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XII. APPENDIX A
GLOSSARY OF TERMS AND SYMBOLS
ADAPTED IN PART FROM REFERENCES 166 and 167

ACCLIMATIZATION: The physiologic 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 DuBois 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 ($H=M\pm C\pm R-E$).

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/h°C.

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.

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 a 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.

HEATSTROKE: 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 41.1°C (106°F).

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 40°C (104°F).

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

INSENSIBLE PERSPIRATION: Water that passes through the skin by diffusion.

MAXIMUM OXYGEN CONSUMPTION ($\dot{V}O_2max$): 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 (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 an 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 ($Aw/SWA_{Du}x100$): 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 meterologic 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
h_c	Convective 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	b/min
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	$Wm^{-2}/°C^{-1}$; $kcal/h^{-1}/m^{-2}°C^{-1}$; $Btu/h^{-1}/ft^{-2}°F^{-1}$
I_a	Thermal insulation of still air layer	clo
I_{cl}	Thermal insulation of clothing layer	clo

SYMBOLS

Symbol	Term	Units
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	$Wm^{-2}/°C^{-1}$; kcal $m^{-2}/h^{-1}/°C^{-1}$; $Btu/h^{-1}/ft^{-2}°F^{-1}$
S	Sweat produced	l,g,kg
SR	Sweat produced per unit time	g/min,g/h,kg/min,kg/h
SV	Stroke volume - amount of blood pumped by the heart per beat	ml
SWA	Area of skin wet with sweat	m^2
%SWA	SWA/A_{Du}x100 = % of body surface wet with sweat	percent
T	Absolute temperature (t+273)	°K,TR
t_a	Ambient air dry bulb temperature	°C, °F
t_{adb}	Ambient dry bulb temperature adjusted for solar radiation	°C, °F
t_{cr}	Body core temperature	°C, °F
t_g	Black globe temperature	°C, °F

SYMBOLS

Symbol	Term	Units
t_{nwb}	Natural wet bulb temperature	°C, °F
t_o	Operative temperature	°C, °F
t_r	Radiant temperature	°C, °F
$\bar{t}_r$	Mean radiant temperature	°C, °F
t_{re}	Rectal temperature	°C, °F
t_{sk}	Skin temperature	°C, °F
$\bar{t}_{sk}$	Mean skin temperature	°C, °F
t_{wb}	Psychrometric wet bulb temperature	°C, °F
t_{wg}	Wet globe temperature	°C, °F
V_a	Air velocity	ms, fpm
$\dot{V}O_2max$	Maximum aerobic capacity	mL/min, l/h
μ	Mechanical efficiency of work	%, percent
ω	Skin wettedness	dimensionless
δ	Stefan-Bolzmann constant	$Wm^{-2}K^4$
ε	Emittance coefficient	dimensionless

APPENDIX B
HEAT-EXCHANGE EQUATION UTILIZING THE SI UNITS

1. 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

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

The value of h_c is different for the different parts of the body [11] 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 investigators have tried to simplify the calculation of convective heat exchange. Most recently the ISO Working Group on the Thermal Environment (ISO-WGTE) developed a draft standard for the Analytical Determination of Heat Stress [16]. One of the simplifications they adopted is to use only the following three values for h_c which are expressed in units of $Wm^{-2}°C^{-1}$, 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 convective 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 h_r and I_{cl} will be explained later in this appendix in more detail. The ISO-WGTE recommended the use of 36°C (96.8°F) 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 work is done in an upright body position, thus h_c does not have to be 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:

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

2. <u>Radiation (R) SI Units</u>

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

$$R=h_r(T_r-T_{sk})^4$$

where:

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

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:

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

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

= $(5.67x10^{-8})Wm^{-2}°K^{-4}$

The effect of the emissivity of the skin on radiant heat exchange is covered by the expression 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 DuBois' formula.

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

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 36°C, just as it was in the equation for convection.

3. 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 IV, the sweating capacity of healthy individuals is influenced by age, sex, state of hydration, and acclimatization.

The draft ISO-WGTE [16] 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 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 36°C

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:

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

where:

I_{cl} = Thermal insulation of clothing (m^2 °C 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 the 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 ($g\ h^{-1}\ m^{-2}$)x0.68

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 the 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.

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