physically fit, well-rested, fully hydrated, under age 40, adequate water intake, 30% relative humidity, natural ventilation with perceptible air movement.

[B] Note: Adjust the temperature reading as follows before going to the temperature column in the table:

Full sun (no clouds): Add 13°
Partly cloudy/overcast: Add 7°
No shadows visible/work is in the shade or at night: no adjustment
For relative humidity of:
10%: Subtract 8°
20%: Subtract 4°
30%: No adjustment
40%: Add 3°
50%: Add 6°
60%: Add 9°

[C] High levels of heat stress, consider rescheduling activities.

Adapted from ACGIH [1993].

Table 6-3: Work/rest schedules for workers wearing chemical-resistant suits[A]

Air Temp (°F)	Light work			Moderate work			Heavy work		
	Full sun	Partly cloudy	No sun[B]	Full sun	Partly cloudy	No sun[B]	Full sun	Partly cloudy	No sun[B]
75	Normal	Normal	Normal	Normal	Normal	Normal	35/25[C]	Normal	Normal
80	30/30	Normal	Normal	20/40	Normal	Normal	10/50	40/20	Normal
85	15/45	40/20	Normal	10/50	25/35	Normal	Caution[D]	15/45	40/20
90	Caution[D]	15/45	40/20	Caution[D]	Caution[D]	25/35	Stop work	Caution[D]	15/45
95	Stop work	Stop work	15/45	Stop work	Stop work	Stop work	Stop work	Stop work	Stop work

[A] Assumes workers are/are wearing: heat-acclimatized, under the age of 40, physically fit, well-rested, and fully hydrated; Tyvek coveralls, gloves, boots, and a respirator. Cooling vests may enable workers to work for longer periods. Adjustments must be made when additional protective gear is worn.

[B] No shadows are visible or work is in the shade or at night.

[C] 35 minutes work and 25 minutes rest each hour.

[D] High levels of heat stress, consider rescheduling activities.

Adapted from U.S. EPA/OSHA [1993].

6.2.2 Reducing Metabolic Heat Load

In most industrial work situations, metabolic heat is not the major part of the total heat load. However, because it represents an extra load on the circulatory system, it can be a critical component in high heat exposures. Heavy and very heavy metabolic rates require substantial rest periods. For some examples of work/rest schedules, see Tables 6-2 and 6-3 in the previous section. Metabolic heat production can be reduced, usually by not more than 200 kcal/h (800 Btu/h), by:

- Mechanization of the physical components of the job
- Reduction of work time (reduce work day, increase rest time, restrict double-shifting) and planned heat exposure times (e.g., U.S. Navy Physiological Heat Exposure Limit [PHEL] times, EPRI Action Times, USF WBGT–based Safe Exposure Times, PHS-TL)
- Increase of the work force.

6.2.3 Enhancing Tolerance to Heat

Stimulating the human heat-adaptive mechanisms can significantly increase the capacity to tolerate work in heat. However, the ability of people to adapt to heat varies widely, which must be kept in mind when considering any group of workers.

A properly designed and applied heat-acclimatization program will dramatically increase the ability of workers to work at a hot job and will decrease the risk for heat-related illnesses and unsafe acts. Heat acclimatization can usually be induced in 7 to 14 days of exposure at the hot job [TBMed 2003; Navy Environmental Health Center 2007; ACGIH 2011]. For workers who have had previous experience with the job, the acclimatization regimen should be no more than 50% exposure on day 1, 60% on day 2, 80% on day 3, and 100% on day 4. For new workers, the schedule should be no more than 20% on day 1 and no more than 20% increase on each additional day.

Being physically fit for the job will not replace heat acclimatization, but can enhance heat tolerance for both heat-acclimatized and nonacclimatized workers [Pandolf et al. 1977; TBMed 2003; Yeargin et al. 2006; Navy Environmental Health Center 2007]. The time required for non–physically fit individuals to develop acclimatization is about 50% greater than for the physically fit. For more information on acclimatization, see Table 4-1.

To ensure that water lost in the sweat and urine is replaced (at least hourly) during the work day, an adequate water supply and intake are essential for heat tolerance and prevention of heat-related illnesses.

Electrolyte balance in the body fluids must be maintained to help prevent heat-related illnesses. For unacclimatized workers who may be on a salt-restricted diet, additional salting of the food, with the concurrence of a physician or other qualified healthcare provider, during the first two days of heat exposure, may be needed to replace the salt lost in the sweat [Lind 1976; TBMed 2003]. The heat-acclimatized worker loses relatively little salt in sweat and therefore usually does not need salt supplementation.

6.2.4 Health and Safety Training

Employers should provide training as mandated by the OSHA Hazard Communication Standard (29 CFR 19190.1200). A heat stress training program should be in place for all workers who work in hot environments. Workers should be trained about the prevention of heat-related illness before they begin work in a hot environment and before heat index levels go up. Heat prevention training should be reinforced on hot days. Prevention of serious heat-related illnesses is dependent on early recognition of the signs and symptoms of impending heat-related illness and initiation of first aid and/or corrective procedures at the earliest possible moment.

Employers should provide a heat stress training program that effectively trains all workers in hot jobs about the following:

a. Recognition of the signs and symptoms of the various types of heat-related illnesses, e.g., heat cramps, heat exhaustion, heat rash, and heat stroke, and in administering first aid procedures (see Table 4-1).

b. The causes and recognition of the various heat-related illnesses and personal care procedures that should be exercised to minimize the risk of their occurrence, for example, drinking enough water, and monitoring the color and amount of urine output (see Appendix B).

c. The proper care and use of heat-protective clothing and equipment and the added burden of heat load on the body caused by exertion, clothing, and personal protective equipment.

d. The effects of non-occupational factors (drugs, alcohol, obesity, etc.) on tolerance to occupational heat stress.

e. The importance of acclimatization.

f. The importance of immediate reporting to the supervisor any symptoms or signs of heat-related illness in themselves or in their coworkers.

g. The employer’s procedures for responding to symptoms of possible heat-related illness and contacting emergency medical services if needed.

In addition to being trained about each of the topics listed above, supervisors should also be trained about:

a) The procedures to follow when a worker has symptoms consistent with heat-related illness, including emergency response procedures.

b) How to monitor weather reports.

c) How to respond to hot weather advisories.

A buddy system should be initiated, in which workers on hot jobs are taught to recognize the early signs and symptoms of heat-related illness. Each worker and supervisor who has received the instructions is assigned the responsibility for observing, at periodic intervals, one or more fellow workers to determine whether they have any early symptoms of a heat-related illness. Any worker who exhibits signs and symptoms of an impending heat-related illness should be sent to the dispensary or first-aid station for more complete evaluation and possible initiation of medical or first-aid treatment. Workers on hot jobs where the heat stress exceeds the RAL or REL (for unacclimatized and acclimatized workers, respectively) should be observed by a fellow worker or supervisor.

6.2.5 Screening for Heat Intolerance

The ability to tolerate heat stress varies widely, even between healthy individuals with similar heat-exposure experiences [Shvartz and Benor 1972; Wyndham 1974a; Strydom 1975; Khogali 1997; Moran et al. 2007]. Heat intolerance factors in young active persons may be congenital (e.g., ectodermal dysplasia or chronic idiopathic anhidrosis), functional (e.g., low physical fitness, lack of acclimatization, low work capacity, or reduced skin area to body mass ratio), or acquired (e.g., sweat gland dysfunction, dehydration, infectious disease, x-ray irradiation, previous heat stroke, large scarred burns, or drugs) [Epstein 1990; Moran et al. 2007]. One way to reduce the risk of heat-related illnesses and disorders within a heat-exposed workforce is to reduce or eliminate the exposure of the heat-intolerant individuals to heat stress. The ability to identify heat-intolerant individuals, without resorting to strenuous, time-consuming heat-tolerance tests, is basic to any such screening process.

Data from laboratory and field studies indicate that individuals with low physical work capacity are more likely to develop higher body temperatures than are individuals with high physical work capacity when exposed to equally hard work in high temperatures. In these studies, none of the individuals with a maximum work capacity (VO_2max) of at least 2.5 liters of oxygen per minute (L/min) were heat intolerant, but 63% of those with VO_2max below 2.5 L/min were. It has also been shown that heat-acclimatized individuals with a VO_2max less than 2.5 L/min had a 5% risk of reaching heat stroke levels of body temperature (40°C or 104°F), whereas those with a VO_2max above 2.5 L/min had only a 0.05% risk [Wyndham 1974a; Strydom 1975].

Medical screening for heat intolerance in otherwise healthy individuals should include obtaining a history of any previous incidents of heat-related illness. Workers who have experienced a heat-related illness may be less heat-tolerant [Leithead and Lind 1964; Armstrong et al. 1990]. In a study by Moran [2007], a heat tolerance test (HTT) was evaluated and found to be efficient at differentiating between a temporary and permanent state of heat susceptibility, either of which could occur following exertional heat stroke. The test is described as a 120 minute exposure to 40°C and 40% relative humidity in a climatic chamber while walking on a treadmill. The person being tested wears shorts and a t-shirt, and walks at a pace of 5 km/h (3 mph) at a 2% elevation. Rectal temperature and heart rate are continuously monitored. Sweat rate is determined by differences in weight and corrected for fluid intake. At the end of test, heat tolerant individuals will be 38 ± 0.3°C, heart rate will be 120 ± 15 bpm, and sweat rate will be 780 ± 160 g/h. Heat intolerance is determined when rectal temperatures are higher than 38.5°C or heart rate exceeds 145 bpm, with larger deviations meaning a more pronounced state of heat intolerance. Moran goes on to suggest that a HTT be conducted within 6-8 weeks after a heat exhaustion or exertional heat stroke episode, and that the test may be repeated 4-8 weeks later to refute or support the diagnosis of heat intolerance.

6.3 Heat-Alert Program

When heat-related illnesses and disorders occur mainly during heat waves in the summer, a Heat-Alert Program (HAP) should be established for preventive purposes. Although such programs differ in detail from worksite to another, the main idea behind them is identical, i.e., to utilize the weather forecast of the National Weather Service. If a heat wave is predicted for the next day or days, a state of Heat Alert is declared to make sure that measures to prevent heat casualties will be strictly observed. Although this sounds quite simple and straightforward, in practical application, it requires the cooperation of the administrative staff, the maintenance and operative workforce, and the medical, industrial hygiene, and/or safety departments. An effective HAP is described below [Dukes-Dobos 1981]. While this HAP is designed with an industrial-setting in mind, many aspects can also be used or modified for outdoor work-settings such as in construction or agriculture.

1. Each year, early in the spring, establish a Heat-Alert Committee, which may consist of an industrial physician or other qualified healthcare provider, industrial hygienist, safety engineer, operation engineer, and a manager. Once established, this committee takes care of the following:

   a. Arrange a training course for all involved in the HAP that provides procedures to follow in the event a Heat Alert is declared; emphasize the prevention and early recognition of heat-related illnesses and first aid procedures when a heat-related illness occurs.

   b. In writing, instruct the supervisors to:

(1) Reverse winterization of the site, i.e., open windows, doors, skylights, and vents according to instructions for greatest ventilating efficiency at places where high air movement is needed;

(2) Check drinking fountains, fans, and air conditioners to make sure that they are functional, that the necessary maintenance and repairs are performed, that they are regularly rechecked, and that workers know how to use them;

c. Ascertain that, in the medical department, as well as at the job sites, all facilities required to give first aid in cases of heat-related illness are in a state of readiness;

d. Establish criteria for the declaration of a Heat Alert. For instance, a Heat Alert would be declared if the area weather forecast for the next day predicts a maximum air temperature of at least 35°C (95°F) or if a maximum of 32°C (90°F) is predicted and is 5°C (9°F) higher than the temperature reached on any of the preceding three days.

2. Procedures to be followed during the state of Heat Alert are as follows:

a. Postpone tasks that are not urgent (e.g., preventive maintenance involving high activity or heat exposure) until the heat wave is over.

b. Increase the number of workers on each team in order to reduce each worker's heat exposure. Introduce new workers gradually to allow acclimatization (follow heat-acclimatization procedure).

c. Increase rest allowances. Let workers recover in air-conditioned rest places.

d. Turn off heat sources that are not absolutely necessary.

e. Remind workers to drink water in small amounts frequently to prevent excessive dehydration, to weigh themselves before and after the shift, and to be sure to drink enough water to maintain body weight.

f. Monitor the environmental heat at the job sites and resting places.

g. Check workers' oral temperature during their most severe heat-exposure period.

h. Exercise additional caution on the first day of a shift change to make sure that workers are not overexposed to heat, because they may have lost some of their acclimatization over the weekend and during days off.

i. Send workers who show signs of a heat disorder, even a minor one, to the medical department. Permission of the physician or other qualified healthcare provider to return to work must be given in writing.

j. Restrict overtime work.

6.4 Auxiliary Body Cooling and Protective Clothing

When high levels of heat-stress occur, there are generally only four approaches to a solution: (1) modify the work; (2) modify the environment; (3) modify the worker by heat acclimatization; or (4) modify the clothing or equipment. To do everything possible to improve human tolerance would require that the individuals should be fully heat acclimated, should have good training in the use of and practice in wearing protective clothing, should be in good physical condition, and should be encouraged to drink as much water as necessary (e.g., 8 oz. of water or other fluids every 15-20 minutes or see Table 8-1) to compensate for sweat water loss.

It may be possible to redesign ventilation systems for occupied spaces to avoid interior humidity and temperature buildup; however, these may not completely solve the heat stress problem. When air temperature is above 35°C (95°F) with an RH of 75-85%, or when there is an intense radiant heat source, a suitable, and in some ways more functional, approach is to modify the clothing to include some form of auxiliary body cooling. Even individuals engaging in heavy exercise while wearing personal protective ensembles can be provided some form of auxiliary cooling for limited periods of time. A properly designed system will reduce heat stress, conserve large amounts of drinking water which would otherwise be required, and allow unimpaired performance across a wide range of climatic factors. A seated individual will rarely require more than 100 W (86 kcal/h or 344 Btu/h) of auxiliary cooling and, the most active individuals, not more than 400 W (345 kcal/h or 1380 Btu/h), unless working at a level where physical exhaustion per se would limit the duration of work. Some form of heat-protective clothing or equipment should be provided for exposures at heat-stress levels that exceed the Ceiling Limit in Figures 8.1 and 8.2.

Auxiliary cooling systems can range from such simple approaches as applying frozen materials under the clothing, to more complex systems, such as cooled garments; however, cost of logistics and maintenance are considerations of varying magnitude in all of these systems. Four auxiliary cooling approaches have been evaluated: (1) water-cooled garments, (2) air-cooled garments, (3) cooling vests, and (4) wetted overgarments. Each of these auxiliary body cooling approaches might be applied in alleviating risk of severe heat stress in a specific industrial setting [Goldman 1973, 1981].

6.4.1 Water-cooled Garments

Water-cooled garments have been designed and constructed in various forms with significant improvements on both engineering and physiological perspectives. Water-cooled garments provide cooling by means of conductive heat exchange between skin and coolant tubing sewn inside a garment in which a network of tubing is distributed onto either a whole body or limited body regions. Water-cooled garments also require an external device for operation, which may include battery, circulating pump, heat exchanger, fluid container, and control pad. The weight and volume of the operating device may limit a wearer's movement and impose an extra weight burden, which will determine the effective use time of the water-cooled garment with consideration of the nature of work and environmental conditions. In addition, at water temperatures at or below the dew point, condensation around the tubes may increase heat loss from the skin through permeable clothing [Nag et al. 1998].

The range of cooling provided by each of the water-cooled garments versus the cooling water inlet temperature has been studied. The rate of increase in cooling, with decrease in cooling water inlet temperature, is 3.1 W/°C for the water-cooled cap with water-cooled vest, 17.6 W/°C for the short water-cooled undergarment, and 25.8 W/°C for the long water-cooled undergarments. A "comfortable" cooling water inlet temperature of 20°C (68°F) should provide 46 W of cooling using the water-cooled cap; 66 W using the water-cooled vest; 112 W using the water-cooled cap with water-cooled vest; 264 W using the short water-cooled undergarment; and 387 W using the long water-cooled undergarment.

6.4.2 Air-cooled Garments

Air-cooled garments, which distribute cooling air next to the skin, are available. The total heat exchange from completely sweat wetted skin when cooling air is supplied to the air-cooled garment is a function of cooling air temperature and cooling airflow rate. Both the total heat exchanges and the cooling power increase with cooling airflow rate and decrease with increasing cooling air inlet temperature. For an air inlet temperature of 10°C (50°F) at 20% RH and a flow rate of 10 ft^3/min (0.28 m^3/min), the total heat exchanges over the body surface would be 233 W in a 29.4°C (84.9°F) 85% RH environment and 180 W in a 51.7°C (125.1°F) at 25% RH environment. Increasing the cooling air inlet temperature to 21°C (69.8°F) at 10% RH would reduce the total heat exchanges to 148 W and 211 W, respectively. Either air inlet temperature easily provides 100 W of cooling.

The use of a vortex tube as a source of cooled air for body cooling is applicable in many hot industrial situations. The vortex tube, which is attached to the worker, requires a constant source of compressed air supplied through an air hose. The hose connecting the vortex tube to the compressed air source limits the area within which the worker can operate. However, unless mobility of the worker is required, the vortex tube, even though noisy, may be considered as a simple cooled air source.

6.4.3 Cooling Vests

Currently available cooling vests may contain as many as 72 cooling packs made of ice or phase change materials; cooling packs may also vary in weight and size. These cooling packs are generally secured to the vest by tape, inserted into the vest pockets, or integrated with the vest, which requires freezing the whole vest before use. The cooling provided by each individual cooling pack will vary with time and with its contact pressure with the body surface, plus any heating effect of the clothing and hot environment; thus, the environmental conditions have an effect on both the cooling provided and the duration of time this cooling is provided. In environments of 29.4°C (84.9°F) at 85% RH and 35.0°C (95°F) at 62% RH, a cooling vest can still provide some cooling for up to four hours of operation (about two to three hours of effective cooling is usually the case). However, in an environment of 51.7°C (125.1°F) at 25% RH, any benefit is negligible after about three hours of operation. With 60% of the cooling packs in place in the vest, the cooling provided may be negligible after two hours of operation. Since the cooling vest does not provide continuous and regulated cooling over an indefinite time period, exposure to a hot environment would require redressing with backup cooling packs every two to four hours. Replacing a cooling vest would have to be accomplished when an individual is not in a work situation. However, the cooling is supplied noise-free and independent of any energy source or umbilical cord that would limit a worker's mobility. The greatest potential for the ice packet vest appears to be for work where other conditions limit the length of exposure, e.g., short duration tasks and emergency repairs. The cooling vest is also relatively cheaper than other cooling approaches.

6.4.4. Wetted Overgarments

A wetted overgarment is a wetted cotton terry cloth coverall or a two-piece cotton cover which extends from just above the boots and from the wrists to a V-neck. When used with impermeable protective clothing, it can be a simple and effective auxiliary cooling garment.

Predicted values can be calculated to determine supplementary cooling and the minimal water requirements to maintain the cover wet in various combinations of air temperature, RH and wind speed. Under environmental conditions of low humidity and high temperatures where evaporation of moisture from the wet cover garment is not restricted, this approach to auxiliary cooling can be effective, relatively simple, and inexpensive.

6.5 Performance Degradation

A variety of options for auxiliary cooling to reduce, if not eliminate, the level of heat stress under most environmental conditions both indoors and outdoors, have been prescribed. However, there is also a degradation in performance associated with wearing protective clothing systems. Performance decrements are associated with wearing encapsulating protective ensembles even in the absence of any heat stress [Joy and Goldman 1968]. The majority of the decrements result from mechanical barriers to sensory inputs to the wearer and from barriers to communication between individuals. Over all, it is clear that elimination of heat stress, while it will allow work to continue, will not totally eliminate the constraints imposed by encapsulating protective clothing systems [Joy and Goldman 1968; Nag et al. 1998].

7. Medical Screening and Surveillance

Employers should establish a medical screening and surveillance program for workers with occupational exposure to hot environments. The goal of a workplace medical screening program is the early identification of signs or symptoms that may be related to heat-related illness. Early detection of symptoms, subsequent treatment, and workplace interventions are intended to minimize the adverse health effects of exposure to hot environments. Medical screening data may also be used for the purposes of medical surveillance to identify work areas, tasks, and processes that require additional prevention efforts.

7.1 Worker Participation

Workers exposed to hot environments that should be included in a medical screening program and could receive the greatest benefit include the following:

- Workers exposed to a hot environment above the RAL.
- Workers with medical conditions that put them at higher risk of heat-related illness.
- Workers with personal risk factors that put them at higher risk of heat-related illness.
- Workers with a prior history of heat-related illness.

7.2 Program Oversight

The employer should assign responsibility for the medical screening and surveillance program to a qualified physician or other qualified health care provider (as determined by appropriate state laws and regulations) who is informed and knowledgeable about the following:

- Potential workplace exposures to heat and hot environments.
- Administration and management of a medical screening program for occupational hazards.
- Identification and management of heat-related illnesses.
- Where respiratory protection is being used, establishment of a respiratory protection program based on an understanding of the requirements of the OSHA respiratory protection standard and types of respiratory protection devices available at the workplace.

7.3 Medical Screening Elements

Recommended elements of a medical screening program for workers at risk for heat-related illnesses and injuries should include worker education, an initial (baseline) medical examination, regularly scheduled follow-up medical examinations, and reports of incidents of heat-related illnesses and injuries. The purpose of initial and periodic medical examinations of persons working at a particular hot job is to determine if the person can meet the total demands and stresses of the hot job with reasonable assurance that the safety and health of the individual and/or fellow workers will not be placed at risk. Based on the findings from these examinations, more frequent and detailed medical examination may be necessary.

7.3.1 Worker Education

All workers in the medical screening program should be provided with information about the purposes of the program, the potential health benefits of participation, and program procedures. Workers should be trained about the signs and symptoms of heat-related illness. They should be instructed to report to their supervisor and the medical director any symptoms consistent with heat-related illness and any accidents or incidents involving potentially high exposure levels. Workers should inform their healthcare provider about their workplace exposures and any possible work-related symptoms..

7.3.2 Medical Examinations

7.3.2.1 Initial Evaluation

The initial evaluation should be conducted on all new workers or workers who are transferring from jobs that do not involve exposure to heat. Unless demonstrated otherwise, it should be assumed that these workers are not acclimatized to work in hot environments.

a. The physician or other qualified healthcare provider should obtain information including:

(1) A medical and surgical history that includes the cardiac, vascular, respiratory, neurologic, renal, hematologic, gastrointestinal, and reproductive systems and information about dermatologic, endocrine, musculoskeletal, and metabolic conditions that might affect heat acclimatization or the ability to eliminate heat.

(2) A complete occupational history, including years of work in each job, the physical and chemical hazards encountered, the physical demands of these jobs, ability to use personal protective equipment, intensity and duration of heat exposure, and nonoccupational exposures to heat and strenuous activities. This history should identify episodes of heat-related disorders and evidence of successful adaptation to work in heat in previous jobs or nonoccupational activities.

(3) A list of all prescribed, over-the-counter medications, and drugs of abuse potentially used by the worker. The physician or other qualified healthcare provider should consider the possible impact of medications that may affect cardiac output, electrolyte balance, renal function, sweating capacity, or autonomic nervous system function. These include diuretics, antihypertensive drugs (atenolol, carvedilol), sedatives (barbiturates), antispasmodics, psychotropics, anticholinergics, and drugs that may alter the thirst (haloperidol) or sweating mechanism (phenothiazines, antihistamines, anticholinergics), or drugs of abuse (narcotics, PCP[1], methamphetamine, MDMA[2], amphetamines). See Table 4-2 for additional information on proposed mechanisms of action of drugs implicated in intolerance of heat. The use of insulin indicates that the worker is being treated for diabetes. This may result in significant dehydration and poor heat tolerance.

(4) Information about personal habits, including the use of alcohol, illicit drugs, and other social drugs, including caffeine.

(5) Cultural attitude toward heat stress. A misperception may exist that someone can be “hardened” against the requirement for fluids when exposed to heat by deliberately becoming dehydrated before work on a regular basis. This misperception is dangerous and must be counteracted through educational efforts.

b. The direct medical evaluation of the worker should include the following:

(1) Physical examination, with special attention to the cardiovascular, respiratory, nervous, and musculoskeletal systems, and the skin.

(2) Clinical chemistry values needed for clinical assessment, such as fasting blood glucose, blood urea nitrogen, serum creatinine, serum electrolytes (sodium, potassium, chloride, bicarbonate), liver function tests (AST[3], ALT[4]), creatine kinase, hemoglobin, and urinary sugar and protein.

(3) Blood pressure evaluation.

(4) Assessment of the ability of the worker to understand the health and safety hazards of the job, understand the required preventive measures, communicate with fellow workers, and have mobility and orientation capacities to respond properly to emergency situations.

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[1] PCP: phencyclidine
[2] MDMA: 3,4-methylenedioxy-*N*-methylamphetamine
[3] AST: aspartate transaminase
[4] ALT: alanine transaminase

(5) For workers who must wear respiratory protection or other personal protective equipment, pulmonary function testing and/or a submaximal stress electrocardiogram may be appropriate. The physician or other qualified healthcare provider should assess the worker's ability to tolerate the total heat stress of a job, which includes the metabolic burdens of wearing and using protective equipment.

c. More detailed medical evaluation may be deemed appropriate by the responsible healthcare professional. Communication between the physician or other qualified healthcare provider performing the preplacement evaluation and the worker's own healthcare provider may be appropriate.

The following are examples of findings on initial evaluation that may indicate the need for further medical evaluation:

(1) History of myocardial infarction, congestive heart failure, coronary artery disease, obstructive or restrictive pulmonary disease, or current use of certain antihypertensive medications indicating the possibility of reduced maximum cardiac output.

(2) The use of prescribed medications that might interfere with heat tolerance or acclimatization (e.g., diuretics). An alternate therapeutic regimen may be available that would be less likely to compromise the worker's ability to work in a hot environment.

(3) The use of antihypertensive medications that might affect heat tolerance. It may be prudent to monitor blood electrolyte values of workers who follow a salt-restricted diet or who take diuretic medications that affect serum electrolyte levels, especially during the initial phase of acclimatization to heat stress. The use of β-blockers (e.g., atenolol) for the treatment of hypertension may also limit performance on the job.

(4) A history of skin disease, an injury to a large area of the skin, or an impairment of the sweating mechanism that might impair heat elimination via sweat evaporation from the skin, specific evaluation may be advisable. Some people have defective sweating mechanisms (anhidrosis) and therefore are heat intolerant.

(5) Obesity may interfere with heat tolerance (see Chapter 4). An obese individual may require special supervision during the acclimatization period.

7.3.2.2 Periodic Evaluations

All workers in the medical screening program should be provided with periodic follow-up medical examinations by a physician or other qualified health care provider. Evaluations should be conducted at regular intervals and at other times as deemed appropriate for the individual worker by the responsible healthcare professional. Evaluations should be based on data gathered in the initial evaluation, ongoing work history, new or changing symptoms, and when heat exposure change in the workplace. Any worker with signs or symptoms of heat-related illness should be examined immediately and may require more frequent screening and extensive testing. Evaluations should include the following:

(1) An occupational and medical history update, and physical examination focused on the cardiovascular, respiratory, nervous, and musculoskeletal systems and the skin - performed annually.

(2) Consideration of specific medical tests when deemed appropriate by the responsible healthcare professional.

7.3.2.3 Written Reports of Medical Findings

Following each medical evaluation, the physician or other qualified health care provider should give each worker a written report containing the following:

- The results of any medical tests performed on the worker.
- A medical opinion in plain language about any medical condition that would increase the worker's risk of heat-related illness.
- Recommendations for limiting the worker's exposure to heat or hot environments.
- Recommendations for further evaluation and treatment of medical conditions detected.

Following each medical examination, the physician should give the employer a written report specifying the following:

- Occupationally pertinent results of the medical evaluation. A medical opinion as to whether any of the worker's medical conditions is likely to have been caused or aggravated by occupational exposures.
- Recommendations for reducing the worker's risk for heat-related illness, which may include use of cooling measures, accommodations or limitations related to work-rest schedules and/or work load, or reassignment to another job, as warranted.

Specific findings, test results, or diagnoses that have no bearing on the worker's ability to work in heat or a hot environment should not be included in the report to the employer. Safeguards to protect the confidentiality of the worker's medical records should be enforced in accordance with all applicable regulations and guidelines.

7.4 Periodic Evaluation of Data and Surveillance Program

Standardized individual medical screening data should be periodically aggregated and evaluated to identify patterns of worker health that may be linked to work activities and practices that require additional primary prevention efforts (i.e., medical surveillance). This analysis should be performed by a qualified healthcare professional or other knowledgeable person to identify patterns of worker health that may be linked to work activities or exposures. Confidentiality of worker's medical records should be enforced in accordance with all applicable regulations and guidelines.

To ensure that control practices provide adequate protection to workers in hot areas, the worksite physician or other qualified healthcare provider can utilize workplace medical surveillance data, the periodic examination, and an interval history to note any significant within- or between-worker events since the individual worker's previous examination. Such events may include repeated accidents on the job, episodes of heat-related disorders, or frequent absences that could be related to heat. These events may lead the physician or other qualified healthcare provider to suspect overexposure of the worker population (from surveillance data), possible heat intolerance of the individual worker, or the possibility of an aggravating stress in combination with heat, such as exposure to hazardous chemicals or other physical agents. Job-specific clustering of heat-related illnesses or injuries should be followed up by industrial hygiene and medical evaluations of the worksite and workers.

7.5 Employer Actions

The employer should ensure that the qualified health care provider's recommended restriction of a worker's exposure to heat or a hot environment or other workplace hazards is followed, and that the RAL is not exceeded without taking additional protective measures. Efforts to encourage worker participation in the medical screening program and to promptly report any symptoms to the program director are important to the program's success. Medical evaluations performed as part of the medical screening program should be provided by the employer at no cost to the participating workers. Where medical removal or job reassignment is indicated, the affected worker should not suffer loss of wages, benefits, or seniority.

7.6 Considerations Regarding Reproduction

7.6.1 Pregnancy

The medical literature provides limited data on potential risks for pregnant women and fertile women with heavy work and/or added heat stress within the permissible limits (e.g., where t_{re} does not exceed 38°C or 100.4°F; see Chapter 5). However, because the human data are limited and because research data from animal experimentation indicate the possibility of heat-related infertility and teratogenicity, a woman who is pregnant or who may potentially become pregnant should be informed that absolute assurances of safety during the entire period of pregnancy cannot be provided. The worker should be advised to discuss this matter with her own healthcare provider.

7.6.2 Fertility

Heat exposure has been associated with temporary infertility in both females and males, with the effects being more pronounced in the male [Rachootin and Olsen 1983; Levine 1984]. In a study examining the time to pregnancy, the time was significantly prolonged in a subgroup of welders and bakers [Thonneau et al. 1997]. Sperm density, motility, and the percentage of normally shaped sperm can decrease significantly when the temperature of the groin is increased above a normal temperature [Procope 1965; Henderson et al. 1986; Mieusset et al. 1987; Jung and Schuppe 2007]. Available data are insufficient to assure that the REL protects against such effects. Thus, the examining physician should question workers exposed to high heat loads about their reproductive histories.

7.6.3 Teratogenicity and Heat-related Abortion

The consequences of hyperthermia during pregnancy depend on the extent of the temperature elevation, the duration, and the stage of fetal development during the occurrence [Edwards 2006]. The body of experimental evidence reviewed by Lary [1984] indicates that, in the nine species of warm-blooded animals studied, prenatal exposure of the pregnant females to hyperthermia may result in a high incidence of embryo deaths and in gross structural defects, especially of the head and central nervous system (CNS). An elevation of the body temperature of the pregnant female to 39.5°-43°C (103.1°-109.4°F) during the first week or two of gestation (depending on the animal species) resulted in structural and functional maturation defects, especially of the CNS, although other embryonic developmental defects were also found. It appears that some basic developmental processes may be involved, but selective cell death and inhibition of mitosis at critical developmental periods may be primary factors. The hyperthermia in these experimental studies did not appear to have an adverse effect on the pregnant female, but only on the developing embryo. The length of hyperthermia in the studies varied from 10 minutes a day over a 2- to 3-week period to 24 hours a day for 1 or 2 days.

Retrospective epidemiologic studies have associated hyperthermia of a day or less, to a week or more, during the first trimester of pregnancy with birth defects, especially defects in CNS development (e.g., anencephaly) [Lary 1984]. In addition, according to Edwards [2006], a hyperthermic episode during pregnancy can result in embryonic death, abortion, growth retardation, and other defects of development. However, some of the information on hyperthermia's effects on a pregnancy stems from examples of women with fevers, so it is difficult to determine whether defects are caused by metabolic changes in the mother due to the infection [Clarren et al. 1979; Pleet et al. 1981; Edwards 2006].

It is important to monitor the body temperature of a pregnant worker exposed to total heat loads above the REL every hour or so to ensure that the body temperature does not exceed 39°-39.5°C (102°-103°F) during the first trimester of pregnancy.

8. Basis for the Recommended Standard

The research data and information on industry experience that served as the basis for the recommendations for this standard are derived from (a) an analysis of the scientific literature; (b) the many new technologies available for assessing heat stress and strain that are currently available; (c) suggested procedures for predicting risk of incurring heat-related disorders, of potentially unsafe acts, and of deterioration of performance; (d) accepted methods for preventing and controlling heat stress; and (e) domestic and international standards and recommendations for establishing permissible heat-exposure limits.

This chapter includes a discussion of special considerations that heavily influence the form and emphasis of the final recommended criteria for this standard for work in hot environments. See Figures 8.1 for the recommended heat stress alert limits for unacclimatized workers and 8.2 for the recommended heat stress exposure limits for acclimatized workers.

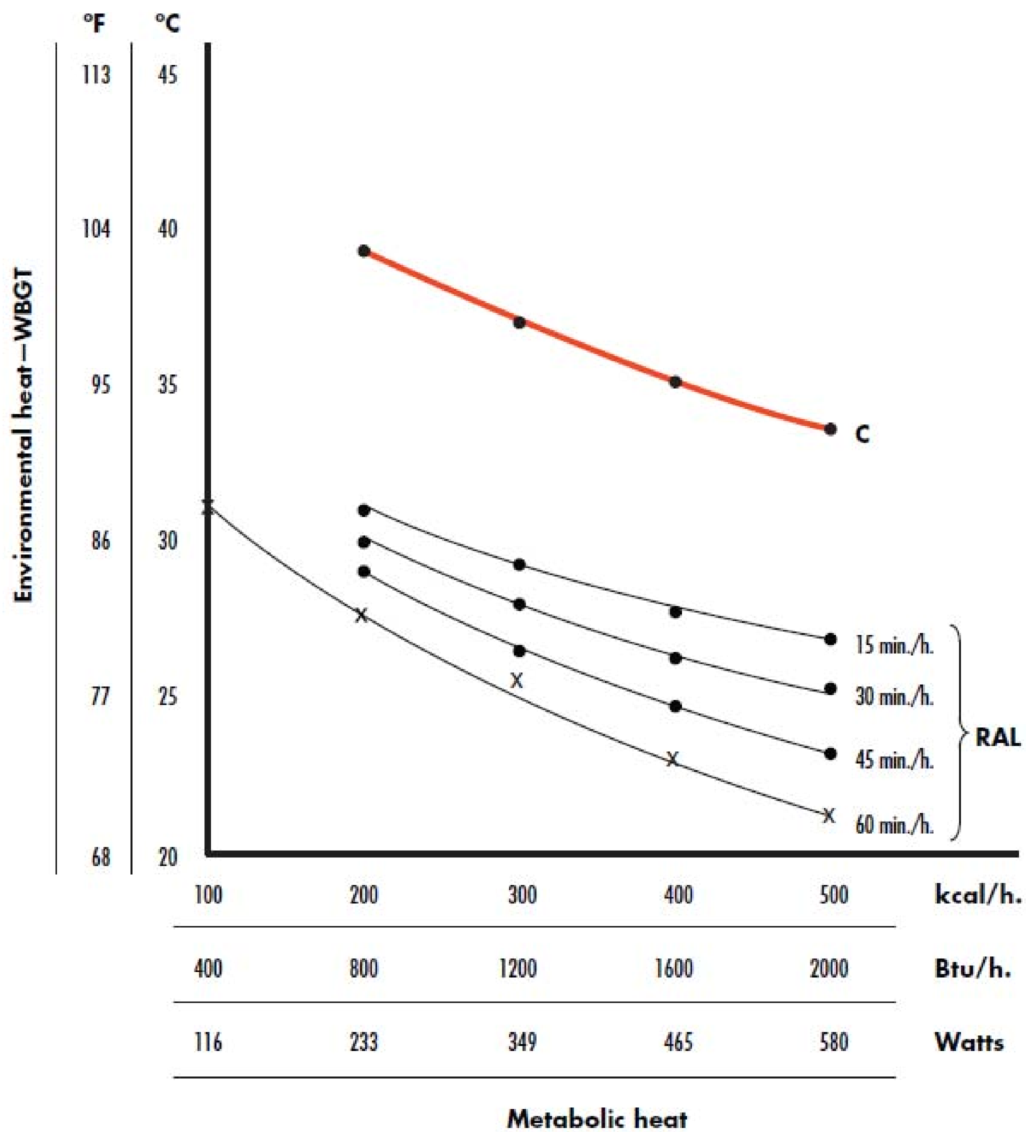


Figure 8.1. Recommended Heat Stress Alert Limits for Unacclimatized Workers
C = Ceiling Limit
RAL = Recommended Alert Limit
*For "standard worker" of 70 kg (154 lbs.) body weight and 1.8 m^2 (19.4 ft^2) body surface
Sources: [Leithead and Lind 1964; Wyndham 1974b; Ramsey 1975; Strydom 1975; ISO 1982a; Spaul and Greenleaf 1984; ACGIH 1985]

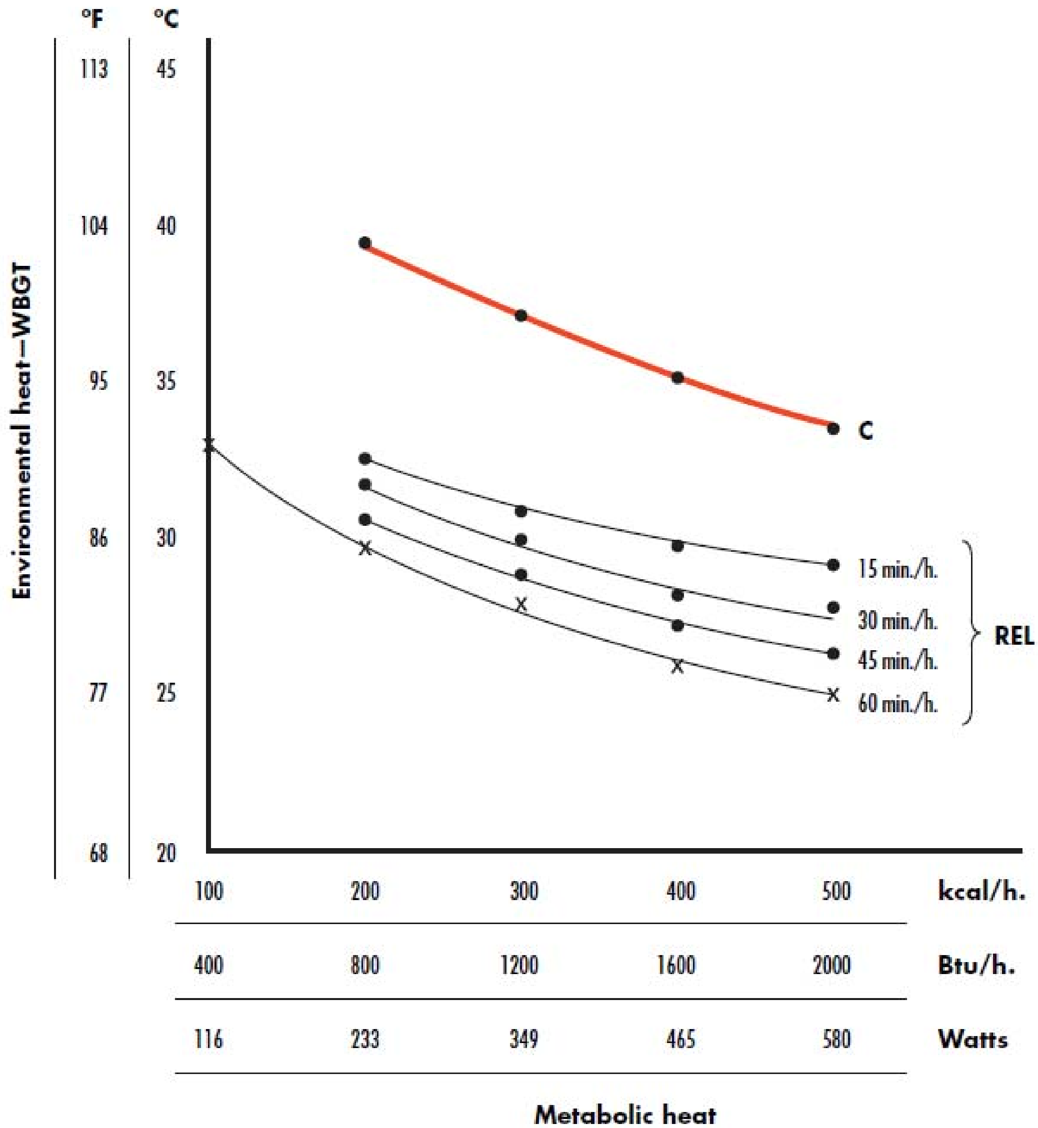


Figure 8.2. Recommended Heat Stress Exposure Limits for Acclimatized Workers
C = Ceiling Limit
REL = Recommended Exposure Limit
*For "standard worker" of 70 kg (154 lbs.) body weight and 1.8 m^2 (19.4 ft^2) body surface
Sources: [Leithead and Lind 1964; Wyndham 1974b; Ramsey 1975; Strydom 1975; ISO 1982a; Spaul and Greenleaf 1984; ACGIH 1985]

8.1 Estimation of Risks

The ultimate objective of a recommended heat-stress standard is to limit the level of health risk (the level of strain and the danger of incurring heat-related illness or injury) associated with the total heat load (environmental and metabolic) imposed on a worker in a hot environment. Risk estimation has become more sophisticated in recent years, but still lacks accuracy. Earlier estimation techniques were usually qualitative or, at best, only semiquantitative.

It is generally estimated that 2/1000 workers are at risk for heat stress and that some occupations (firefighters, agricultural workers, construction workers, forestry workers) confer an even greater risk for occupational exposure to heat stress due to the high physical (metabolic) workloads required to perform the job, as well as exposure to hot environments and the necessity of wearing PPE [Davies et al. 1976; Slappendel et al. 1993; Kirk and Sullman 2001; Parsons 2003; Maeda et al. 2006]. One of the early semiquantitative procedures for estimating the risk of adverse health effects under conditions of heat exposure was designed by Lee and Henschel [1963]. The procedure was based on the known laws of thermodynamics and heat exchange. Although designed for the "standard man" under a standard set of environmental and metabolic conditions, it incorporated correction factors for environmental, metabolic, and worker conditions that differed from standard conditions. A series of graphs were presented that could be used to semiquantitatively predict the percentage of exposed individuals of different levels of physical fitness and age likely to experience health or performance consequences under each of 15 different levels of total stress. Part of the difficulty with early attempts to develop procedures for estimating risk was the lack of sufficient reliable industry-experience data to validate the estimates.

Much empirical data on the relationship between heat stress and strain (including death from heat stroke) in South Africa's deep, hot mines have been accumulated. From laboratory data, a series of curves has been prepared to predict the probability of a worker's body temperature reaching dangerous levels during work under various levels of heat stress [Wyndham and Heyns 1973; Stewart 1979]. Based on these data and epidemiologic data on heat stroke among miners, estimates of probabilities of reaching dangerously high rectal temperatures were made. If a body temperature of 40°C (104°F) is accepted as the threshold temperature at which a worker is in imminent danger of fatal or irreversible heat stroke, then the estimated probability of reaching this body temperature is 10^{-6} for a worker exposed to an effective temperature (ET) of 34.6ºC (94.3ºF), 10^{-4} at 35.3ºC (95.5ºF), 10^{-2} at 35.8ºC (96.4ºF), and $10^{-0.5}$ at 36.6ºC (97.9ºF). If a body temperature of 38.5 to 39.0°C (101.3–102.2°F) is accepted as the critical temperature, then the ET at which the body temperature reaches these values can also be derived for 10^{-1} to 10^{-6} probabilities. These ET correlates were established for conditions with relative humidity near 100%; whether they are equally valid for these same ET values for low humidity has not been determined. Probabilities of body temperature reaching designated levels at various ET values have also been presented for unacclimatized men [Wyndham and Heyns 1973; Strydom 1975; Stewart 1979]. Although these estimates have proven to be useful in preventing heat casualties under the conditions of work and heat found in the South African mines, their direct application to industrial environments in general may not be warranted.

A World Health Organization (WHO) scientific group on health factors involved in working under conditions of heat stress concluded that "it is inadvisable for deep body temperature to exceed 38ºC (100.4ºF) in prolonged daily exposure to heavy work. In closely controlled conditions, the deep body temperature may be allowed to rise to 39ºC (102.2°F)" [WHO 1969]. This does not mean that when a worker's rectal temperature (t_{re}) reaches 38°C (100.4ºF) or even 39°C (102.2ºF), the worker will necessarily become a heat casualty. The physiological response to heat stress (regardless of whether metabolic or environmental) is quite variable in the human population. In fact, it is well documented that many motivated non-elite distance runners complete marathon-style runs with $t_{re} \geq 41$°C (105.8°F) and t_{re} of 41.9°C (107.4°F) have been measured in soccer players without any physical symptoms or lasting sequelae, whereas there are cases in which heat stroke and death have occurred in individuals with body core temperatures less than 40°C running less than 10 km under mild environmental conditions [American College of Sports Medicine 2007; Taylor et al. 2008]. If, however, the t_{re} exceeds 38°C (100.4ºF), the risk of heat casualties increases. The 38ºC (100.4ºF) t_{re}, therefore, has a modest safety margin, which is required because of the degree of accuracy with which the actual environmental and metabolic heat loads are assessed. Therefore, heat injury is determined by both core temperature and symptomology, rather than core temperature alone. Non-thermal contribution to heat injury must also be determined (poor acclimatization, dehydration, alcohol consumption, previous heat injury, age, and drug use) [American College of Sports Medicine 2007; Taylor et al. 2008].

Some safety margin is also justified by the recent finding that the number of unsafe acts committed by a worker increases with an increase in heat stress [Ramsey et al. 1983]. The data, derived by using safety sampling techniques to measure unsafe behavior during work, showed an increase in unsafe behavioral acts with an increase in environmental temperature. The incidence was lowest at WBGTs of 17–23°C (62.6–73.4ºF), whereas a WBGT that exceeds 28°C (82°F) confers the greatest risk of heat stress [American College of Sports Medicine 2007]. Unsafe behavior also increased as the level of physical work of the job increased [Ramsey et al. 1983].

8.2 Correlation between Exposure and Effects

The large amount of data published from controlled laboratory studies and from industrial heat-stress studies upholds the generality that the level of physiologic strain increases with increasing total heat stress (environmental and metabolic) and the length of exposure. All heat-stress/heat-strain indices are based on this relationship. This generally holds for heat-acclimatized and heat-unacclimatized individuals, for women and men, for all age groups, and for individuals with different levels of physical performance capacity and heat tolerance. In each case, differences between individuals or between population groups in the extent of physiologic strain resulting from a given heat stress relate to levels of heat acclimatization and physical work capacity. The individual variability may be large; however, with extreme heat stress, the variability decreases as the limits of the body's systems for physiologic regulation are reached. This constancy of the heat-stress/heat-strain relationship has provided the basic logic for predicting heat-related strain by means of computer programs encompassing the many variables.

Sophisticated models are available to predict physiologic strain as a function of heat load and physical activity and are capable of being modified by a variety of confounding factors. These models range from graphic presentations of relationships to programs for handheld and desk calculators and computers [Witten 1980; Kamon and Ryan 1981]. The strain factors that can be predicted for the average worker are heart rate, body and skin temperature, sweat production and evaporation, skin wettedness, tolerance time, productivity, and required rest allowance. Confounding factors include amount, fit, insulation, and moisture vapor permeability characteristics of the clothing worn, physical work capacity, body hydration, and heat acclimatization. From some of these models, it is possible to predict when and under what conditions the physiologic strain factors will reach or exceed values that are considered acceptable from the standpoint of health.

These models are useful in industry to predict when any combination of stress factors is likely to result in unacceptable levels of strain, which then would require introduction of control and correction procedures to reduce the stress. The regression of heat strain on heat stress is applicable to population groups, and, with the use of a 95% confidence interval, it can be applied as a modified form of risk prediction. However, due to the variability in the human physiological response to heat stress (metabolic and/or environmental), the models do not, as presently designed, provide information on the level of heat stress at which one worker in 10, in 1,000, or in 10,000 will incur heat exhaustion, heat cramps, or heat stroke.

8.3 Physiologic Monitoring of Heat Strain

When the first *NIOSH Criteria for a Recommended Standard: Occupational Exposure to Hot Environments* was published in1972 (and revised in 1986), physiologic monitoring was not considered a viable adjunct to the WBGT index, engineering controls, and work practices for the assessment and control of industrial heat stress. However, by the revised 1986 version, it was proposed that monitoring body temperature and/or the work and recovery heart rate of workers exposed to environmental conditions in excess of the threshold limit values (TLVs) of the American Conference of Governmental Industrial Hygienists (ACGIH) could be a safe and relatively simple approach [Fuller and Smith 1980, 1981; Siconolfi et al. 1985]. All the heat-stress indices assume that, providing the worker population is not exposed to heat-work conditions that exceed the permissible value; most workers will not incur heat-related illnesses or injuries. Inherent in this is the assumption that a small proportion of the workers may become heat casualties. The ACGIH TLV assumes that nearly all healthy heat-acclimatized workers will be protected at heat-stress levels that do not exceed the TLV.

Physiologic monitoring (heart rate and/or oral temperature) of heat strain could help protect all workers, including the heat-intolerant worker exposed at hot worksites. In one field study, the recovery heart rate was taken with the worker seated at the end of a cycle of work from 30 seconds to 1 minute (P_1), 1.5 to 2 minutes (P_2), and 2.5 to 3 minutes (P_3). Oral temperature was measured with a clinical thermometer inserted under the tongue for 4 minutes. The data indicate that, 95% of the time, the oral temperature was below 37.5°C (99.5°F) when the P_1 recovery heart rate was 124 bpm or less, and 50% of the time the oral temperature was below 37.5°C (99.5°F) when the P_1 was less than 145 bpm. From these relationships, a table for assessing heat strain and suggested remedial actions was developed. If the P_3 heart rate is lower than 90 bpm, then the work-heat-stress conditions are satisfactory; if the P_3 approximates 90 bpm and/or the P_1–P_3 recovery is approximately 10 bpm, it indicates that the work level is high but there is little increase in body temperature; if P_3 is greater than 90 bpm and/or P_1–P_3 is less than 10 bpm, it indicates a no-recovery pattern and the heat-work stress exceeds acceptable levels, and corrective actions should be taken to prevent heat injury or illness [Fuller and Smith 1980, 1981]. The corrective actions may be of several types (engineering, work practices, etc.). In spite of the above, recent studies have indicated that body heat is still stored for up to 60 minutes of rest after cessation of work. Although T_{re} decreases, muscle temperature remains elevated, probably due to sequestration of warm blood in the muscle tissue. Therefore, even in recovery, subjects are still under heat stress [Kenny et al. 2008]. This fact must be taken into consideration when any corrective actions (engineering controls, administrative controls, or the use of PPE) are adopted.

Historically, obtaining recovery heart rates at 1- or 2-hour intervals or at the end of several work cycles during the hottest part of the workday of the summer season presented logistical problems, but available advanced technologies allow many of these problems to be overcome. Wearable sensors, capable of continuous monitoring and recording of physiological responses, have been introduced to the market. Probably the most common example is the heart-rate-recording wristwatch, which is used by many joggers and enables continuous automated heart-rate measurements in real time in an accurate and reliable manner. The data obtained from the heart rate-recording wristwatches can also be stored, downloaded onto a computer, and analyzed at a later time. The single-use disposable digital oral thermometer, capable of measuring oral temperatures of workers at regular intervals, makes monitoring of body temperature possible under most industrial situations without interfering with the normal work pattern. It would not be necessary to interrupt work to insert the thermometer under the tongue and to remove it after 4 to 5 minutes. However, ingestion of fluids and mouth breathing would have to be controlled for about 15 minutes before an oral temperature is taken. Moreover, oral temperatures are not the most accurate indicator of body core temperature and may not be practical in the worker that is feeling nauseated or has already vomited.

A more accurate technology, involving ingestible capsules (CorTemp® Ingestible Core Body Temperature Sensor, Palmetto, FL) capable of recording and telemetering intestinal "core" temperature on a continuous basis, has been in use by the research community for ~20 years and may eventually be used occupationally. The problem with ingestible temperature sensing capsules is that they must be ingested the evening before use and only function until passed from the body during defecation. Another drawback is the cost of the capsules and monitoring equipment.

Other sophisticated wearable physiological sensor systems (LifeShirt®, VivoMetics, Ventura, CA) have been or are under development, and one system has been evaluated for its accuracy against standard physiological monitoring systems found in modern laboratories (Coca et al., 2010). A new system, called the Zephyr BioHarness® (Zephyr Bioharness, British Columbia, Canada), has moved from the research arena to commercial application. This device is capable of monitoring heart rate, respiratory rate, skin temperature, ECG, body position, vector magnitude, and R-R interval (the R-R interval is the time between 2 QRS waves in the electrocardiogram in which the R-wave segment of the QRS complex is usually of the greatest magnitude. The time between two R waves correspond to the heart rate). These systems, and others in development, may revolutionize the real-time monitoring of workers in occupations which put them at risk for heat injury.

The obvious advantages of these automated systems would be that data could be immediately observed and trends established from which actions could be initiated to prevent excessive heat strain. The obvious disadvantages are as follows: it requires time to attach the transducers to the worker at the start and remove them at the end of each workday; the transducers for rectal or ear temperature, as well as stick-on electrodes or thermistors, are not acceptable for routine use by some people; and electronic components require careful maintenance for proper operation. Also, the telemetric signals are often disturbed by the electromagnetic fields that may be generated by the manufacturing process. However, recent devices appearing on the market have addressed many of these problems, thus leading the way to the common use of wearable physiological monitoring systems while working in an occupation that exposes the worker to possible heat injury.

8.4 Recommendations of U.S. Organizations and Agencies

8.4.1 The American Conference of Governmental Industrial Hygienists (ACGIH)

The American Conference of Governmental Industrial Hygienists (ACGIH) TLV for heat stress refers to heat stress conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse health effects [ACGIH 2011]. The TLV goal is to maintain core body temperature within +1°C of normal (37°C), although exceptions can be made under certain circumstances [ACGIH 2009]. ACGIH suggests using a decision-making tree to evaluate the risk of heat stress and strain to the worker. The guidance is based on the workers being acclimatized, adequately hydrated, and unmedicated, and that the healthy worker can be repeatedly exposed without adverse health effects. In addition, there is Action Limit guidance which is designed to be protective to unacclimatized workers.

Those workers who are more tolerant of working in the heat and are under medical supervision may work under heat stress conditions that exceed the TLV, but in no instance should the deep body temperature exceed the 38°C (100.4°F) limit for an extended period. However, acclimatized workers may be able to work safely under supervision with a core body temperature not to exceed 38.5°C (101.3 °F). The TLV permissible heat-exposure values consider both the environmental heat factors and metabolic heat production. The environmental factors are expressed as the WBGT. ACGIH provides instructions for adjusting the WBGT values based on clothing type. The worker's metabolic heat production is expressed as work-load category: light work = <180 kcal/h; moderate work = 180-300 kcal/h; heavy work = 300-415kcal/h; and very heavy work = > 520 kcal/h.

Along with the metabolic heat production, work demands need to be considered using a table that includes WBGT values for 100% work, 75% work/25% rest, 50% work/50% rest, and 25% work/75% rest. If work demands vary, or work and rest environments are different, a TWA should be calculated.

There is additional guidance for limiting heat strain and for heat stress management. This guidance includes: monitoring heart rate, core body temperature, heat stress-related symptoms, profuse sweating rates, and weight loss; and having general and job-specific controls in place.

8.4.2 Occupational Safety and Health Administration (OSHA)

Standards Advisory Committee on Heat Stress (SACHS)

In January 1973, the Assistant Secretary of Labor for OSHA appointed a Standards Advisory Committee on Heat Stress (SACHS) to conduct an in-depth review and evaluation of the *NIOSH Criteria for a Recommended Standard.... Occupational Exposure to Hot Environments* and to develop a proposed standard that would establish work practices to minimize the effects of hot environmental conditions on workers [Ramsey 1975]. The purpose of the standard was to minimize the risk of heat-related illnesses to exposed workers. The 15 committee members represented worker, employer, state, federal, and professional groups.

The recommendations for a heat-stress standard were derived by the SACHS by majority vote on each statement. Any statement which was disapproved by an overwhelming majority of the members was excluded from the recommendations. The recommendations established the threshold Wet Bulb Globe Temperature (WBGT) values for continuous exposure at three levels of physical work: light, <200 kcal/h (<800 Btu/h), 30°C (86°F); moderate, 200–300 kcal/h (804–1200 Btu/h), 27.8°C (82°F); and heavy, >300 kcal/h (>1200 Btu/h), 26.1°C (79°F), with low air velocities up to 300 fpm. These values were similar to the ACGIH TLVs at the time. When the air velocity exceeds 300 fpm, the threshold WBGT values are increased 2.2°C (4°F) for light work and 2.8°C (5°F) for moderate and heavy work. The logic behind this recommendation was that the instruments used for measuring the WBGT index did not satisfactorily reflect the advantage gained by the worker when air velocity is increased beyond 300 fpm, therefore a higher threshold WBGT was sufficient to protect workers from heat exposure. Data presented by Kamon et al. [1979]questioned this assumption, because the clothing worn by the worker reduced the cooling effect of increased air velocity. However, under conditions in which heavy protective clothing or clothing with reduced air and/or vapor permeability is worn, higher air velocities may, to a limited extent, facilitate air penetration of the clothing and enhance convective and evaporative heat transfer. A modern WBGT with appropriate anemometry measurements could be used to take air velocity into account for this purpose.

The SACHS recommendations contained a list of work practices that were to be initiated whenever the environmental conditions and work load exceed the threshold WBGT values based on a 120-minute TWA. Also included were directions for medical surveillance, training of workers, and workplace monitoring. The threshold WBGT values recommended by the OSHA SACHS were in substantial agreement with the ACGIH TLVs at the time and the ISO standard. The OSHA SACHS recommendations have not been promulgated into an OSHA heat-stress standard.

In 2011, OSHA and NIOSH cobranded an infosheet on protecting workers from heat-related illness. This document included risk factors, health problems, first aid, and prevention. Since 2011, OSHA has launched a nationwide education and outreach campaign (i.e., Heat Illness Prevention Campaign) every summer to raise awareness and educate workers and employers about the hazards of working in the heat and preventing heat-related illnesses. OSHA worked with California OSHA (Cal/OSHA) and adapted many of that state's campaign materials for national purposes. Many of these materials target at-risk populations, and those with limited English proficiency. OSHA has also partnered with the National Oceanic and Atmospheric Administration (NOAA) to include worker safety precautions when excessive heat watch, warning, and advisories are issued [OSHA-NIOSH 2011; OSHA 2012b]. A smart phone downloadable application was developed by OSHA to provide a way for employers or workers to calculate the heat index based on current location and view risk levels as well as protective measures [OSHA 2012a]. OSHA has also been making efforts to utilize social media to spread the life-saving message of Water. Rest. Shade. OSHA continues to reach out to state and local partners, national and local conferences, consultation programs, employers, trade associations, unions, community and faith based organizations, consulates, universities, and health care and safety professionals.

8.4.2.1 Cal/OSHA

In 2005, the California Standards Board put into effect emergency heat regulations based on a Cal/OSHA investigation. Cal/OSHA drafted the Heat Illness Prevention standard in collaboration with the Labor and Workforce Development Agency, worker and employer communities, the Standards Board, and other interested parties; and in 2006, the state of California adopted the heat stress standard [Wilson 2008]. The standard (Title 8, Chapter 4, § 3395, Heat Illness Prevention) applies to all outdoor places of employment and addresses: (1) access to potable drinking water, (2) access to shade, (3) high heat procedures, and (4) employee and supervisor training. Concerns over the Cal/OSHA standard have included a lack of heat stress threshold that accounts for humidity and lack of mandatory rest breaks.

In 2010, Cal/OSHA used a heat-related illness prevention campaign to target low wage, non-English speaking, outdoor workers to reduce heat-related illnesses and fatalities. The campaign included media ads, radio spots, promotional items, posters, DVDs, postcards, training kits, and community and employer outreach and training. A subsequent evaluation of the campaign concluded that a sustained effort is needed in order to achieve long-term behavior change. Enforcement, as well as education, is important to have an enduring impact and change longstanding attitudes and cultural norms [Cal/OSHA 2010]. In addition, the report concluded that many immigrant workers are afraid of contacting government agencies about hazards at work, so Cal/OSHA is looking at making a hotline available using community members to handle phone calls. Cal/OSHA launched another campaign in 2012 to prevent worker deaths and illnesses due to heat exposure in all outdoor workplaces in California.

8.4.2.2 Washington State Department of Labor and Industries

In 2008, Washington State Department of Labor and Industries filed the Outdoor Heat Exposure Rule, WAC 296-62-095. The rule applies to all employers with employees performing work in an outdoor environment from May 1 through September 30 annually. The rule also stipulates this is only if employees are exposed to temperatures at or above 89°F, wearing double-layer woven clothes (e.g., coveralls, jackets, and sweatshirts) in temperatures at or above 77°F, or wearing nonbreathing clothes (e.g., vapor barrier clothing or PPE such as chemical resistant suits) in temperatures at or above 52°F [Washington State Legislature].

The Outdoor Heat Exposure Rule states that an outdoor heat exposure safety program must be addressed in the employer's written accident prevention program. Employers must also encourage their workers to drink water or other acceptable beverages, and must provide at least 1 quart of water per hour for each employee. Employers must also relieve from duty any workers showing signs or symptoms of heat-related illness, and provide a sufficient means to reduce their body temperature. The rule also states the necessity of appropriate training being provided to workers prior to beginning work in excessive heat, as well as the need for appropriate training of supervisors.

8.4.3 American Industrial Hygiene Association (AIHA)

AIHA states that the best way to protect workers from the stresses of thermal environments is to help workers and supervisors understand the fundamentals of thermoregulation and exposure control [AIHA 2003]. AIHA's *The Occupational Environment: Its Evaluation, Control, and Management* [AIHA 2003] contains a thorough overview of many of the heat exposure limits available, including WBGT recommendations, time-weighted averages, NIOSH recommendations, ACGIH TLVs, and ISO recommendations. AIHA's comparison of the different recommendations finds that, when metabolic heat assumptions and threshold limit proposals are compared, a pattern of consistency is observed: resting, 32-33°C; light, 30°C; moderate, 27-28°C; heavy, 25-26°C; and very heavy, 23-25°C. See Table 5-1. In conclusion, AIHA finds that the WBGT threshold values are basically equivalent.

8.4.4 The Armed Services

The 2003 publication (TBMED 507/AFPAM 48-52 (I)), entitled *Heat Stress Control and Heat Casualty Management*, addresses, in detail, the procedures for the assessment, measurement, evaluation, and control of heat stress and the recognition, prevention, and treatment of heat-related illnesses and injuries [DOD 2003]. The document may be applicable to many industrial- and outdoor worker-type settings. The WBGT index is used for the measurement and assessment of the environmental heat load.

The Navy Environmental Health Center developed a technical manual (NEHC-TM-OEM 6260.6A) entitled *Prevention and Treatment of Heat and Cold Stress Injuries* [DOD 2007]. This document includes information on risk factors, hydration status, heat stress injuries, treatment, and follow-up. Like the 2003 publication mentioned above, this document uses the WBGT index.

In addition, both TBMED 507/AFPAM 48-52 and NEHC-TM-OEM 6260.6A include examples of water intake tables based on WBGT, level of work, and the number of minutes worked or the work-rest schedule (see Table 8-1).

Table 8-1: Recommendations for fluid replacement during warm weather conditions

WBGT Index (°F)	Easy Work (250 W)		Moderate Work (425 W)		Hard Work (600 W)	
	Work/Rest (min)	**Water Intake[1] (qt/hr)**	**Work/Rest (min)**	**Water Intake (qt/hr)**	**Work/Rest (min)**	**Water Intake (qt/hr)**
78-81.9	Unlimited	0.5	Unlimited	0.75	40/20	0.75

82-84.9	Unlimited	0.5	50/10	0.75	30/30	1.0
85-87.9	Unlimited	0.75	40/20	0.75	30/30	1.0
88-89.9	Unlimited	0.75	30/30	0.75	20/40	1.0
90+	50/10	1.0	20/40	1.0	10/50	1.0

[1] Fluid needs can vary based on individual differences (± 0.25 qt/hr) and exposure to full sun or full shade (± 0.25 qt/hr).
Rest = sitting or standing, in the shade if possible.
Individual water needs vary by 0.25 quarts/hour.
Fluid intake should not exceed 1.5 quarts/hour; daily fluid intake generally should not exceed 12 quarts (note: this is not to suggest limiting fluid intake by highly conditioned persons, who may require greater than 12 quarts daily).
Adapted from DOD [2007].

8.4.5 American College of Sports Medicine (ACSM)

In 2007, the American College of Sports Medicine (ACSM) published a revised position statement, *Exertional Heat Illness during Training and Competition* [American College of Sports Medicine 2007]. To be competitive, the long distance runner must be in excellent physical condition, exceeding the physical fitness of most industrial workers. For long distance races, such as the marathon, the fastest competitors run at 12 to 15 miles per hour, which must be classified as extremely hard physical work. When the thermal environment reaches even moderate levels, overheating can be a problem.

To reduce the risk of heat-related injuries and illnesses, the ACSM has prepared a list of recommendations to serve as advisory guidelines to be followed during distance running when the environmental heat load exceeds specific values. These recommendations include the following: (1) races of 10 km or longer should not be conducted when the WBGT exceeds 28°C (82.4°F); (2) all summer events should be scheduled for early morning, ideally before 8 a.m., or after 6 p.m.; (3) race sponsors must provide fluids; (4) runners should be encouraged to drink 300–360 mL of fluids 10 to 15 minutes before the race; (5) fluid ingestion at frequent intervals during the race should be permitted, with water stations at 2- to 3-km intervals for races 10 km or longer, and runners should be encouraged to drink 100–200 mL at each water station; (6) runners should be instructed on recognition of early signs and symptoms of heat-related illness; and (7) provisions should be made for the care of heat-related illness cases.

In these recommendations, the WBGT is the heat-stress index of choice. The "red flag" high-risk WBGT index value of 23°–28°C (73.4°–82.4°F) would indicate that all runners must be aware that heat injury is possible, and any person particularly sensitive to heat or humidity should probably not run. An "amber flag" indicates moderate risk with a WBGT of 18°–23°C (64.4°–73.4°F). It is assumed that the air temperature, humidity, and solar radiation are likely to increase during the day.

8.5 International and Foreign Standards and Recommendations

Several nations have developed and published standards, recommendations, and guidelines for limiting the exposure of workers to potentially harmful levels of occupational heat stress. These documents range from official national position standards to unofficial suggested practices and procedures and to unofficially sanctioned guidelines proposed by institutions, research groups, or individuals concerned with the health and safety of workers under conditions of high heat load. Most of these documents have in common the use of (1) the WBGT as the index for expressing the environmental heat load and (2) some method for estimating and expressing the metabolic heat production. The permissible total heat load is then expressed as a WBGT value for all levels of physical work, ranging from resting to very heavy work.

8.5.1 The International Organization for Standardization (ISO)

As of 2012, the International Organization for Standardization (ISO) has members from 164 countries that develop standards using a consensus–based approach. ISO standards are developed through a multi-stakeholder process with technical committees created from industry experts, consumer associations, academia, non-government organizations, and governments [International Organization for Standardization 2012].

8.5.1.1 ISO 7243

In 1989, the ISO revised ISO 7243: *Hot environments—Estimation of heat stress on working man, based on the WBGT-index (wet bulb globe temperature)* [ISO 1989]. ISO 7243 can be used to assess a hot environment with a simple method based on the WBGT. It can easily be used in an industrial environment for evaluating the stresses on an individual [ISO 1989].

The ISO standard index values are based on the assumption, as are most other recommended heat-stress limit values, that the worker is a normal healthy individual, physically fit for the level of activity being done, and wearing standard summer-weight work clothing with a thermal insulation value of about 0.6 clo (not including the still-air-layer insulation).

The environmental measurements specified in the ISO standard for the calculation of the WBGT are (1) air temperature, (2) natural wet bulb temperature, and (3) black globe temperature. From these, WBGT index values can be calculated or can be obtained as a direct integrated reading with some types of environmental measuring instruments. The measurements must, of course, be made at the place and time of the worker's exposure.

8.5.1.2 ISO 7933

ISO 7933: Ergonomics of the thermal environment -- Analytical determination and interpretation of heat stress using calculation of the predicted heat strain describes a method for predicting the sweat rate and the internal core temperature that the human body will develop in response to the working conditions [ISO 2004b]. The main objectives of ISO 7933:2004 include (1) the evaluation of the thermal stress in conditions likely to lead to excessive core temperature increase or water loss for the standard subject, and (2) the determination of exposure times with which the physiological strain is acceptable (no physical damage is to be expected).

8.5.1.3 ISO 8996

ISO 8996: Ergonomics of the thermal environment – Determination of metabolic heat, last revised in 2004, specifies methods for determining the metabolic rate in a working environment, assessing working practices, and determining the energetic cost of a job or activity [ISO 2004c].

8.5.1.5 ISO 9886

ISO 9886: Ergonomics -- Evaluation of thermal strain by physiological measurements describes methods for measuring the physiological strain on humans by considering four parameters [ISO 2004a]. ISO 9886 provides the principles and practical guidance for measuring body core temperature, skin temperatures, heart rate, and body mass loss.

8.5.1.6 ISO 9920

ISO 9920: Ergonomics of the thermal environment -- Estimation of thermal insulation and water vapour resistance of a clothing ensemble specifies methods for estimating the thermal characteristics (resistance to dry heat loss and evaporative heat loss) for a clothing ensemble based on values for known garments, ensembles and textiles [ISO 2007].

8.5.2 Canada

The Canadian Centre for Occupational Health and Safety uses two types of exposure limits: occupational exposure limits to protect industrial workers, and thermal comfort limits to protect office workers. Some Canadian jurisdictions have adopted ACGIH TLVs as occupational exposure limits and others use them as guidelines to control heat stress in the workplace. Thermal comfort limits are set using the CSA Standard CAN/CSA Z412-00 (R2005) - "Office Ergonomics" which gives acceptable ranges of temperature and relative humidity for offices [Canadian Centre for Occupational Health and Safety 2011]. In addition to the standards, Health Canada, concerned with the changing climate and longer, more intense heat events, has been developing extreme heat event-related materials to educate and raise awareness among workers and the general public.

8.5.3 Japan

In Japan, the Society for Occupational Health decides the heat and cold stress threshold limit values, and the thermal standard for offices is decided by the Ministry of Health, Labor and Welfare [Tanaka 2007]. These standards are based on acclimatized, healthy male workers who wore normal working clothes for summer, and drank adequate salt water (salt concentration of around 0.1%). The working period was either continuous for one hour or intermittent for two hours.

Table 8-2: Occupational exposure limits for heat stress in Japan

Work Load	OELs	
	WBGT (°C)	CET[B] (°C)
RMR[A] –1 (Very light, -130 kcal/h)	32.5	31.6
RMR –2 (Light, -190 kcal/h)	30.5	30.0
RMR –3 (Moderate, –250 kcal/h)	29.0	28.8
RMR –4 (Moderate, –310 kcal/h)	27.5	27.6
RMR –5 (Heavy, –370 kcal/h)	26.5	27.0

[A] Relative Metabolic Rate (RMR) = (Metabolic energy expenditure during work – Metabolic energy expenditure at rest)/Basal metabolic rate corresponding to the work period
[B] Corrected effective temperature
Adapted from Japan Society for Occupational Health [Japan Society for Occupational Health 2005] and Tanaka [2007].

9. Indices for Assessing Heat Stress and Strain

During the past 75 years, several schemes have been devised for assessing and/or predicting the level of heat stress and/or strain that a worker might experience when working at hot industrial jobs. Some are based on the measurements of a single environmental factor (wet bulb), while others incorporate all of the important environmental factors (dry bulb, wet bulb, and mean radiant temperatures and air velocity). For all of the indices, either the level of metabolic heat production is directly incorporated into the index or the acceptable level of index values varies as a function of metabolic heat production.

To have industrial application, an index must, at a minimum, meet the following criteria:

- Feasibility and accuracy must be proven with use.
- All important factors (environmental, metabolic, clothing, physical condition, etc.) must be considered.
- Required measurements and calculations must be simple.
- The measuring instruments and techniques applied should result in data which truly reflect the worker's exposure but do not interfere with the worker's performance.
- Index exposure limits must be supported by corresponding physiologic and/or psychological responses which reflect an increased risk to safety and health.
- It must be applicable for setting limits under a wide range of environmental and metabolic conditions.

The measurements required, advantages, disadvantages, and applicability to routine industrial use of some of the more frequently used heat-stress/heat-strain indices will be discussed under the following categories: (1) Direct Indices, (2) Rational Indices, (3) Empirical Indices, and (4) Physiological Monitoring.

9.1 Direct Indices

9.1.1 Dry Bulb Temperature

The dry bulb temperature (t_a) is commonly used for estimating comfort conditions for sedentary people wearing conventional indoor clothing (1.4 clo including the surface air layer). With light air movement and relative humidity of 20 to 60%, air temperatures of 22°-25.5ºC (71.6-77.9ºF) are considered comfortable by most people. If work intensity is increased to moderate or heavy work, the comfort air temperature is decreased about 1.7ºC (3ºF) for each 25 kcal (100 Btu or 29 W) increase in the hourly metabolic heat production. Conversely, if the air temperature and/or the metabolic heat production are progressively increased above the comfort zone, the level of heat stress and heat strain will increase.

Dry bulb temperature is easily measured, but its use when the temperature is above the comfort zone is not justified, except for work situations where the worker is wearing completely vapor- and air-impermeable encapsulating protective clothing. Even under these conditions, appropriate adjustments must be made when significant solar and long wave radiation are present [Goldman 1981].

9.1.2 Wet Bulb Temperature

The psychrometric wet bulb temperature (t_{wb}) may be an appropriate index for assessing heat stress and predicting heat strain under conditions where radiant temperature and air velocity are not large factors and where t_{wb} approximates t_a (high humidities). For normally clothed individuals at low air velocities, a wet bulb temperature of about 30°C (86°F) is the upper limit for unimpaired performance on sedentary tasks and 28°C (82.4°F is the upper limit) for moderate levels of physical work. As t_{wb} increases above these threshold values, performance deteriorates and accidents increase. The wet bulb temperatures under these hot, humid conditions have been used to predict risk of heat stroke occurring in South African and German mines [Stewart 1979].

Wet bulb temperature is easy to measure in industry with a sling or aspirated psychrometer, and it should be applicable in any hot, humid situation where t_{wb} approaches skin temperature, radiant heat load is minimal, and air velocity is light.

9.2 Rational Indices

9.2.1 Operative Temperature

The operative temperature (t_o) expresses the heat exchange between a worker and the environment by radiation and convection in a uniform environment as it would occur in an actual industrial environment. The t_o can be derived from the heat-balance equation where the combined convection and radiation coefficient is defined as the weighted sum of the radiation and convection heat-transfer coefficients, and it can be used directly to calculate heat exchange by radiation and convection. The t_o considers the intrinsic thermal efficiency of the clothing. Skin temperature must be measured or assumed. The t_o presents several difficulties. For convective heat exchange, a measure of air velocity is necessary. Not included are the important factors of humidity and metabolic heat production. These omissions make its applicability to routine industrial use somewhat limited.

9.2.2 Belding-Hatch Heat-Stress Index

The Belding and Hatch Heat-Stress Index (HSI) [Belding and Hatch 1955] has had wide use in laboratory and field studies of heat stress. One of its most useful features is the table of physiologic and psychologic consequences of an 8-hour exposure at a range of HSI values. The HSI is essentially a derivation of the heat-balance equation that includes the environmental and metabolic factors. It is the ratio (times 100) of the amount of body heat that is required to be lost to the environment by evaporation for thermal equilibrium (E_{re}) divided by the maximum amount of sweat evaporation allowed through the clothing system that can be accepted by the environment (E_{max}). It assumes that a sweat rate of about one liter per hour over an 8-hour day can be achieved by the average, healthy worker without harmful effects. This assumption, however, lacks epidemiologic proof. In fact, there are data that indicate that a permissible eight liters per 8-hour day of sweat production is too high and, as the 8-hour sweat production exceeds five liters, workers will dehydrate more than 1.5% of the body weight, thereby increasing the risk of heat-related illness and injuries. The graphic solution of the HSI which has been developed assumes a 35°C (95°F) skin temperature and a conventional long-sleeved shirt and trouser ensemble. The worker is assumed to be in good health and acclimatized to the average level of daily heat exposure.

The HSI is not applicable at very high heat-stress conditions. It also does not identify correctly the heat-stress differences resulting from hot and dry or hot and humid conditions. The strain resulting from metabolic vs. environmental heat is not differentiated. Because E_{req}/E_{max} is a ratio, the absolute values of the two factors are not addressed, i.e., the ratio for an E_{reg} and E_{max} of 300 or 500 or 1,000 each would be the same (100); yet the strain would be expected to be greater at the higher E_{req} and E_{max} values.

The environmental measurements require data on air velocity which provide, at best, an approximation under industrial work situations; in addition, t_a, $t_{wb,}$ and t_r must be measured. Metabolic heat production must also be measured or estimated. The measurements are, therefore, difficult and/or time-consuming, which limits the application of the HSI as a field monitoring technique.

The heat transfer coefficients used in the original HSI have been revised by McKarns and Brief as a result of observations on clothed subjects [McKarns and Brief 1966]. Their modification of the HSI nomograph facilitates the practical use of the index, particularly for the analysis of factors contributing to the heat stress. The McKarns and Brief modification also permits the calculation of allowable exposure time and rest allowances at different combinations of environmental and metabolic heat loads; however, the accuracy of these calculations is affected by the limitations of the index mentioned above. HSI programs for a programmable handheld calculator are available.

9.2.3 Skin Wettedness (%SWA)

Several of the rational heat-stress indices are based on the concept that, in addition to the sweat production required for temperature equilibrium (E_{req}) and the maximum amount of sweat that can be evaporated (E_{max}), the efficiency of sweat evaporation will also affect heat strain. The less efficient the evaporation, the greater will be the body surface area that has to be wetted with sweat to maintain the required evaporative heat transfer; the ratio of wetted to nonwetted skin area times 100% (SWA = E_{req}/E_{max}).

This concept of wettedness gives new meaning to the E_{req}/E_{max} ratio as an indicator of strain under conditions of high humidity and low air movement where evaporation is restricted [Goldman 1973, 1978; Gonzalez et al. 1978; Candas et al. 1979; Kamon and Avellini 1979; ISO 1982b]. The skin wettedness indices consider the variables basic to heat balance (air temperature, humidity, air movement, radiative heat, metabolic heat, and clothing characteristics) and require that these variables be measured or calculated for each industrial situation where an index will be applied. These measurement requirements introduce exacting and time-consuming procedures. In addition, wind speed at the worksite is difficult to measure with any degree of reliability; at best, it can generally be only an approximation. These indices are satisfactory as a basis for calculating the magnitude of thermal stress and strain and for recommending engineering and work practice controls; however, as procedures for routine environmental monitoring, they are too complicated, require considerable recording equipment, and are time-consuming.

9.3 Empirical Indices

Some of the earlier and most widely used heat-stress indices are those based upon objective and subjective strain response data obtained from individuals and groups of individuals exposed to various levels and combinations of environmental and metabolic heat-stress factors.

9.3.1 The Effective Temperature (ET, CET, and ET*)

The effective temperature (ET) index is the first and, until recently, the most widely used of the heat-stress indices. The ET combines dry bulb and wet bulb temperatures and air velocity. In a later version of the ET, the Corrected Effective Temperature (CET), the black globe temperature (t_g) is used instead of t_a to take the effect of radiant heating into account. The index values for both the ET and the CET were derived from subjective impressions of equivalent heat loads between a reference chamber at 100% humidity and low air motion and an exposure chamber where the temperature and air motion were higher and the humidity lower. The recently developed new effective temperature (ET*) uses 50% reference in place of the 100% reference rh for the ET and CET. The ET* has all the limitations of the rational heat-stress indices mentioned previously; however, it is useful for calculating ventilation or air-conditioning requirements for maintaining acceptable conditions in buildings.

The ET and CET have been used in studies of physical, psychomotor, and mental performance changes as a result of heat stress. In general, performance and productivity decrease as the ET or CET exceed about 30°C (86°F). The World Health Organization has recommended as unacceptable for heat-unacclimatized individuals values that exceed 30°C (86°F) for sedentary activities, 28°C (82.4°F) for moderate work, and 25.5°C (79.7°F) for hard work. For the fully heat-acclimatized individuals, the tolerable limits are increased about 2°C (3.5ºF).

The data on which the original ET was based came from studies on sedentary subjects exposed to several combinations of t_a, t_{wb}, and V_a, all of which approximated or slightly exceeded comfort conditions. The responses measured were subjective impressions of comfort or equal sensations of heat which may or may not be directly related to values of physiologic or psychologic strain. In addition, the sensations were the responses to transient changes. The extrapolation of the data to various amounts of metabolic heat production has been based on industrial experience. The ET and CET have been criticized on the basis that they seem to overestimate the effects of high humidity and underestimate the effects of air motion and thus tend to overestimate the heat stress.

In the hot, humid mines of South Africa, heat-acclimatized workers doing hard physical work showed a decrease in productivity beginning at ET of 27.7ºC (81.9°F) (at 100% rh with minimal air motion), which is approximately the reported threshold for the onset of fatal heat stroke during hard work [Wyndham 1974a; Strydom 1975]. These observations lend credence to the usefulness of the ET or CET as a heat-stress index in mines and other places where the humidity is high and the radiant heat load is low.

The limitations of ET have led to the development of the concept of the four-hour sweat rate (P4SR). The P4SR was developed in environmental chambers at the National Hospital for Nervous Diseases in London and formally evaluated in Singapore for seven years (summarized by [Macpherson 1960; Parsons 2003]). The P4SR is the approximate amount of sweat excreted by presumably healthy young men acclimatized to a particular environment for a duration of four hours. This value is used as an index value of sweating, but not as a predictor of the specific amount of sweat produced by a group of subjects. The P4SR is, therefore, an empirical index or measure that can be obtained by the following steps:

If $t_g \neq t_a$ then increase the wet bulb temperature by 0.4 ($t_g - t_a$) °C.

If the metabolic rate M > 63 Wm^{-2}, then increase the wet bulb temperature by the amount indicated in a special nomogram.

If the subjects are clothed, increase the wet bulb temperature by 1.5 I_{clo} (°C).

These modifications are additive. Thus the basic four-hour sweat rate (B4SR) is determined from a nomogram developed from this analysis. From this, the nomogram is used to calculate P4SR.

Since it was determined that the sweat rate outside the prescriptive zone was not an adequate indicator of heat strain, the P4SR has been used to make adjustments to account for this inadequate level of prediction of heat strain. Although useful for the defined conditions, the applicability of P4SR is limited in many industrial settings since the effects of clothing on heat stress are oversimplified. Therefore, the P4SR is most useful as a heat storage index [Parsons 2003].

9.3.2 The Wet Bulb Globe Temperature (WBGT)

The Wet Bulb Globe Temperature (WBGT) index was developed in 1957 as a basis for environmental heat-stress monitoring to control heat casualties at military training camps. It has the advantages that the measurements are few and easy to make; the instrumentation is simple, relatively inexpensive, and rugged; and the calculations of the index are straightforward. The data obtained from the WBGT can be collected as a continuous recording by a Squirril data logging system (Grant Instruments, Ltd., Cambridgeshire, UK) [Åstrand et al. 2003]. For indoor use, only two measurements are needed: natural wet bulb and black globe temperatures (dry heat). For outdoors in sunshine, the air temperature must also be measured.

The calculation of the WBGT for indoors is:

$$\mathrm{WBGT} = 0.7t_{nwb} + 0.3t_g$$

The calculation of the WBGT for outdoors is:

$$\mathrm{WBGT} = 0.7t_{nwb} + 0.2t_g + 0.1t_a$$

The WBGT combines the effect of humidity and air movement (in t_{nwb}), air temperature and radiation (in t_g), and air temperature (t_a) as a factor in outdoor situations in the presence of sunshine. If there is no radiant heat load (no sunshine), the t_g reflects the effects of air velocity and air temperature. WBGT measuring instruments are commercially available which give t_a, t_{nwb}, and t_g separately or as an integrated WBGT in a form for digital readouts. A printer can be attached to provide tape printouts at selected time intervals for WBGT, t_a, t_{nwb}, V_a, and t_g values.

The application of the WBGT index for determining training schedules for military recruits during the summer season has resulted in a striking reduction in heat casualties [Minard 1961]. This dramatic control of heat casualty incidence stimulated its application to hot industrial situations.

In 1972, the first NIOSH *Criteria for a Recommended Standard.... Occupational Exposure to Hot Environments* [NIOSH 1972] recommended the use of the WBGT index for monitoring industrial heat stress. The rationale for choosing the WBGT and the basis for the recommended guideline values was described in 1973 [Dukes-Dobos and Henschel 1973]. The WBGT was used as the index for expressing environmental heat load in the ACGIH TLVs - Heat Stress adopted in 1974 [ACGIH 1985]. Since then, the WBGT has become the index most frequently used and recommended for use throughout the world, including its use in the International Standards Organization document *Hot Environments-Estimation of Heat Stress on Working Man*

Based on the WBGT Index (Wet Bulb Globe Temperature) 1982 [ISO 1982a] (see Chapter 9 Basis for the Recommended Standard for further discussion of the adoption of the WBGT as the recommended heat stress index). However, when impermeable clothing is worn, the WBGT will not be a relevant index because evaporative cooling (wet bulb temperature) will be limited. The air temperature or adjusted dry bulb temperature is the pertinent factor.

The WBGT index meets the criteria of a heat stress index that are listed earlier in this chapter. In addition to the WBGT TLVs for continuous work in a hot environment, recommendations have also been made for limiting WBGT heat stress when 25, 50, and 75% of each working hour is at rest (ACGIH-TLVs, OSHA-SACHS, AIHA). Regulating work time in the heat (allowable exposure time) is a viable alternative technique for permitting necessary work to continue under heat-stress conditions that would be intolerable for continuous exposure.

9.3.3 Wet Globe Temperature (WGT)

Next to the t_a and t_{wb}, the wet globe thermometer (Botsball) is the simplest, most easily read, and most portable of the environmental measuring devices. The wet globe thermometer consists of a hollow 3-inch copper sphere covered by a black cloth which is kept at 100% wettedness from a water reservoir. The sensing element of a thermometer is located at the inside center of the copper sphere, and the temperature inside the sphere is read on a dial on the end of the stem.

Presumably, the wet sphere exchanges heat with the environment by the same mechanisms that a nude man with a totally wetted skin would in the same environment; that is, heat exchange by convection, radiation, and evaporation are integrated into a single instrument reading [Botsford 1971]. The stabilization time of the instrument ranges from about 5 to 15 minutes, depending on the magnitude of the heat-load differential (5 minutes for 5°C (9°F) and 15 minutes for >15°C (59°F)).

The WGT has been used in many laboratory studies and field situations where it has been compared with the WBGT [Ciricello and Snook 1977; Johnson and Kirk 1980; Beshir 1981; Beshir et al. 1982; Parker and Pierce 1984]. In general, the correlation between the two is high (r = 0.91 - 0.98); however, the relationship between the two is not constant for all combinations of environmental factors. Correction factors ranging between 1°C (1.8°F) and 7ºC (12.6°F) have been suggested. A simple approximation of the relationship is WBGT = WGT + 2°C for conditions of moderate radiant heat and humidity. These approximations are probably adequate for general monitoring in industry. If the WGT shows high values, it should be followed with WBGT or other detailed measurements. The WGT, although adequate for screening and monitoring, does not yield data for solving the equations for heat exchange between the worker and the industrial environment, but a color-coded WGT display dial provides a simple and rapid indicator of the level of heat stress.

9.4 Physiologic Monitoring

The objectives of a heat-stress index are twofold: (1) to provide an indication of whether a specific total heat stress will result in an unacceptably high risk of heat-related illness or injuries and (2) to provide a basis for recommending control procedures. The physiologic responses to an increasing heat load include increases in heart rate, core body temperature, skin temperature, and sweat production. In a specific situation, any one or all of these responses may be elicited. The magnitude of the response(s) will, in general, reflect the total heat load. The individual integrates the stress of the heat load from all sources, and the physiologic responses (strain) to the heat load are the biological corrective actions designed to counteract the stress and thus permit the body to maintain an optimal internal temperature. Acceptable increases in physiologic responses to heat stress have been recommended by several investigators [WHO 1969; Fuller and Smith 1980, 1981]. It appears that monitoring the physiologic strain directly under regular working conditions would be a logical and viable procedure for ensuring that the heat strain did not exceed pre-designated values. Measuring one or more of the physiologic responses (heart rate and/or oral temperature) during work has been recommended and is, in some industries, used to ensure that the heat stress to which the worker is exposed does not result in unacceptable strain [Fuller and Smith 1980, 1981]. However, several of the physiologic strain monitoring procedures are either invasive (ingestible plastic thermister used to determine intestinal temperature), socially unacceptable (rectal catheter) or interfere with communication (ear thermometer, e.g., Thermoscan®). Physiologic monitoring requires medical supervision and the consent of the worker. See the end of the chapter for Table 9-1, examples of physiological monitoring used to prevent heat-related illnesses.

9.4.1 Work and Recovery Heart Rate

One of the earliest procedures for evaluating work and heat strain is that introduced by Brouha in which the body temperature and pulse rate are measured during recovery following a work cycle or at specified times during the workday [Brouha 1960]. At the end of a work cycle, the worker sits on a stool, an oral thermometer is placed under the tongue, and the pulse rate is counted from 30 seconds to 1 minute (P_1), from 1-1/2 to 2 minutes (P_2), and from 2-1/2 to 3 minutes (P_3) of seated recovery. If the oral temperature exceeds 37.5°C (99.5°F), the P1 exceeds 110 beats per minutes (bpm), and/or the P_1-P_3 is fewer than 10 bpm, the heat and work stress is assumed to be above acceptable values. These values are group averages and may or may not be applicable to an individual worker or specific work situation. However, these values should alert the observer that further review of the job is desirable.

A modified Brouha approach is being used for monitoring heat stress in some hot industries. An oral temperature and a recovery heart rate pattern have been suggested by Fuller and Smith [1980, 1981] as a basis for monitoring the strain of working at hot jobs. The ultimate criterion of high heat strain is an oral temperature exceeding 37.5ºC (99.5ºF). The heart rate recovery pattern is used to assist in the evaluation. If the P_3 is 90 bpm or fewer, the job situation is satisfactory; if the P_3 is about 90 bpm and the P_1-P_3 is about 10 bpm, the pattern indicates that the physical work intensity is high, but there is little if any increase in body temperature; if the P_3 is greater than 90 bpm and the P_1-P_3 is fewer than 10 bpm, the stress (heat + work) is too high for the individual and corrective actions should be introduced. These individuals should be examined by a physician or other qualified healthcare provider, and the work schedule and work environment should be evaluated.

The field data reported by Jensen and Dukes-Dobos [1976] corroborate the concept that the P_1 recovery heart rate and/or oral temperature is more likely to exceed acceptable values when the environmental plus metabolic heat load exceeds the ACGIH TLVs for continuous work. The recovery heart rate can be easily measured in industrial situations where being seated for about five minutes will not seriously interfere with the work sequence; in addition, the instrumentation required (a wearable electronic heart rate monitor) can be simple and inexpensive. Certainly, the recovery and work heart rates can be used on some jobs as early indicators of the strain resulting from heat exposure in hot industrial jobs. The relatively inexpensive, noninvasive electronic devices now available (and used by joggers and others) should make self-monitoring of work and recovery pulse rates practical.

9.4.2 Body Temperature

The WHO scientific group on Health Factors involved in Working Under Conditions of Heat Stress recommended that the deep body temperature should not, under conditions of prolonged daily work and heat, be permitted to exceed 38ºC (100.4ºF) or oral temperature of 37.5ºC (99.5ºF), although the tolerance to elevated body temperature is quite variable [Taylor et al. 2008]. The limit has generally been accepted by the experts working in the area of industrial heat stress and strain.

Monitoring the body temperature (internal or oral) would, therefore, appear to be a direct, objective, and reliable approach. Measuring internal body temperature (rectal, esophageal, or aural) does present the serious problem of being generally socially unacceptable to the workers. However, newer technologies, involving an ingestible plastic thermister capable of telemetering "core" (intestinal) temperatures, are in wide use (CorTemp; HQInc. Palmetto, FL). The disadvantage of the ingestible thermister involves a lengthy (hours) migration from the mouth to the small intestine prior to being able to record accurate temperatures [Lee et al. 2000; Williams et al. 2011].

Oral temperatures, on the other hand, are easy to obtain, especially now that inexpensive disposable oral thermometers are available. However, to obtain reliable oral temperatures requires a strictly controlled procedure. The thermometer must be correctly placed under the tongue for 3 to 5 minutes before the reading is made, mouth breathing is not permitted during this period, no hot or cold liquids should be consumed for at least 15 minutes before the oral temperature is measured, and the thermometer must not be exposed to an air temperature higher than the oral temperature either before the thermometer has been placed under the tongue or until after the thermometer reading has been taken. In hot environments, this may require that the thermometers be kept in a cool insulated container or immersed in alcohol, except when in the worker's mouth. Oral temperature is usually lower than deep body temperature by about 0.55°C (0.8°F). With the advent of digital oral thermometers, accurate oral temperatures may be obtained within <30 seconds, thus avoiding some of the issues found with standard alcohol oral thermometers. Given worker permission (permission is assumed should the monitoring of body temperature be made a condition of employment and the person accepts the job), there is no reason body temperature monitoring cannot be applied in many hot industrial jobs. Evaluation of the significance of any oral temperature must follow established medical and occupational hygiene guidelines.

It must be noted that tolerance to increased T_{re} varies widely in individuals. Non-elite runners have been documented to have completed a marathon run with a T_{re} of >41°C (105.8 °F) and a T_{re} of 41.9 °C (107.4 °F) has been recorded in soccer players with no adverse physiological consequences [American College of Sports Medicine 2007; Taylor et al. 2008]. Therefore, recovery heart rate will be different in heat tolerant individuals than in those who are less heat tolerant (see Chapter 5 and 9 for a more detailed discussion).

9.4.3 Skin Temperature

The use of skin temperature (T_{sk}) as a basis for assessing the severity of heat strain and estimating tolerance can be supported by thermodynamically and field derived data. To move body heat from the deep tissues (core) to the skin (shell) where it is dissipated to the ambient environment requires an adequate heat gradient. As the skin temperature rises and approaches the core temperature, this temperature gradient is decreased and the rate (and amount) of heat moved from the core to the shell is decreased and the rate of core heat loss is reduced. To restore the rate of heat loss or core-shell heat gradient, the body temperature would have to increase. An increased skin temperature, therefore, drives the core temperature to higher levels in order to reestablish the required rate of heat exchange. As the core temperature is increased above 38°C (100.4°F), the risk of an ensuing heat-related illness is increased.

From these observations, it has been suggested that a reasonable estimate of tolerance time for hot work could be made from the equilibrium lateral thigh or chest skin temperature [Iampietro 1971; Shvartz and Benor 1972; Goldman 1978, 1981, 1985b, 1985a]. Under environmental conditions where evaporative heat exchange is not restricted, skin temperature would not be expected to increase much, if at all. Also, in such situations, the maintenance of an acceptable deep body temperature should not be seriously jeopardized, except under very high metabolic loads or restricted heat transfer. However, when convective and evaporative heat loss is restricted (e.g., when wearing impermeable protective clothing), an estimate of the time required for skin temperature to converge with deep body temperature should provide an acceptable approach for assessing heat strain, as well as for predicting tolerance time. Indeed, it has been recently shown that increased T_{sk} contributes to a decrease in aerobic performance and this effect is further enhanced when in conjunction with significant (≥4%) dehydration [Kenefick et al. 2010]. Moreover, although T_{sk} is generally 2-4°C below body core temperature (T_{core}), T_{sk} can be used to estimate T_{core} when other methodologies are not available [Lenhardt and Sessier 2006].

9.4.4 Dehydration

Under heat-stress conditions where sweat production may reach 6 to 8 liters in a workday, voluntary replacement of the water lost in the sweat is usually incomplete. The normal thirst mechanism is not sensitive enough to urge us to drink enough water or other fluids to prevent dehydration. If dehydration exceeds 1.5-2% of the body weight, tolerance to heat stress begins to deteriorate, heart rate and body temperature increase, and work capacity decreases [Greenleaf and Harrison 1986]. When dehydration exceeds 5%, it may lead to collapse and to dehydration heat-related illness. Since the feeling of thirst is not an adequate guide for water replacement, workers in hot jobs should be encouraged to drink water or other fluids every 15 to 20 minutes. The water should be cool [10°-15°C (50-59°F)], but neither warm nor cold. For work that requires an increased level of activity in a hot environment for a prolonged period of time (≥2 hours), carbohydrate and electrolyte containing sports drinks (e.g., Gatorade) should be used in place of water in order to replace the electrolytes lost from sweating and to avoid hyponatremia (serum sodium concentration < 136 mEq/L) from excessive consumption of plain water [TBMed 2003; Montain and Cheuvront 2008]. Drinking from disposable drinking cups is preferable to using drinking fountains. The amount of dehydration can be estimated by measuring body weight at intervals during the day or at least at the beginning and end of the workshift. The worker should drink enough water to prevent a loss in body weight. However, as this may not be a feasible approach in all situations, following a recommended water drinking schedule is usually satisfactory.

1 Table 9-1: Examples of physiological monitoring used to prevent heat-related illness

Monitoring Method	When Assessed	How Assessed	Additional Information
Heat Exposure History	• Before work begins	• Interview or questionnaire	• A history of heat-related illness increases the risk of a repeat occurrence, so worker should be monitored more closely. • Some workers might choose to alert their employers of medical conditions which increase the risk of heat-related illnesses.
Heart Rate (Pulse Rate)	• Before work begins to determine baseline and then after heat exposure (e.g., 1st minute and 3rd minute after the work period ends)	• Count the number of beats per minute (use a watch), or monitor with heart rate sensor	• The heart rate should fall rapidly, approaching the baseline. • Heart rate will remain elevated in a worker experiencing a heat-related illness.
Temperature			• Increased temperature indicates that the body is not cooling itself as rapidly as necessary.
	• Initial baseline and again after the work period	• *Oral temperature* – measure with an oral thermometer	• Oral temperature is inaccurate if the workers drinks cool beverages frequently (as is recommended).
	• Initial baseline and again after the work period.	• *Tympanic temperature* – measure with an infrared thermometer	• Tympanic temperature is a more reliable indicator of core temperature than oral.
	• Continuous	• *Core*	• Core temperature is the

	sensing devices measure temperature during both work and rest periods	*temperature* – measure with electronic or color-changing sensing devices (e.g., ingestible, in-ear, or part of skin patches)	most reliable measure of body temperature. • Modern advances in sensing technology are making core temperature measurements increasingly practical.
Body weight	• Initial baseline and immediately after heat exposure	• Can use bathroom scale with good precision • Must wear same clothing for before and after work measurement • Account for moisture (sweat) in the clothes	• Daily weight loss can indicate that the worker is not drinking sufficient amounts of fluids. • The need to account for moisture in sweat dampened clothing can be a complication.
Blood Pressure	• Initial baseline and again after the work period	• Blood pressure cuff	• Blood pressure does not recover as quickly when a worker is suffering heat-related illness. • Posture can affect blood pressure in workers with heat-related illness and is the basis for some physiological monitoring methods.
Respiratory Rate	• Initial baseline and again after	• Count breaths per	• Breathing rate does not return to baseline as

	the work period	minute using stop watch	quickly when a worker is suffering heat-related illness.
Alertness	• During and after the work period	• Converse with the worker	• Assess whether the worker shows signs of confusion, or other cognitive symptoms of heat-related illness.

Adapted from [OSHA].

10. Research Needs

The past decade has brought an enormous increase in our knowledge of heat stress and strain, their relation to health and productivity, techniques and procedures for their assessment and their health risks. In spite of this, there are several areas where further research is required before occupational heat-related health and safety problems can be completely prevented.

10.1 Exposure Times and Patterns

In some hot industries, the workers are exposed to heat most of the day; other workers may be exposed only part of the time. Although there is general agreement on the heat-stress/strain relation with resultant health and safety risks for continuous exposure (8-hour workday), controversy continues on acceptable levels of heat stress for intermittent exposure where the worker may spend only part of the working day in the heat.

- Is a 1-hour, a 2-hour, or an 8-hour TWA required for calculating risk of health effects?
- How long are acceptable exposure times for various total heat loads?
- Are the health effects (heat-related illnesses) and risks the same for intermittent as for continuous heat exposure?
- Do workers exposed intermittently each day to various lengths and amount of heat stress develop heat acclimatization similar to that achieved by continuously exposed workers?
- Are the electrolyte and water balance problems the same for intermittently as for continuously heat-exposed workers?

10.2 Deep Body Temperature

The WHO Scientific Group recommended that "it is considered inadvisable for a deep body temperature to exceed 38°C (100.4°F) for prolonged daily exposures (to heat) in heavy work" [WHO 1969] and that a deep body temperature of 39°C (102.2°F) should be considered reason to terminate exposure, even when deep body temperature is being monitored. Are these values equally realistic for short-term acute heat exposures as for long-term chronic heat exposures? Are these values strongly correlated with increased risk of incurring heat-related illnesses? Are these values considered maximal, which are not to be exceeded, mean population levels, or 95th percentile levels? Is the rate at which deep body temperature rises to 38° or 39°C important in the health-related significance of the increased body temperature? Does a 38° or 39°C deep body temperature have the same health significance if reached after only one hour of exposure as when reached after more than one hour of exposure?

10.3 Electrolyte and Water Balance

The health effects of severe acute negative electrolyte and water balance during heat exposure are well documented. However, the health effects of the imbalances, when derived slowly over periods of months or years, are not known; nor are the effects known for long term electrolyte loading with and without hyper or hypohydration. An appropriate electrolyte and water regimen for long-term work in the heat requires more data derived from further laboratory and epidemiologic studies.

10.4 Effects of Chronic Heat Exposure

All of the experimental and most of the epidemiologic studies of the health effects of heat stress have been directed toward short exposures of days or weeks in length and toward the acute heat-related illnesses. Little is known about the health consequences of living and working in a hot environment for a working lifetime. Do such long exposures to heat have any morbidity or mortality implications? Does experiencing an acute heat-related illness have any effects on future health and longevity? It is known that individuals with certain health disorders (e.g., diabetes, cardiovascular disease) are less heat tolerant. There is some evidence that the reverse may also be true; e.g., chronic heat exposure may render an individual more susceptible to both acute and chronic diseases and disorders [Dukes-Dobos 1981]. The chronic effect of heat exposure on blood pressure is a particularly sensitive problem because hypertensive workers may be under treatment with diuretics and on restricted salt diets. Such treatment may be in conflict with the usual emphasis on increased water and salt intake during heat exposure.

10.5 Circadian Rhythm of Heat Tolerance

The normal daily variation in core body temperature from the high point in the mid-afternoon to the low point in the early morning is about 0.5°C [Cheung et al. 2000]. Superimposed on this normal variation in body temperature would, supposedly, be the increase due to heat exposure. In addition, the WHO report recommends that the 8-hour TWA body temperature of workers in hot industries should not exceed 38°C (100.4°F) [WHO 1969]. The question remains: Is this normal daily increase in body temperature additive to the increase resulting from heat stress? Does tolerance to increased body temperature and the connected health risk follow a similar diurnal pattern? Would it be necessary to establish different permissible heat exposure limits for day and night shift workers in hot industries?

10.6 Heat Tolerance and Shift Work

It has been estimated that about 30% of workers are on some type of work schedule other than the customary day work (9 a.m.-5 p.m.). Shift work, long days-short week, and double shifts alter the usual living patterns of the worker and result in some degree of sleep deprivation. What effect these changes in living patterns have on heat tolerance is mostly undocumented. Before these changes in work patterns are accepted, it is prudent that their health and safety implications in conjunction with other stress be known.

10.7 The Effects of Global Climate Change on Outdoor Workers

Global climate change could have a significant effect on outdoor workers, such as those in agriculture, fishing, construction, and many service areas. Climate change will not necessarily add to the number of high-risk exposures of these workers; however, it may add to the severity, prevalence, and distribution of the already known hazards [Schulte and Chun 2009]. Schulte and Chun identify seven categories of climate-related hazards: (1) increased ambient temperature, (2) air pollution, (3) ultraviolet exposure, (4) extreme weather, (5) vector-borne diseases and expanded habitats, (6) industrial transitions and emerging industries, and (7) changes in the built environment. The relationship between these categories and the possible occupational health effect outcomes can be seen in Figure 10.1. In addition, another result of climate change is a reduced work capacity and productivity in heat-exposed jobs with resulting loss of income which is also likely to cause mental health and economic effects [Kjellstrom 2009; Kjellstrom et al. 2009b; Berry et al. 2010; Kjellstrom et al. 2010; McMichael 2013].

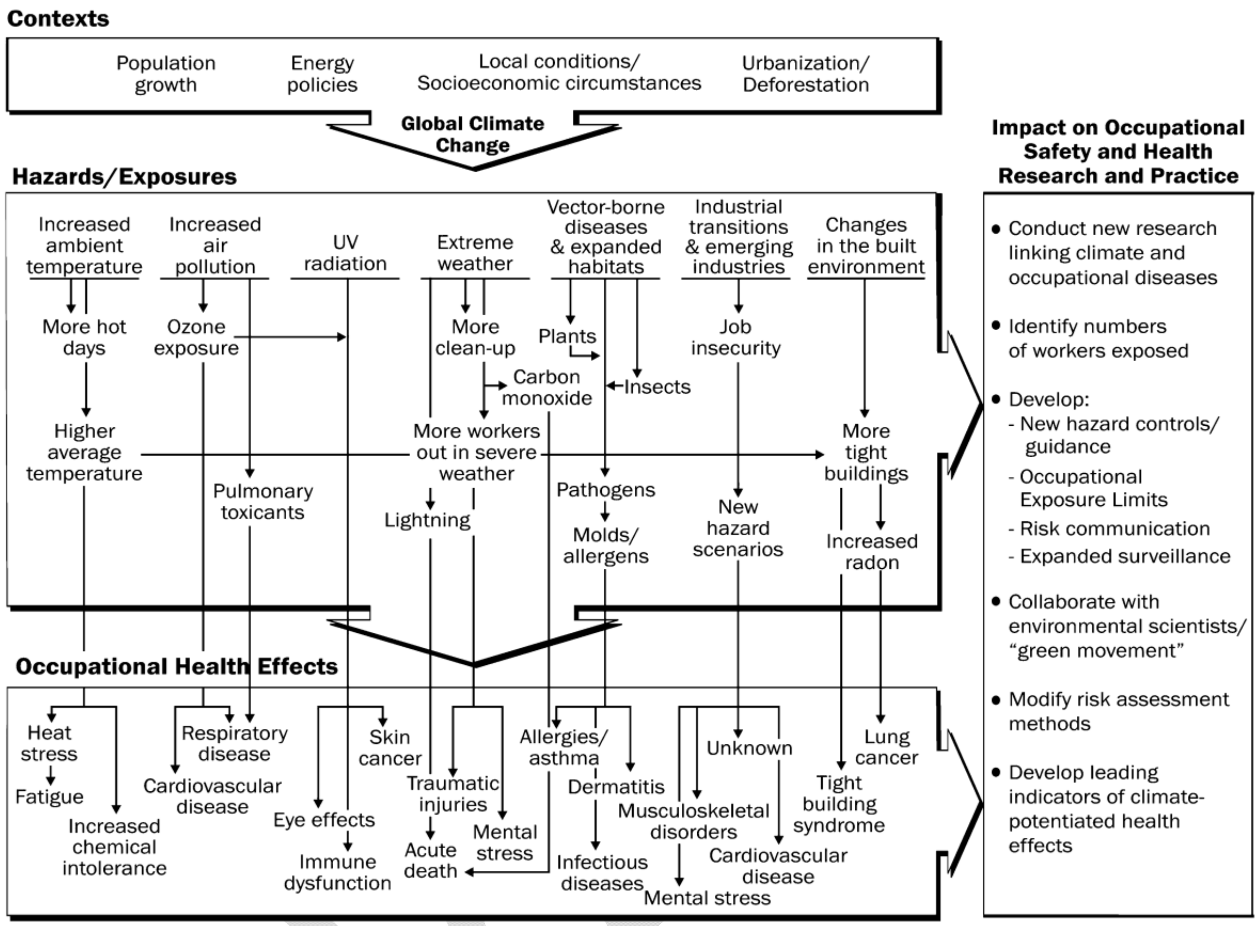


Figure 10.1: Relationship between climate change and occupational safety and health [Schulte and Chun 2009].

How climate change effects on the workforce can be addressed is still a relatively new area of research. Some climate change-related risks will likely be reduced by general improvements in public health, while other risks can be managed by ‘adaptation policies and actions’ [Kjellstrom et al. 2009b; Kjellstrom and Weaver 2009; Nilsson and Kjellstrom 2010]. The idea to develop a program to capture the growing evidence on climate change and health emerged at a 1998 Intergovernmental Panel on Climate Change meeting, and was eventually presented as the ‘high occupational temperature health and productivity suppression’ (Hothaps) program [Kjellstrom et al. 2009a]. The Hothaps program is a multi-center health research and prevention program used to quantify the extent to which workers are affected by, or adapt to, heat exposure while working, and how global heating during climate change may increase such effects. Programs like Hothaps and others will help to capture the current heat-related events, likely leading to new heat-related occupational safety and health recommendations and regulations in the future.

10.8 Heat Stress and Toxicology

Exposure to heat can affect how well chemicals are absorbed into the body. Since the 1890s, animal studies have shown that exposure to heat exacerbates chemical absorption and toxicity [Leon 2008]. Leon goes on to state that changes to the body's core temperature can alter absorption, distribution, metabolism and excretion of the toxicants. Increases in respiration will lead to further toxicant exposure through inhalation, while increases in sweat and skin blood flow will lead to more efficient transcutaneous absorption of toxicants [Gordon 2003; Leon 2008]. The relationships between how heat and other factors can affect the physiological response to toxicants can be seen in Figure 10.2.

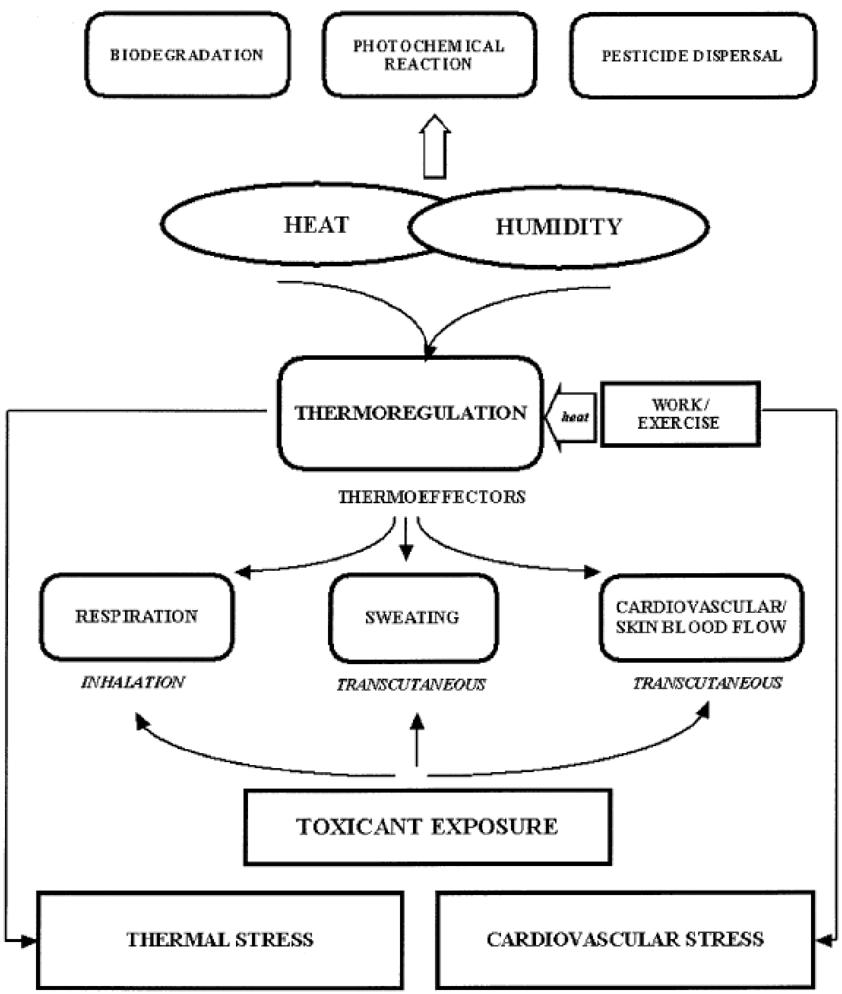


Figure 10.2: How heat, humidity, work, and thermoregulation affect the physiological response to toxicants.
Adapted from Gordon [2003].

Animal studies examining thermal stress and the effects on chemical toxicity, while showing that heat plays a role on toxins absorption, are also difficult to interpret when trying to compare differences between humans and the animal models. Test animals tend to be sedentary with no option for exercise, are acclimatized to ideal environmental conditions, and use hypothermia as their predominant thermoregulatory response to chemical toxicants [Gordon 2003; Leon 2008]. In vitro and in vivo studies have suggested that heat stress, with or without exercise, will activate thermoeffectors (e.g., skin blood flow, sweating, respiration) that will, in turn, accelerate pesticide absorption in humans [Gordon and Leon 2005]. Gordon and Leon also mention an in vitro model used to show blood flow, temperature, and relative humidity and the effect on absorption of the pesticide, parathion, as well as human studies showing the accelerating effects of perspiration on the absorption of organophosphorous compounds. Pesticides, in particular, are also a hazard to workers in the heat, as high temperatures will accelerate dispersion and increase the density of airborne particles and some workers will remove their PPE due to discomfort in the heat [Gordon 2003].

Most of what is known about toxicants is derived from animal studies in which the animals were kept in comfortable temperatures; therefore, a better understanding of the mechanisms involved between heat exposure and toxicants in humans is still needed [Gordon 2003; Gordon and Leon 2005]. With changes in the climate and hotter temperatures, the need for more information on toxicants and their relationship to heat stress will become increasingly important [Leon 2008].

Appendix A: Heat Exchange Equation Utilizing the SI Units

Convection (C) SI Units

The rate of heat exchange between a person and the ambient air can be stated algebraically:

$$C = h_c(t_a - \bar{t}_{sk})$$

Where:

h_c is the mean heat transfer coefficient,

t_a = air temperature

$\bar{t}_{sk}$ = air temperature

The value of h_c is different for the different parts of the body [Nishi 1981] depending mainly on the diameter of the part, e.g., at the torso the value of h_c is about half of what it is at the thighs. The value used for h_c is generally the average of the h_c values for the head, chest, back, upper arms, hands, thighs, and legs. The value of h_c varies between 2 and 12 depending on body position and activity.

Other factors which influence the value of h_c are air speed and direction and clothing. The value of $\bar{t}_{sk}$ can also vary depending on the method used for the measurements, the number and location of the measuring points over the body, and the values used for weighting the temperatures measured at the different location.

Numerous investigations have tried to simplify the calculation of convection heat exchange. The ISO Working Group on the Thermal Environment (ISO-WGTE) developed a draft standard for the Analytical Determination of Heat Stress [ISO 1982b]. One of the simplifications they adopted is to use only the following three values for h_c which are expressed in units of $W_m^{-2o}C^{-1}$, corresponding to the SI system.

a. When air speed is very low and is due only to natural convection
   $h_c = 2.38(\bar{t}_{sk} - t_a)^{0.25}$

b. In forced convection when relative air speed (V_{ar}) is less than $1ms^{-1}$
   $h_c = 3.5 + 5.2V_{ar}$

c. In forced convection, when V_{ar} is greater than $1ms^{-1}$
$h_c = 8.7V_{ar}^{0.6}$

The expression V_{ar} is defined as the ratio of the air velocity relative to the ground and the speed of the body or parts of the body relative to the ground. If the body movement is due to muscular work, V_{ar} can be calculated by the following equation:

$$V_{ar} = V_a + 0.0052(M-58)$$

Where:

V_a = air velocity in ms^{-1} and
M = metabolic heat production (Wm^{-2})

For simplicity, however, it is recommended to add to V_a 0.7 ms^{-1} as a correction for the effect of physical work.

The ISO-WGTE recommends also to include in the equation for calculating the convection heat exchange a separate coefficient for clothing, called reduction factor for loss of sensible heat exchange due to the wearing of clothes (F_{cl}) which can be calculated by the following equation:

$$F_{cl} = 1/1 + (h_c + h_r)I_{cl} \text{ (dimensionless)}$$

Where:

h_r = the heat transfer coefficient for radiant heat exchange
I_{cl} = the thermal insulation of clothing

Both hr and I_{cl} will be explained later in this appendix in more detail. The ISO-WGTE recommended the use of 36ºC (96.8ºF) for t_{sk} on the assumption that most workers engaged in industrial hot jobs would have a t_{sk} very close to this temperature, thus any error resulting due to this simplification will be small. They also assumed that most corrected for different body positions when calculating the convective heat exchange of workers.

The final equation for C to be used according to the ISO-WGTE is:

$$C = h_cF_{cl}\ (t_a-36)\ (Wm^{-2})$$

Radiation (R) SI Units

The rate of radiant heat exchange between a person and the surrounding solid objects can be stated algebraically:

$$R = h_r (T_{ry}\text{-}T_{sk})^4$$

Where:

h_r = the coefficient for radiant heat exchange
T_r = the mean radiant temperature in ºK
T_{sk} = the mean weighted skin temperature in ºK

The value of h_r depends on the body position of the exposed worker and on the emissivity of the skin and clothing, as well as on the insulation of clothing. The body position will determine how much of the total body surface will be actually exposed to radiation, and the emissivity of the skin and clothing will determine how much of the radiant heat energy will be absorbed on those surfaces. The insulation of clothing determines how much of the radiant heat absorbed at the surface of the garments will actually be transferred to the skin.

The ISO-WGTE recommended a linearized equation for calculating the value of R using SI units:

$$R = h_r F_{cl} (t_r - t_{sk}) \ (Wm^{-2} / ºC^{-1})$$

The effect of insulation and emissivity of the clothing material on radiant heat exchange is covered by the addition of the clothing coefficient F_{cl} which is also used in the equation for C as described above.

They also recommend a simplified equation for calculating an approximate value for h_r:

$$h_r = 4E_{sk} A_r / A_{Du} [(t_r + t_{sk})/2 + 273]^3$$

= is the universal radiation constant

$$= (5.67 \times 10^{-8}) \ Wm^{-2} \, ºK^{-4}$$

The effect of the emissivity of the skin on radiant heat exchange is covered by the expression $\underline{E}_{sk}$ which has the value of 0.97 in the infrared range. The effect of body position is covered by the expression A_r/A_{Du}, which is the ratio of the skin surface area exposed to radiation and the total skin surface area, as estimated by DeBois' formula.

$$A_{Du} = 0.00718 \times Weight^{0.425} / Height^{0.725}$$

In this equation body weight must be expressed in kg, height in cm, and the value of A_{Du} is then obtained in m^2. Some values given for the ratio A_r/A_{Du} by the ISO-WGTE are:

Standing 0.77
Seated 0.70
Crouched 0.67

The value of t_r (mean radiant temperature) can be calculated by the following equation:

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

For further simplification, the value of t_{sk} can be assumed to be 36ºC, just as it was in the equation for convection.

Evaporation (E) SI Units

E_{req} is the amount of heat which must be eliminated from the body by evaporation of sweat from the skin in order to maintain thermal equilibrium. However, major limitations to the maximum amount of sweat which can be evaporated from the skin (E_{max}) are:

a. The human sweating capacity,
b. The maximum vapor uptake capacity of the ambient air,
c. The resistance of the clothing to evaporation.

As described in Chapter 5, the sweating capacity of healthy individuals is influenced by age, sex, state of hydration, and acclimatization.

The draft ISO-WGTE [ISO 1982b] standard recommends that an hourly sweat rate of 650 grams for an unacclimatized person and 1,040 grams for an acclimatized one is the maximum which can be considered permissible for the average worker while performing physical work in heat. However, these limits should not be considered as maximum sweating capacities but related to levels of heat strain at which the risk of heat-related illnesses is minimal.

In the same vein, for a full workshift the total sweat output should not exceed 3,250 grams for an unacclimatized person and 5,200 grams for an acclimatized one if deterioration in performance due to dehydration is to be prevented. It follows from the foregoing that if heat exposure is evenly distributed over an 8-hour shift, the maximum acceptable hourly sweat rate is about 400 grams for an unacclimatized person and 650 grams for an acclimatized person.

Thus, if the worker's heat exposure remains within the limits of the recommended standard, the maximum sweating capacity will not be exceeded, and the limitation of evaporation will be due only to the maximum vapor uptake capacity of the ambient air. The E_{max} can be described with the equation recommended by the ISO-WGTE:

$$E_{max} = (p_{sk,s} - p_a)/R_e$$

Where:

E_{max} = maximum water vapor uptake capacity (Wm^{-2})

$P_{sk,s}$ = saturated water vapor pressure at 36ºC

skin temperature (5.9 kP_a)

p_a = partial water vapor pressure at ambient air temperature (kP_a)

R_e = total evaporative resistance of the limiting layer of air and clothing ($m^2 kP_a\ W^{-1}$). This can be calculated by the following equation:

$$R_e = 1 / 16.7 / h_c / F_{pcl}$$

Where:

h_c = convective heat exchange coefficient (Wm^{-2} / C^{-1})

F_{pcl} = reduction factor for loss in latent heat exchange due to clothing (dimensionless). This factor can be calculated by the following equation:

$$F_{pcl} = 1 / 1 + 0.92 h_c / I_{cl}$$

Where:

I_{cl} = Thermal insulation of clothing (m^2 ºC W^{-1})

What this means is that the maximum vapor uptake capacity of the air depends on the temperature, humidity, and velocity of the ambient air and clothing worn. However, the relationship of these variables in respect to human heat tolerance is quite complex. Further complications are caused by the fact that in order to be able to evaporate a certain amount of sweat from the skin, it is necessary to sweat more than that amount, because some of the sweat will drip off the skin or will be picked up by the clothing. To calculate the additional amount of sweat required due to dripping the ISO-WGTE recommended the following equations:

$$S_{req} = E_{req}$$

Where:

S_{req} = Required Sweat (Wm^{-2}). This quantity can also be expressed as ($g\ h^{-1}\ m^{-2}$) x 0.68

E_{req} = Required Evaporation (Wm^{-2}) can be calculated by the equation $E_{req} = M + C + R$

η = Evaporative efficiency of sweating of a nude person. It can be calculated by the following equation:

$$\eta = 1 - 0.5 / e^{-6.6(1-w)}$$

Where:

e = the base of natural logarithm
w = E_{req}/E_{max}, also called the "Wettedness Index"

There are not enough experimental data available to calculate the loss of evaporative efficiency of sweat due to the wicking effect of clothing. However, if the workers wear thin knitted cotton underwear, this can actually enhance the cooling efficiency of sweat, because after wicking the sweat off the skin, it spreads it more evenly over a larger area, thus enhancing evaporation and preventing dripping. Since the thin knitted material clings to the skin, the evaporative cooling will affect the skin without much loss to the environment. If a loosely fitting garment wicks up the sweat, there may be a substantial loss in evaporative cooling efficiency. However, if the heat exposure (M+C+R) remains below the human sweating capacity, the exposed worker will be able to increase the sweat excretion to compensate for the loss of its cooling efficiency. A compensatory increase of sweating does not add much to the physiologic strain if water and electrolytes are replaced satisfactorily and if water vapor uptake capacity of the ambient air is not exhausted.

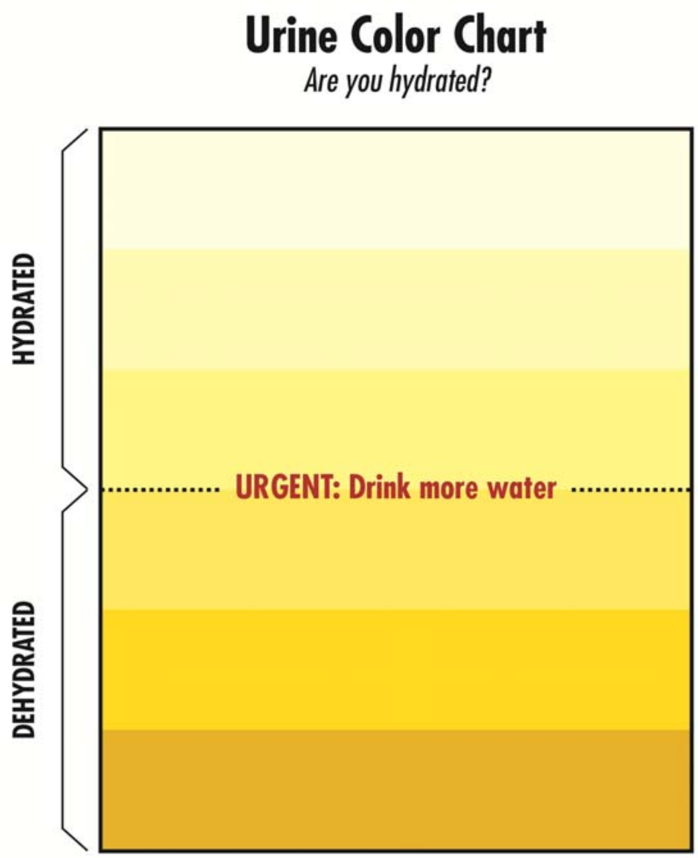
In order to make sure that in the S_{req} index the wettedness modifies the value of S_{req} only to the extent to which it increases physiologic strain, the E_{req}/E_{max} ratio affects the value of S_{req} in an exponential manner.

The closer the value of E_{req} comes to E_{max}, the greater will be the impact of w on S_{req}. This is in accord with the physiologic strain as well as the subjective feeling of discomfort.

In this manner, the S_{req} index is an improvement over other rational heat-stress indices, but at the same time the calculations involved are more complex. With the availability of pocket-sized programmable calculators, the problem of calculations required is greatly reduced. However, it is questionable whether it is worthwhile to perform a complex calculation with variables which cannot be measured accurately. These variables include: the mean weighted skin temperature, the velocity and direction of the air, the body position and exposed surface area, the insulation and vapor permeability of the clothing, and the metabolic heat generated by the work.

For practical purposes, simplicity of the calculations may be preferable to all-inclusiveness. Also, the utilization of familiar units (the British units or metric units instead of SI suggested, e.g., kcal, Btu, and W to express energy in heat production) may assist in wider application of the calculations. They can be useful in analysis of a hot job for determining the optimal method of stress reduction and for prediction of the magnitude of heat stress so that proper preventive work practices and engineering controls can be planned in advance.

Appendix B: Urine Chart



Urine charts can be implemented as a training tool to demonstrate the concept of color change between the urine of a well-hydrated worker and that of a dehydrated worker. When conducting an investigation to evaluate the validity and sensitivity of urine color, Armstrong et al. [1998] found that urine color was as good an index as urine osmolality, urine specific gravity, urine volume, plasma osmolality, plasma sodium, and plasma total protein, at tracking changes in body water and hydration status. In an earlier study, the author suggested that urine color could be used in industrial settings where close estimates of urine specific gravity or urine osmolality are acceptable [Armstrong et al. 1994; Armstrong et al. 2010].

While the urine chart is a good indicator of hydration status for most workers with normal pale yellow to deep amber urine, urine color can also be affected by diet, medications, and illnesses or disorders. See the Table B-1 below.

1 Table B-1: Causes of abnormal colors in urine

Color	**Causes** ***Diet***	***Medications***	***Medical conditions***
Clear		• Diuretics	
Cloudy or milky			• Urinary tract infection • Bacteria • Crystals • Fat • White or red blood cells • Mucus
Yellow	• Vitamins		
Orange	• B complex vitamins • Carotene • Carrots	• Rifampin • Sulfasalazine (Azulfidine) • Phenazopyridine (Pyridium) • Laxatives • Chemotherapy drugs	• Medical conditions (liver or bile duct)
Red or pink	• Beets • Blackberries • Rhubarb	• Rifampin (Rifadin, Rimactane) • Phenazopyridine • Laxatives containing senna	• Blood (infection or cancer) • Toxins (chronic lead or mercury poisoning)
Port wine or purple			• Poryphyria (inherited disease)
Green or blue	• Food dyes	• Amitriptyline • Indonethacin (Indocin) • Propofol (Diprivan) • Medications containing methylene blue	• Familial hypercalcemia (inherited disorder) • Urinary tract infection with *Pseudomonas* sp.

Brown	• Fava beans • Rhubarb • Aloe • Kidney or liver disorders (cirrhosis)	• Antimalarial drugs (chloroquine, primaquine) • Antibiotics (metronidazole, nitrofurantoin) • Laxatives containing cascara or senna • Methocarbamol (muscle relaxant)	• Urinary tract infections

Adapted from [Mayo Clinic 2011; Medline Plus 2011; Watson 2011].

Appendix C: Heat Index

NOAA's National Weather Service
Heat Index

Temperature (°F)

Relative humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

Source: NOAA[2012]

The National Oceanic and Atmospheric Administration (NOAA) issues heat alerts based on the heat index values as seen in the chart above. The Heat Index is a measure of how hot it feels when relative humidity is taken into account with the actual air temperature. Since heat index values were devised for shady, light wind conditions, exposure to full sunshine can increase heat index values by up to 15°F.

NOAA may also issue an extreme heat advisory:

- *Excessive Heat Outlook*
  Extended excessive heat (heat index of 105-110°F) over the next 3-7 days.

- *Excessive Heat Watch*
  Excessive heat may occur within the next 24 to 72 hours.

- *Excessive Heat Warning*
  The heat index will be life threatening in the next 24 hours. Excessive heat is imminent or has a high probability of occurring.

- *Excessive Heat Advisory*
  Heat index may be uncomfortable, but not life threatening if precautions are taken.

NOAA has four bands of colors that are associated with four risk levels; below is a table modified by OSHA for use on worksites.

Table C-1: Heat index protective measures for worksites

Heat index	**Risk level**	**Protective measures**
Less than 91°F	Lower (caution)	Basic health and safety planning
91°F to 103°F	Moderate	Implement precautions and heighten awareness
103°F to 115°F	High	Additional precautions to protect workers
Greater than 115°F	Very high to extreme	Even more aggressive protective measures

Adapted from OSHA[2012c].

Additional information about protective measures mentioned in the above table can be found on OSHA's website.

Bibliography

ACGIH [1985]. TLVs, threshold limit values for chemical substances and physical agents in the work environment and biological exposure indices with intended changes for 1985-86. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

ACGIH [1993]. Limits for heat-acclimatized adults.

ACGIH [2009]. TLVs and BEIs : threshold limit values for chemical substances and physical agents and biological exposure indices.

ACGIH [2011]. TLVs and BEIs : threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati.

AIHA [1971]. Ergonomics Guide to assessment of metabolic and cardiac costs of physical work. Am Ind Hyg Assoc J *32*(8): 560-564.

AIHA [2003]. The Occupational Environment: Its Evaluation, Control, and Management (2nd ed.). Fairfax, VA: AIHA Press.

Allen RW, Ells MD, Hart AW [1976]. Industrial hygiene. Englewood Cliffs, N. J.: Prentice-Hall pp. xv, 363 p.

American College of Sports Medicine [2007]. Position Stand. Exertional Heat Illness during Training and Competion. Med Sci Sports Exerc: 556-572.

Armed Forces Health Surveillance C [2011]. Surveillance Snapshot: reportable medical events of heat injury in relation to heat index, June-September 2011. MSMR *18*(10): 19.

Armstrong CG, Kenney WL [1993]. Effects of age and acclimation on responses to passive heat exposure. J Appl Physiol *75*(5): 2162-2167.

Armstrong L, Pumerantz A, Fiala K, Roti M, Kavouras S, Casa D, Maresh C [2010]. Human hydration indices: acute and longitudinal reference values. International journal of sport nutrition and exercise metabolism *20*(2): 145-153.

Armstrong LE, Casa DJ, Maresh CM, Ganio MS [2007a]. Caffeine, fluid-electrolyte balance, temperature regulation, and exercise-heat tolerance. Exerc Sport Sci Rev *35*(3): 135-140.

Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO [2007b]. American College of Sports Medicine position stand. Exertional heat illness during training and competition. Med Sci Sports Exerc *39*(3): 556-572.

Armstrong LE, De Luca JP, Hubbard RW [1990]. Time course of recovery and heat acclimation ability of prior exertional heatstroke patients. Med Sci Sports Exerc *22*(1): 36-48.

Armstrong LE, Maresh CM, Castellani JW, Bergeron MF, Kenefick RW, LaGasse KE, Riebe D [1994]. Urinary indices of hydration status. Int J Sport Nutr *4*(3): 265-279.

Armstrong LE, Soto JA, Hacker FT, Jr., Casa DJ, Kavouras SA, Maresh CM [1998]. Urinary indices during dehydration, exercise, and rehydration. Int J Sport Nutr *8*(4): 345-355.

Armstrong LE, Stoppani J [2002]. Central nervous system control of heat acclimation adaptations: an emerging paradigm. Rev Neurosci *13*(3): 271-285.

ASHRAE [1981a]. ASHRAE handbook, 1981 fundamentals. Atlanta: The Am Soc Heat Ref Air Cond.

ASHRAE [1981b]. Physiological principles, comfort, and health, 1981 fundamentals handbook.

Åstrand P-O, Rodahl K [1977]. Textbook of work physiology : physiological bases of exercise (2d ed.). New York: McGraw-Hill pp. xvi, 681 p.

Åstrand P-O, Rodahl K, Dahl HA, Strømme SB [2003]. Textbook of Work Physiology. Champaign: Human Kinetics.

Avellini BA, Kamon E, Krajewski JT [1980a]. Physiological responses of physically fit men and women to acclimation to humid heat. J Appl Physiol *49*(2): 254-261.

Avellini BA, Shapiro Y, Pandolf KB, Pimental NA, Goldman RF [1980b]. Physiological responses of men and women to prolonged dry heat exposure. Aviat Space Environ Med *51*(10): 1081-1085.

Banister EW, Brown SR [1968]. The relative energy requirements of physical activity, exercise physiology. New York: Academic Press.

Bar-Or O, Lundegren HM, Buskirk ER [1969]. Heat tolerance of exercising obese and lean women. J Appl Physiol *26*(4): 403-409.

Belding HS [1971]. Evaluation of stresses of exposure to heat: University of Pittsburgh.

Belding HS [1973]. Control of exposures to heat and cold. In: National Institute for Occupational Safety and Health. and United States. Public Health Service. Division of Occupational Health. (Eds.), The industrial environment - its evaluation & control 3rd ed. Washington, DC: U. S. Govt. Print. Off. pp. 563-572.

Belding HS, Hatch TF. (1955). Index for evaluating heat stress in terms of reslting physiological strain. *Heat Pip Air Condit, 27*, 129-135.

Benedict RF [1977]. Fundamentals of temperature, pressure and flow measurements. New York: John Wiley and Sons.

Berger RA [1982]. Applied exercise physiology. Philadelphia: Lea & Febiger pp. x, 291 p.

Berry HL, Bowen K, Kjellstrom T [2010]. Climate change and mental health: a causal pathways framework. Int J Public Health *55*(2): 123-132.

Beshir MY [1981]. A comprehensive comparison between WBGT and Botsball. Am Ind Hyg Assoc J *42*: 81-87.

Beshir MY, Ramsey JD, Burford CL [1982]. Threshold values for Botsball: a field study of ergonomics. Ergonomics *25*: 247-254.

Botsford JH [1971]. A wet globe thermometer for environmental heat measurement. Am Ind Hyg Assoc J *32*(1): 1-10.

Brouha L [1960]. Physiology in industry; evaluation of industrial stresses by the physiological reactions of the worker. New York,: Pergamon Press pp. xii, 145 p.

Bureau of Labor Statistics. (2010). Census of Fatal Occupational Injuries (Publication.:

Bureau of Labor Statistics. (2011). Occupational Outlook Handbook, 2010-2011 (Publication.:

Burke LM [2008]. Sports supplements debate: a risky practice that produces expensive urine or legitimate performance boosts that can be found in a acket or bottle? In: Taylor NAS and Groeller H (Eds.), Physiological Bases for Human Performance during Work and Exercise. Edinburgh: Churchhill Livingstone Elsevier pp. 577-584.

Buskirk ER, Bass DE [1980]. Climate and exercise. In: Johnson WR and Buskirk ER (Eds.), Structural and physiological aspects of exercise and sport. Princeton, N.J.: Princeton Book Co. pp. 190-205.

Cal/OSHA [2010]. Heat Illness Prevention Campaign: Final Performance and Evaluation Report. In: http://www.dir.ca.gov/DOSH/HeatIllnessCampaign/HeatIllnessPreventionCampaignReport.pdf]. Date accessed: September 14 2012.

Canadian Centre for Occupational Health and Safety [2011, April 1]. Thermal Comfort for Office Work. In: http://www.ccohs.ca/oshanswers/phys_agents/thermal_comfort.html]. Date accessed: September 5 2012.
Candas V, Libert JP, Vogt JJ [1979]. Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. J Appl Physiol *47*(6): 1194-1200.
Casa DJ, Csillan D, Armstrong LE, Baker LB, Bergeron MF, Buchanan VM, Carroll MJ, Cleary MA, Eichner ER, Ferrara MS, Fitzpatrick TD, Hoffman JR, Kenefick RW, Klossner DA, Knight JC, Lennon SA, Lopez RM, Matava MJ, O'Connor FG, Peterson BC, Rice SG, Robinson BK, Shriner RJ, West MS, Yeargin SW [2009]. Preseason heat-acclimatization guidelines for secondary school athletics. J Athl Train *44*(3): 332-333.
CDC [2008]. Heat-related deaths among crop workers--United States, 1992--2006. MMWR Morb Mortal Wkly Rep *57*(24): 649-653.
Cena K, Clark JA, Politechnika Wroclawska. [1981]. Bioengineering, thermal physiology, and comfort. Amsterdam ; New York: Elsevier Scientific Pub. Co.; New York, N.Y. : Elsevier/North-Holland [distributor] p. 289.
Centers for Disease Control and Prevention [2009, July 31, 2009]. Extreme Heat: A Prevention Guide to Promote Your Personal Health and Safety. In: http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp]. Date accessed:
Chang SX, Ge XS [1983]. Preliminary research in the measurement of the solar radiation by transient technique. Solar Energy *30*: 391-395.
Cheung SS, McLellan TM, Tenaglia S [2000]. The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. Sports Med *29*(5): 329-359.
Chung NK, Pin CH [1996]. Obesity and the occurrence of heat disorders. Mil Med *161*(12): 739-742.
Ciricello VM, Snook SH [1977]. The prediction of WBGT from Botsball. Am Ind Hyg Assoc J *38*: 264-271.
Clarren SK, Smith DW, Harvey MA, Ward RH, Myrianthopoulos NC [1979]. Hyperthermia--a prospective evaluation of a possible teratogenic agent in man. [Research Support, U.S. Gov't, P.H.S.]. J Pediatr *95*(1): 81-83.
Coolerado [2012]. Psychrometric Charts. In: http://www.coolerado.com/products/psychometric-charts/]. Date accessed: September 7 2012.
Cooper KE, Veale WL, Kasting NW [1982]. Temperature regulation, fever and antipyreics. In: Barnett HJM (Ed.), New uses for old drugs. New York: Raven Press.
Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA [2002]. Temperature and mortality in 11 cities of the eastern United States. Am J Epidemiol *155*(1): 80-87.
Dasler AR. (1977). *Heat stress, work function and physiological heat exposure limits in man*, Gaithersburg, Maryland.
Davies CTM, Brotherhood JR, Collins KJ, Doré C, Imms F, Musgrove J, Weiner JS, Amin MA, Ismail HM, El Karim M, Omer AHS, Sukkar MY [1976]. Energy expenditure and physiological performance of Sudanese cane cutters. Br J Indust Med *33*: 181-186.
DiBenedetto JP, Worobec SM [1985]. Exposure to hot environments can cause dermatological problems. Occup Health Saf *54*: 35-38.
Dinman BD, Horvath SM [1984]. Heat disorders in industry. A reevaluation of diagnostic criteria. J Occup Med *26*(7): 489-495.

DOD. (1980). *Occupational and environmental health: prevention, treatment, and control of heat injury*: Depts of Army, Navy and Air Force.

DOD. (2003). *Technical Bulletin: Heat Stress Control and Heat Casualty Management (TB MED 507/AFPAM 48-152 (I))*. Washington DC.

DOD. (2007). *Prevention and Treatment of Heat and Cold Stress Injuries*. Portsmouth, Virginia.

Drinkwater BL, Denton JE, Kupprat IC, Talag TS, Horvath SM [1976]. Aerobic power as a factor in women's response to work in hot environments. J Appl Physiol *41*(6): 815-821.

Drinkwater BL, Horvath SM [1979]. Heat tolerance and aging. Med Sci Sports *11*(1): 49-55.

Duffie JA, Beckman WA [1980]. Solar engineering of thermal processes. New York: Wiley pp. xvii, 762.

Dukes-Dobos FN [1981]. Hazards of heat exposure. A review. Scand J Work Environ Health *7*(2): 73-83.

Dukes-Dobos FN, Henschel A [1973]. Development of permissible heat exposure limits for occupational work. Ashrae Journal-American Society of Heating Refrigerating and Air-Conditioning Engineers: 57-62.

Edwards MJ [2006]. Review: Hyperthermia and fever during pregnancy. [Review]. Birth Defects Res A Clin Mol Teratol *76*(7): 507-516.

Ellis FP [1972]. Mortality from heat illness and heat-aggravated illness in the United States. Environ Res *5*(1): 1-58.

Ely BR, Ely MR, Cheuvront SN [2011]. Marginal effects of a large caffeine dose on heat balance during exercise-heat stress. Int J Sport Nutr Exerc Metab *21*(1): 65-70.

Epstein Y [1990]. Heat intolerance: predisposing factor or residual injury? Med Sci Sports Exerc *22*(1): 29-35.

Food and Nutrition Board, Institute of Medicine. (2005). *Dietary reference intakes for water, potassium, sodium, chloride and sulfate*. Retrieved. from.

Frye AJ, Kamon E [1981]. Responses to dry heat of men and women with similar aerobic capacities. J Appl Physiol *50*(1): 65-70.

Fuller FH, Smith PE, Jr. (1980). *The effectiveness of preventive work practices in a hot workshop (pub no 81-108).* Paper presented at the NIOSH workshop on recommended heat stress standards, Cincinnati.

Fuller FH, Smith PE, Jr. [1981]. Evaluation of heat stress in a hot workshop by physiological measurements. Am Ind Hyg Assoc J *42*(1): 32-37.

Gagge AP [1970]. Effects of radiant flux, an independent variable that describes thermal radiation on man/physiological and behavioral temperature regulation. Springfield, IL: Charles C. Thomas.

Gagnon D, Kenny GP [2011]. Sex modulates whole-body sudomotor thermosensitivity during exercise. J Physiol *589*(Pt 24): 6205-6217.

Garg A [1982]. Treatise on Solar Energy. In: Fundamentals of Solar Energy, Vol 1. New York: John Wiley and Sons.

Garg A, Chaffin DB, Herrin GD [1978]. Prediction of metabolic rates for manual materials handling jobs. Am Ind Hyg Assoc J *39*(8): 661-674.

Gisolfi CV [2000]. Is the GI System Built For Exercise? News Physiol Sci *15*: 114-119.

Givoni B, Rim Y [1962]. Effect of the thermal environment and psychological factors upon subjects' responses and performance of mental work. Ergonomics *5*: 99-119.

Golden JS, Hartz D, Brazel A, Luber G, Phelan P [2008]. A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. Int J Biometeorol *52*(6): 471-480.
Goldman RF [1973]. Clothing, its physiological effects, adequacy in extreme thermal environments, and possibility of future improvements. Arch Sci Physiol (Paris) *27*(2): 137-147.
Goldman RF [1978]. Prediction of human heat tolerance. In: Folinsbee LJ (Ed.), Environmental stress : individual human adaptations. New York: Academic Press pp. 53-69.
Goldman RF [1981]. Evaluating the effects of clothing on the wearer. In: Cena K, Clark JA and Politechnika Wroc*awska. (Eds.), Bioengineering, thermal physiology, and comfort. Amsterdam ; New York: Elsevier Scientific Pub. Co.; New York, N.Y. : Elsevier/North-Holland [distributor] pp. 41-55.
Goldman RF [1985a]. Heat stress in industrial protective encapsulating garments. In: Levine SP and Martin WF (Eds.), Protecting personnel at hazardous waste sites Vol. 10. Boston: Butterworth Publishers pp. 215-266.
Goldman RF [1985b]. Personal protective equipment. In: Levine SP and Martin WF (Eds.), Protecting personnel at hazardous waste sites. Boston: Butterworth Publishers.
González-Alonzo J, Eiken O, Mekjavic IB [2008]. A critical core temperature and the significance of absolute work rate. In: Taylor NAS and Groeller H (Eds.), The Physiological Bases of Human Performance during Work and Exercise. Ediburgh: Churchill Livinstone Elevier pp. 481-485.
Gonzalez RR, Berglund LG, Gagge AP [1978]. Indices of thermoregulatory strain for moderate exercise in the heat. J Appl Physiol *44*(6): 889-899.
Gordon CJ [2003]. Role of environmental stress in the physiological response to chemical toxicants. Environ Res *92*(1): 1-7.
Gordon CJ, Leon LR [2005]. Thermal stress and the physiological response to environmental toxicants. [Review]. Rev Environ Health *20*(4): 235-263.
Grayson J, Kuehn LA [1979]. Heat transfer and heat loss. In: Lomax P (Ed.), Body temperature, regulation, drug effects, and therapeutic implications. New York: Dekker pp. 72.
Greenleaf JE [1979]. Hyperthermia and exercise. International review of physiology *20*: 157-208.
Greenleaf JE, Harrison MH [1986]. Water and Electrolytes. Acs Symposium Series *294*: 107-124.
Hancock PA [1981]. Heat stress impairment of mental performance: a revision of tolerance limits. Aviat Space Environ Med *52*(3): 177-180.
Hancock PA [1982]. Task categorization and the limits of human performance in extreme heat. Aviat Space Environ Med *53*(8): 778-784.
Havenith G [1999]. Heat balance when wearing protective clothing. Ann Occup Hyg *43*(5): 289-296.
Heat Stress Management Program for the Nuclear Power Industry - Interim Report. (1986). [Report prepared for the Electric Power Research Institute, Palo Alto, CA].
Hellon RF, Lind AR [1958]. The influence of age on peripheral vasodilatation in a hot environment. J Physiol *141*(2): 262-272.
Henderson J, Baker HW, Hanna PJ [1986]. Occupation-related male infertility: a review. Clin Reprod Fertil *4*(2): 87-106.
Henschel A [1967]. Obesity as an occupational hazard. Can J Public Health *58*(11): 491-493.

Henschel A [1971]. The environment and performance. In: Simonson E (Ed.), Physiology of work capacity and fatigue Vol. 14. Springfield, Ill.,: Thomas pp. 325-347.
Henschel A, Burton LL, Margolies L, Smith JE [1969]. An analysis of the heat deaths in St. Louis during July, 1966. Am J Public Health Nations Health *59*(12): 2232-2242.
Herman RM, Brower JB, Stoddard DG, Casano AR, Targovnik JH, Herman JH, Tearse P [2007]. Prevalence of somatic small fiber neuropathy in obesity. Int J Obes (Lond) *31*(2): 226-235.
Horvath SM [1985]. Hot and cold environments. In: Cralley and Cralley (Eds.), Patty's industrial hygiene and toxicology 2nd ed., pp. 3B.
Iampietro PF [1971]. Use of skin temperature to predict tolerance to thermal environments. Aerosp Med *42*: 396-399.
Inbar O, Morris N, Epstein Y, Gass G [2004]. Comparison of thermoregulatory responses to exercise in dry heat among prepubertal boys, young adults and older males. Exp Physiol *89*(6): 691-700.
Inoue Y, Havenith G, Kenney WL, Loomis JL, Buskirk ER [1999]. Exercise- and methylcholine-induced sweating responses in older and younger men: effect of heat acclimation and aerobic fitness. Int J Biometeorol *42*(4): 210-216.
International Organization for Standardization [2012]. ISO. In: http://www.iso.org/iso/home.htm]. Date accessed: September 5, 2012
ISO [1982a]. Hot environments--estimation of heat stress on working man based on the WBGT index (ISO 7243).
ISO [1982b]. Thermal environments--analytical detrmination of thermal stress (ISO/DP7933): International Standards Organization.
ISO [1989]. Hot environments--estimation of heat stress on working man based on the WBGT index (ISO 7243).
ISO [1990]. Determination of Metabolic Rate (ISO 8996).
ISO [1993]. Evaluation of Cold Environments – Determination of Required Clothing Insulation (IREQ) (ISO TR 11079).
ISO [2004a]. Ergonomics -- Evaluation of thermal strain by physiological measurements (Standard No. ISO 9886). Switzerland.
ISO [2004b]. Ergonomics of the thermal environment -- Analytical determination and interpretation of heat stress using calculation of the predicted heat strain (Standard No. ISO 7933). Switzerland.
ISO [2004c]. Ergonomics of the thermal environment -- Determination of metabolic rate (Standard No. ISO 8996). Switzerland.
ISO [2007]. Ergonomics of thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble (Standard No. ISO 9920). Switzerland.
Jackson EK [2006]. Renin and Angiotensin. In: Brunton LL, Lazo JS and Parker KL (Eds.), Goodman & Gilman’s The Pharmacologic Basis of Therapeutics 11th ed. New York: McGraw Hill pp. 789-821.
Japan Society for Occupational Health [2005]. Recommendation of occupational exposure limits 2005–2006. J Occup Health *47*: 354–370.
Jensen RC, Dukes-Dobos FN. (1976). *Validation of proposed limits for exposure to industrial heat.* Paper presented at the Standards of occupational exposure to hot environments.

Johnson AT, Kirk GD [1980]. Correlation of WBGT and botsball sensors. Am Ind Hyg Assoc J *41*(5): 361-366.
Joy RJ, Goldman RF [1968]. A method of relating physiology and military performance. A study of some effects of vapor barrier clothing in a hot climate. Mil Med *133*(6): 458-470.
Jung A, Schuppe HC [2007]. Influence of genital heat stress on semen quality in humans. [Review]. Andrologia *39*(6): 203-215.
Kamon E, Avellini B [1979]. Wind speed limits to work under hot environments for clothed men. J Appl Physiol *46*(2): 340-345.
Kamon E, Ryan C [1981]. Effective heat strain index using pocket computer. Am Ind Hyg Assoc J *42*(8): 611-615.
Karpovich PV, Sinning WE [1971]. Physiology of muscular activity [by] Peter V. Karpovich and Wayne E. Sinning. Philadelphia,: Saunders pp. xiii, 374 p.
Kenefick RW, Cheuvront SN, Palombo LF, Ely BR, Sawka MS [2010]. Skin temperature modifies the impact of hypohydration on aerobic performance. J Appl Physiol *109*: 79-86.
Kenney WL, Tankersley CG, Newswanger DL, Hyde DE, Puhl SM, Turner NL [1990]. Age and hypohydration independently influence the peripheral vascular response to heat stress. J Appl Physiol *68*(5): 1902-1908.
Kenny GP, Webb P, Ducharme MB, Reardon FD, Jay O [2008]. Calorimetric measurement of postexercise net heat loss and residual heat storage. Med Sci Sports Exerc *40*(9): 1629-1636.
Kenny GP, Yardley J, Brown C, Sigal RJ, Jay O [2010]. Heat stress in older individuals and patients with common chronic diseases. CMAJ *182*(10): 1053-1060.
Kerslake DM [1972]. The stress of hot environments. Cambridge [Eng.]: University Press pp. x, 316.
Khagali M, Hayes JSR [1983]. Heatstroke and temperature regulation. Sydney: Academic Press.
Khogali M [1997]. Heat illness alert program. Practical implications for management and prevention. Ann N Y Acad Sci *813*: 526-533.
Kilbourne EM, Choi K, Jones TS, Thacker SB [1982]. Risk factors for heatstroke. A case-control study. JAMA *247*(24): 3332-3336.
Kirk PM, Sullman MJM [2001]. Heart rate strain in cable hauler choker setters in New Zealand logging operations. Applied Ergonomics *32*: 389-398.
Kjellstrom T [2009]. Climate change, direct heat exposure, health and well-being in low and middle-income countries. Glob Health Action *2*.
Kjellstrom T, Butler AJ, Lucas RM, Bonita R [2010]. Public health impact of global heating due to climate change: potential effects on chronic non-communicable diseases. Int J Public Health *55*(2): 97-103.
Kjellstrom T, Gabrysch S, Lemke B, Dear K [2009a]. The 'Hothaps' programme for assessing climate change impacts on occupational health and productivity: an invitation to carry out field studies. Glob Health Action *2*.
Kjellstrom T, Holmer I, Lemke B [2009b]. Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change. Glob Health Action *2*.
Kjellstrom T, Weaver HJ [2009]. Climate change and health: impacts, vulnerability, adaptation and mitigation. N S W Public Health Bull *20*(1-2): 5-9.

Knochel JP [1974]. Environmental heat illness. An eclectic review. Arch Intern Med *133*(5): 841-864.

Knowlton K, Lynn B, Goldberg RA, Rosenzweig C, Hogrefe C, Rosenthal JK, Kinney PL [2007]. Projecting heat-related mortality impacts under a changing climate in the New York City region. Am J Public Health *97*(11): 2028-2034.

Kuehn LA. (1973). *Response of the globe temperature*: Dept. of National Defense, OCHIEM, N.859, Canada.

Kuehn LA, Machattie LE [1975]. A fast responding and direct reading WBGT index meter. AIHA J *36*: 325-331.

Lary JM [1984]. Hyperthermia and teratogenicity. In: Anghileri LJ and Robert J (Eds.), Hyperthermia in cancer treatment. Boca Raton, Fla.: CRC Press.

Lee DH, Henschel A. (1963). *Evaluation of thermal environment in shelters* (No. TR-8).

Lee SMC, Williams WJ, Fortney-Schneider [2000]. Core temperature measurement during supine exercise: esophageal, rectal, and intestinal temperatures. Aviat Space Environ Med *71*(9): 939-945.

Leithead CS, Lind AR [1964]. Heat stress and heat disorders [by] C. S. Leithead [and] A. R. Lind. London,: Cassell pp. xiii, 304.

Lenhardt R, Sessier DI [2006]. Estimation of mean-body temperature from mean-skin and core temperature. Anesthesiology *105*(6): 1117-1121.

Leon LR [2008]. Thermoregulatory responses to environmental toxicants: the interaction of thermal stress and toxicant exposure. Toxicol Appl Pharmacol *233*(1): 146-161.

Levine RJ [1984]. Male fertility in hot environment. JAMA *252*(23): 3250-3251.

Lind AR [1976]. Limits of exposure to work in hot climates without a rise in body temperature. In: Horvath SM and Jensen RC (Eds.), Standards for occupational exposures to hot environments (Pub No. 76-100) Vol. 3: U.S. Dept of Health, Education, and Welfare, National Institute for Occupational Safety and Health pp. 9-16.

Lind AR [1977]. Human tolerance to hot climates. In: Lee DHK, Falk HL, Murphy SD and American Physiological Society (1887-) (Eds.), Handbook of physiology, a critical, comprehensive presentation of physiological knowledge and concepts. Bethesda, Md.: American Physiological Society pp. viii, 659.

Lind AR, Bass DE [1963]. Optimal exposure time for development of acclimatization to heat. Fed Proc *22*: 704-708.

Lind AR, Humphreys PW, Collins KJ, Foster K, Sweetland KF [1970]. Influence of age and daily duration of exposure on responses of men to work in heat. J Appl Physiol *28*(1): 50-56.

Luber G, McGeehin M [2008]. Climate change and extreme heat events. Am J Prev Med *35*(5): 429-435.

Luginbuhl RC, Castillo DN, Loringer KA [2008]. Heat-related deaths among crop workers--United States, 1992--2006. Morbidity and mortality weekly report *57*(24): 649-653.

Macpherson RK [1960]. Physiological responses to hot environments. An account of work done in Singapore, 1948-1953, at the Royal Naval Tropical Research Unit, with an appendix on preliminary work done at the National Hospital for Nervous Diseases, London. London,: H. M. Stationery Off. pp. xv, 323.

Maeda T, Kaneko S, Ohta M, Tanaka K, Sasaki A, Fukushima T [2006]. Risk factors for heatstroke among Japanese forestry workers. J Occup Health *48*: 223-229.

Marg K [1983]. Evaporative Cooling ... Heat-Stress and Its Effect on Worker Productivity, Quality, and Safety. Plant Engineering *37*(3): 73-74.

Mayo Clinic [2011, September 30, 2011]. Urine Color: Causes. In: http://www.mayoclinic.com/health/urine-color/DS01026/DSECTION=causes]. Date accessed: September 18 2012.

McArdle WD, Katch FI, Katch VI [1996a]. Exercise at medium and high altitude. In: Exercise Physiology: Energy, nutrition, and human performance 4th ed. Baltimore: Williams & Wilkins pp. 481-498.

McArdle WD, Katch FI, Katch VI [1996b]. Exercise Physiology (4th ed.). Baltimore: Williams and Wilkins.

McArdle WD, McArdle FI, Katch VL [2010]. Exercise Performance and Environmental Stress. In: McArdle WD, McArdle FI and Katch VL (Eds.), Exercise Physiology. Nutrition, Energy, and Human Performance 7th ed. Philadelphia: Lippincott Williams & Wilkins pp. 633-634.

McCullough EA, Arpin EJ, Jones B, Konz SA, Rohles FH [1982]. Heat transfer characteristics of clothing worn in hot industrial environments. Ashrae Journal-American Society of Heating Refrigerating and Air-Conditioning Engineers *88*: 1077-1094.

McKarns JS, Brief RS. (1966). Nomographs give refuned estimate of heat stress index. *Heat Pip Air Condit, 38,* 113-116.

McMichael AJ [2013]. Globalization, climate change, and human health. N Engl J Med *368*(14): 1335-1343.

Medline Plus [2011, September 16, 2011]. Urine - abnormal color. In: http://www.nlm.nih.gov/medlineplus/ency/article/003139.htm]. Date accessed: September 18 2012.

Mekjavic IB, Eiken O [2006]. Contribution of threshold and nonthermal factors to the regulation of body temperature in humans. J Appl Physiol *100*: 2065-2072.

Meyer F, Bar-Or O, MacDougall D, Heigenhauser GJ [1992]. Sweat electrolyte loss during exercise in the heat: effects of gender and maturation. [Research Support, Non-U.S. Gov't]. Med Sci Sports Exerc *24*(7): 776-781.

Mieusset R, Bujan L, Mansat A, Pontonnier F, Grandjean H [1987]. Effects of artificial cryptorchidism on sperm morphology. Fertil Steril *47*(1): 150-155.

Minard D [1961]. Prevention of heat casualties in Marine Corps recruits. Period of 1955-60, with comparative incidence rates and climatic heat stresses in other training categories. Mil Med *126*: 261-272.

Minard D [1973]. Physiology of heat stress. In: National Institute for Occupational Safety and Health. and United States. Public Health Service. Division of Occupational Health. (Eds.), The industrial environment - its evaluation & control 3rd ed. Washington, DC: U. S. Govt. Print. Off. pp. 399-410.

Minard D, Copman L [1963]. Elevation of body temperature in disease. In: Hardy JD (Ed.), Temperature: its measurement and control in science and industry Vol. 3. New York: Reenhold Co pp. 253.

Minson CT, Wladkowski SL, Cardell AF, Pawelczyk JA, Kenney WL [1998]. Age alters the cardiovascular response to direct passive heating. J Appl Physiol *84*(4): 1323-1332.

Montain SJ, Cheuvront SN [2008]. Fluid, electrolyte and carbohydrate requirements for exercise. In: Taylor NAS and Groeller H (Eds.), Physiological Bases for Human Performance during Work and Exercise. Edinburgh: Churchhill Livingstone Elsevier pp. 56-573.

Moran DS, Erlich T, Epstein Y [2007]. The heat tolerance test: an efficient screening tool for evaluating susceptibility to heat. [Case Reports]. J Sport Rehabil *16*(3): 215-221.

Morley J, Beauchamp G, Suyama J, Guyette FX, Reis SE, Callaway CW, Hostler D [2012]. Cognitive function following treadmill exercise in thermal protective clothing. European Journal of Applied Physiology *112*(5): 1733-1740.

Moseley PL [1994]. Mechanisms of heat adaptation: thermotolerance and acclimatization. J Lab Clin Med *123*(1): 48-52.

Mutchler JE, Malzahn DD, Vecchio JL, Soule RD [1976]. An improved method for monitoring heat stress levels in the workplace. American Industrial Hygiene Association journal *37*(3): 151-164.

Nag PK, Pradhan CK, Nag A, Ashtekar SP, Desai H [1998]. Efficacy of a water-cooled garment for auxiliary body cooling in heat. Ergonomics *41*(2): 179-187.

Navy Environmental Health Center. (2007). *Prevention and Treatment of Heat and Cold Stress Injuries*.

Nilsson M, Kjellstrom T [2010]. Climate change impacts on working people: how to develop prevention policies. Glob Health Action *3*.

NIOSH [1972]. Occupational exposure to hot environments; criteria for a recommended standard. Rockville, MD: U. S. Govt. Print. Off.

NIOSH [1985]. Occupational safety and health guidance manual for hazardous waste site activities. Cincinnati, OH: U.S. G.P.O.

NIOSH. (1986a). *Criteria for a Recommended Standard - Occupational Exposure to Hot Environments - Revised Criteria 1986*.

NIOSH. (1986b). *Working in Hot Environments, Revised 1986*.

NIOSH. (1997). *Fire Fighter Dies of Heat Stroke While Making a Fire Line During a Wildland Fire in California*: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Fatality Assessment and Control Evaluation (FACE) Investigation Report No. 97CA01001.

NIOSH. (1999). *U.S. Department of the Interior, Grand Canyon National Park, Grand Canyon, Arizona*. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, HETA #99-0321-2873.

NIOSH. (2002). *Landscape Mowing Assistant Dies from Heat Stroke*: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Fatality Assessment and Control Evaluation (FACE) Investigation Report No. 02-MI-75-01.

NIOSH. (2003a). *Assessment of Physical Hazards at an Automobile Parts Manufacturing Facility*. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, HETA 2003-0268-3065.

NIOSH. (2003b). *Evaluation of Heat Stress at a Glass Bottle Manufacturer*. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for

Disease Control and Prevention, National Institute for Occupational Safety and Health, HETA 2003-0311-3052.

NIOSH. (2004). *Construction Laborer Dies from Heat Stroke at End of Workday*: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Fatality Assessment and Control Evaluation (FACE) Investigation Report No. 03KY053.

NIOSH. (2006a). *Heat Stress and Strain Evaluation Among Aluminum Potroom Employees – Texas*. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, HETA 2006-0307-3139.

NIOSH. (2006b). *Migrant Farm Worker Dies From Heat Stroke While Working on a Tobacco Farm - North Carolina*: Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Fatality Assessment and Control Evaluation (FACE) Investigation Report No. 2006-04.

Nishi Y [1981]. Measurement of thermal balance of man. In: Cena K, Clark JA and Politechnika Wroc*awska. (Eds.), Bioengineering, thermal physiology, and comfort. Amsterdam ; New York: Elsevier Scientific Pub. Co.; New York, N.Y. : Elsevier/North-Holland [distributor] pp. 29-39.

NOAA [2012]. Heat: A Major Killer. In: http://www.nws.noaa.gov/os/heat/index.shtml]. Date accessed: 2012.

Nunneley SA [1978]. Physiological responses of women to thermal stress: a review. Med Sci Sports *10*(4): 250-255.

O'Neal EK, O'Neal P, Bishop [2010]. Effects of work in a hot environment on repeated performances of multiple types of simple mental tasks. International journal of industrial ergonomics *40*(1): 77-81.

OSHA-NIOSH [2011]. OSHA-NIOSH Infosheet: Protecting Workers from Heat Illness.

OSHA. Monitoring Workers at Risk of Heat-related Illness. In: http://www.osha.gov/SLTC/heatillness/heat_index/monitoring_workers.html]. Date accessed: April 24, 2013

OSHA. (1999). *OSHA Technical Manual, Section III, Chapter 4, Heat stress*. Retrieved 06/28/2011. from http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html

OSHA [2012a]. Heat Safety Tool. In: http://www.osha.gov/SLTC/heatillness/heat_index/heat_app.html]. Date accessed: September 14 2012.

OSHA [2012b]. OSHA's Campaign to Prevent Heat Illness in Outdoor Workers. In: http://www.osha.gov/SLTC/heatillness/index.html]. Date accessed: September 14 2012.

OSHA [2012c]. Using the Heat Index: A Guide for Employers. In: http://www.osha.gov/SLTC/heatillness/heat_index/using_heat_protect_workers.html]. Date accessed: September 13 2012.

Pandolf KB, Burse RL, Goldman RF [1977]. Role of physical fitness in heat acclimatisation, decay and reinduction. Ergonomics *20*(4): 399-408.

Pandolf KB, Griffin TB, Munro EH, Goldman RF [1980a]. Heat intolerance as a function of percent of body surface involved with miliaria rubra. Am J Physiol *239*(3): R233-240.

Pandolf KB, Griffin TB, Munro EH, Goldman RF [1980b]. Persistence of impaired heat tolerance from artificially induced miliaria rubra. Am J Physiol *239*(3): R226-232.

Parker RD, Pierce FD [1984]. Comparison of heat stress measuring techniques in a steel mill. Am Ind Hyg Assoc J *45*(6): 405-415.
Parsons KC [2003]. Human Thermal Control: The effects of hot, moderate, and cold environments on human health, comfort, and performance (2nd ed.). London: Taylor and Francis.
Pleet H, Graham JM, Jr., Smith DW [1981]. Central nervous system and facial defects associated with maternal hyperthermia at four to 14 weeks' gestation. Pediatrics *67*(6): 785-789.
Procope BJ [1965]. Effect of repeated increase of body temperature on human sperm cells. [In Vitro]. Int J Fertil *10*(4): 333-339.
Rachootin P, Olsen J [1983]. The risk of infertility and delayed conception associated with exposures in the Danish workplace. J Occup Med *25*(5): 394-402.
Ramsey JD [1975]. Heat stress standard: OSHA's Advisory Committee recommendations. Natl Saf News: 89-95.
Ramsey JD, Beshir MY [2003]. Thermal standards and measurement techniques. In: DiNardi SR (Ed.), The occupational environment: its evaluation and control 2nd ed.: American Industrial Hygiene Association.
Ramsey JD, Burford CL, Beshir MY, Jensen RC [1983]. Effects of workplace thermal conditions on safe work behavior. J Safety Research *14*: 105-114.
Ramsey JD, Morrissey SJ [1978]. Isodecrement curves for task performance in hot environments. Appl Ergon *9*(2): 66-72.
Roller WL, Goldman RF [1967]. Estimation of solar radiation environment. Int J Biometeorol *11*: 329-336.
Roti MW, Casa DJ, Pumerantz AC, Watson G, Judelson DA, Dias JC, Ruffin K, Armstrong LE [2006]. Thermoregulatory responses to exercise in the heat: chronic caffeine intake has no effect. Aviat Space Environ Med *77*(2): 124-129.
Rowell LR [1977]. Competition between skin and muscle for blood flow during exercise. In: Nadel ER and American College of Sports Medicine. (Eds.), Problems with temperature regulation during exercise. New York: Academic Press pp. 49-76.
Rowell LR [1993]. Human Cardiovascular Control. In. New York: Oxford University Press pp. 162-203.
Rutstein DD, Mullan RJ, Frazier TM, Halperin WE, Melius JM, Sestito JP [1983]. Sentinel Health Events (occupational): a basis for physician recognition and public health surveillance. Am J Public Health *73*(9): 1054-1062.
Schulte PA, Chun H [2009]. Climate change and occupational safety and health: establishing a preliminary framework. J Occup Environ Hyg *6*(9): 542-554.
Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, Wilhelm JL [1996]. Heat-related deaths during the July 1995 heat wave in Chicago. N Engl J Med *335*(2): 84-90.
Serafin WE [1996]. Drugs used in the treatment of asthma. In: Hardman JG, Limbird LE, Molinoff PB, Ruddon RW and Gillman AG (Eds.), Goodman & Gilman's The Pharmacologic Basis of Therapeutics 9th ed. New York: McGraw Hill pp. 659-682.
Shibolet S, Lancaster MC, Danon Y [1976]. Heat stroke: a review. Aviat Space Environ Med *47*(3): 280-301.
Shvartz E, Benor D [1972]. Heat strain in hot and humid environments. Aerosp Med *43*(8): 852-855.

Siconolfi SF, Garber CE, Lasater TM, Carleton RA [1985]. A simple, valid step test for estimating maximal oxygen uptake in epidemiologic studies. Am J Epidemiol *121*(3): 382-390.
Slappendel C, Laird I, Kawachi I, Marshall S, Cryer C [1993]. Factors affecting work-related injury among forestry workers: a review. J Safety Res *24*: 19-32.
Smith JI, Ramsey JD [1980]. Designing physically demand tasks to minimize levels of worker stress. Industr Engineering *14*(44-50).
Spaul WA, Greenleaf JE [1984]. Heat Stress Field Study. US Navy Med *75*: 25-33.
Springer K [1985]. If you can't stand the heat. Ohio Monitor *58*: 4-9.
Stegman J [1981]. Exercise physiology. Chicago: Year Book Medical Publisher, Inc.
Stewart JM. (1979). *The use of heat transfer and limiting physiological criteria as a basis for setting heat stress limits*. Paper presented at the 2nd International Mine Ventilation Congress, Reno, NV.
Strydom NB [1971]. Age as a causal factor in heat stroke. J of the South African Institute of Mining and Metallurgy *72*: 112-114.
Strydom NB [1975]. Physical work and heat stress. In: Zenz C (Ed.), Occupational medicine: principles and practical applications. Chicago,: Year Book Medical Publishers pp. 469-492.
Strydom NB, Kotze HF, van der Walt WH, Rogers GG [1976]. Effect of ascorbic acid on rate of heat acclimatization. J Appl Physiol *41*(2): 202-205.
Tanaka M [2007]. Heat stress standard for hot work environments in Japan. Ind Health *45*(1): 85-90.
Taylor NAS, Kondo N, Kenny WL [2008]. The physiology of acute heat exposure, with implications for human performance in the heat. In: Taylor NAS and Groeller H (Eds.), Physiological bases of human performance during work and exercise 1st ed. Edinburgh: Elsevier pp. 341-358.
TBMed. (2003). *Heat Stress Control and Heat Casualty Management*. Retrieved. from.
Thonneau P, Ducot B, Bujan L, Mieusset R, Spira A [1997]. Effect of male occupational heat exposure on time to pregnancy. Int J Androl *20*(5): 274-278.
Tipton M, Pandolf K, Sawka M, Werner J, Taylor N [2008]. Physiological adaptation to hot and cold environments. In: Taylor N and Groeller H (Eds.), Physiological Bases of Human Performance during Work and Exercise. Edinburgh: Churchill Livingstone Elevier pp. 379-400.
Undem BJ [2006]. Pharmacotherapy of asthma. In: Brunton LL, Lazo JS and Parker KL (Eds.), Goodman & Gilman’s The Pharmacologic Basis of Therapeutics 11th ed. New York: McGraw Hill pp. 717-736.
US EPA/OSHA. (1993). *A guide to heat stress in agriculture (EPA-750-b-92-001)*. Retrieved. from http://www.osha.gov/SLTC/heatillness/heat_index/work_rest_schedules.html.
Vogt JJ, Candas V, Libert JP [1982]. Graphical determination of heat tolerance limits. Ergonomics *25*(4): 285-294.
Vroman NB, Buskirk ER, Hodgson JL [1983]. Cardiac output and skin blood flow in lean and obese individuals during exercise in the heat. J Appl Physiol *55*(1 Pt 1): 69-74.
Wallace RF, Kriebel D, Punnett L, Wegman DH, Amoroso PJ [2007]. Prior heat illness hospitalization and risk of early death. Environ Res *104*(2): 290-295.

Washington State Legislature. WAC 296-62-09510 Scope and purpose. In: http://apps.leg.wa.gov/WAC/default.aspx?cite=296-62-09510]. Date accessed: March 25, 2013

Watson S [2011, September 9, 2011]. The Truth About Urine. In: http://www.webmd.com/urinary-incontinence-oab/features/the-truth-about-urine]. Date accessed: September 18 2012.

Wells CL, Buskirk ER [1971]. Limb sweating rates overlying active and nonactive muscle tissue. J Appl Physiol *31*(6): 858-863.

WHO. (1969). *Health factors involved in working under conditions of heat stress*. Geneva: World Health Organization.

Williams WJ, Coca A, Roberge R, Shepherd A, Powell J, Shaffer RE [2011]. Physiological responses to wearing a prototype firefighter ensemble compared with a standard ensemble. J Occup Environ Hyg *8*: 49-57.

Williams WJ, Schneider SM, Stuart CA, Gretebeck RJ, Lane HW, Whitson PA [2003]. Effect of dietary sodium and fluid/electrolyte regulation in humans during bed rest. Aviat Space Environ Med *74*(1): 37-46.

Wilson E. (2008). Heat Stress Prevention Heats Up in California. *EHS Today*.

Witten L. (1980). *Comments on mathematical models for thermoregulatory behavior*. Paper presented at the NIOSH workshop on recommended heat stress standards, Cincinnati.

Wyndham CH [1973]. The physiology of exercise under heat stress. Annu Rev Physiol *35*: 193-220.

Wyndham CH [1974a]. 1973 Yant Memorial Lecture: research in the human sciences in the gold mining industry. Am Ind Hyg Assoc J *35*(3): 113-136.

Wyndham CH [1974b]. Research in the human sciences in the gold mining industry. Am Ind Hyg Assoc J *35*: 113-136.

Wyndham CH, Heyns AJ [1973]. The probability of heat stroke developing at different levels of heat stress. Arch Sci Physiol (Paris) *27*(4): 545-562.

Yeargin SW, Casa DJ, Armstrong LE, Watson G, Judelson DA, Psathas E, Sparrow SL [2006]. Heat acclimatization and hydration status of American football players during initial summer workouts. J Strength Cond Res *20*(3): 463-470.