criteria for a recommended standard . . . .

OCCUPATIONAL EXPOSURE TO HOT ENVIRONMENTS

Revised Criteria 1986

NIOSH

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTERS FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

Criteria for a Recommended Standard....

Occupational Exposure to Hot Environments

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U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health
Division of Standards Development and Technology Transfer

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

April 1986

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DHHS (NIOSH) Publication No. 86-113

FOREWORD

The Occupational Safety and Health Act of 1970 (Public Law 91-596) states that the purpose of Congress expressed in the Act is "to assure so far as possible every working man and woman in the Nation safe and healthful working conditions and to preserve our human resources...by," among other things, "providing medical criteria which will assure insofar as practicable that no worker will suffer diminished health, functional capacity, or life expectancy as a result of his work experience." In the Act, the National Institute for Occupational Safety and Health (NIOSH) is authorized to "develop and establish recommended occupational safety and health standards..." and to "conduct such research and experimental programs as...are necessary for the development of criteria for new and improved occupational safety and health standards..."

The Institute responds to these mandates by means of the criteria document. The essential and distinguishing feature of a criteria document is that it recommends a standard for promulgation by an appropriate regulatory body, usually the Occupational Safety and Health Administration (OSHA) or the Mine Safety and Health Administration (MSHA) of the U.S. Department of Labor. NIOSH is also responsible for reviewing existing OSHA and MSHA standards and previous recommendations by NIOSH, to ensure that they are adequate to protect workers in view of the current state of knowledge. Updating criteria documents, when necessary, is an essential element of that process.

A criteria document, Criteria for a Recommended Standard....Occupational Exposure to Hot Environments, was prepared in 1972. The current revision presented here takes into account the vast amount of new scientific information on working in hot environments which is pertinent to safety and health. Included are ways of predicting the health risks, procedures for control of heat stress, and techniques for prevention and treatment of heat-related illnesses.

External review consultants drawn from academia, business associations, labor organizations, private consultants, and representatives of other governmental agencies, contributed greatly to the form and content of this revised document. However, responsibility for the conclusions reached and the recommendations made, belongs solely to the Institute. All comments by reviewers, whether or not incorporated into the document are being sent with it to the Occupational Safety and Health Administration (OSHA) for consideration in standard setting.

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ACKNOWLEDGMENTS

This revised document was prepared by the staff of the Division of Standards Development and Technology Transfer with assistance from the Division of Biomedical and Behavioral Sciences. The responsibility for the development of the document was that of Austin Henschel, Ph.D., with the assistance of Francis N. Dukes-Dobos, M.D., Jay Klemme, M.D., and Nelson A. Leidel, Sc.D. Robert Bernstein, M.D., Ph.D., Paul Caplan, Burt J. Cooper, Jim Ferguson, Jerome Flesch, John Jankovic, Richard Ronk, William D. Wagner, Mary Kay White, Ph.D., and Ralph D. Zumwalde are gratefully acknowledged for their contributions to the critical review of this document. A special appreciation is extended to Carolyn A. Browning and Myrtle Heid for their editorial review, and to Judy Curless and Constance Klinker for their support in typing and finalizing the document for publication.

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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 recommended standard found in this document. This recommended standard should prevent or greatly reduce the risk of adverse health effects to exposed workers and will be subject to review and revision as necessary.

Heat-induced occupational illnesses, injuries, and reduced productivity occur in situations in which 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. However, at some level 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-induced illnesses, disorders, 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 casualty. 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-induced illnesses and unsafe acts among a group of workers in a hot environment, or the recurrence of such problems in, individual workers, represents "sentinel health events" (SHE's) which indicate that heat control measures, medical screening, or environmental monitoring measures may not be adequate [1]. One or more occurrences of heat-induced illness in a particular worker indicates the need for medical inquiry about the possibility of temporary or permanent loss of the worker's ability to tolerate heat stress. The recommended requirements in the following sections are intended to establish the permissible limits of total heat stress so that the risk of incurring heat-induced 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 (RAL's) given in Figure 1, should be able 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 (REL's) given in Figure 2, should 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 in reference [2].

At combinations of environmental and metabolic heat exceeding the Ceiling Limits (C) in Figures 1 and 2, no worker shall be exposed without adequate heat-protective clothing and equipment. 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, the Ceiling Limits were calculated using the heat balance equation given in Chapter III, Section A.

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 I, IV, VI, and VII. 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 and comments of peer reviewers. This may include both absolute and relative exclusionary indicators related to age, stature, gender, percent body fat, medical and occupational history, specific chronic diseases or therapeutic regimens, and the results of such tests as the maximum aerobic capacity ($\dot{V}O_2max$), electrocardiogram (EKG), pulmonary function tests (PFTs), and chest x rays (CXRs).

The medical surveillance program shall be designed and implemented in such a way as 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 IV, VI, and VII). The medical program shall provide for 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.

Section 1 - Workplace Limits and Surveillance

(a) Recommended Limits

(1) Unacclimatized workers: Total heat exposure to workers shall 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 RAL's given in Figure 1.

(2) Acclimatized workers: Total heat exposure to workers shall 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 REL's given in Figure 2.

(3) Effect of Clothing: The recommended limits given in Figures 1 and 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 1 and 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 Chapter III, Section C.

(4) Ceiling Limits: No worker shall be exposed to combinations of metabolic and environmental heat exceeding the applicable Ceiling Limits (C) of Figures 1 or 2 without being provided with and properly using appropriate and adequate heat-protective clothing and equipment.

(b) Determination of Environmental Heat

(1) Measurement methods: Environmental heat exposures shall 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 (as described in Chapters V and IX). The WBGT shall 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.

(2) Measurement requirements: Environmental heat measurements shall 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 shall be measured at each area and during each period of constant heat levels where employees are exposed. Hourly TWA WBGTs shall be calculated for the combination of jobs (tasks), including all scheduled and unscheduled rest periods.

(3) Modifications of work conditions: Environmental heat measurements shall 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 shall 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.

(4) Initiation of measurements: A WBGT or an individual environmental factors profile shall 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 shall be instituted. After the environmental profiles have been established, measurements shall be made as described in (b)(1), (2), and (3) of this section during the time of year and days when the profile indicates that total heat exposures above the applicable RAL's or REL's 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.

(c) Determination of Metabolic Heat

(1) Metabolic heat screening estimates: For initial screening purposes, metabolic heat rates for each worker shall either be measured as required in (c)(2) of this section or shall be estimated from Table V-3 to determine whether the total heat exposure exceeds the applicable RAL or REL. For determination of metabolic heat, Table V-3 shall be used only for screening purposes unless other reliable and valid baseline data have been developed and confirmed by the indirect open-circuit method specified in (c)(2) of this Section. When computing metabolic heat estimates using Table V-3 for screening purposes, the metabolic heat production in kilocalories per minute shall be calculated using the upper value of the range given in Table V-3 for each body position and type of work for each specific task(s) of each worker's job.

EXAMPLE:

As shown in Table V-3 (D, Sample calculation), for a task that requires the worker to stand and use both arms, the values to be added would be 0.6 kilocalories per minute (kcal/min) for standing, 3.5 kcal/min for working with both arms, and 1.0 kcal/min for basal metabolism, for a total metabolic heat of 5.1 kcal/min for a worker who weighs 70 kilograms (kg)(154 lb). For a worker that has other than a 70-kg weight, the metabolic heat shall be corrected by the factor (actual worker weight in kg/70 kg). Thus for an 85-kg worker the factor would be (85/70) = 1.21 and the appropriate estimate for metabolic heat would be (1.21)(5.1) = 6.2 kcal/min for the duration of the task.

(2) Metabolic heat measurements - Whenever the combination of measured environmental heat (WBGT) and screening estimate of metabolic heat exceeds the applicable RAL or REL (Figures 1 and 2), the metabolic heat production shall be measured using the indirect open-circuit procedure (see Chapter V) or an equivalent method.

Metabolic heat rates shall 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:

For the example in (c)(1), if the task was performed by an acclimatized 70-kg worker for the entire 60 minutes of each hour, the screening estimate for the 1-hour TWA metabolic heat would be (5.1 kcal/min)(60 min) = about 300 kcal/h. Using the applicable Figure 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 1 indicates that metabolic heat measurement of the worker would be required above a WBGT of 25°C (77°F).

(d) Physiologic Monitoring

Physiologic monitoring may be used as an adjunct monitoring procedure to those estimates and measurements required in the preceding Parts (a), (b), and (c) of this section. The total heat stress shall be considered to exceed the applicable RAL or REL when the physiologic functions (e.g., core or oral body temperature, work and recovery pulse rate) exceed the values given in Chapter IX, Section D.

Section 2 - <u>Medical Surveillance</u>

(a) General

(1) The employer shall institute a medical 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 shall assure that all medical examinations and procedures are performed by or under the direction of a licensed physician.

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

(b) Preplacement Medical Examinations

For the purposes of the preplacement medical examination, all workers shall be considered to be unacclimatized to hot environments. At a minimum, the preplacement medical examination of each prospective worker for a hot job shall 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 shall contain relevant information on the cardiovascular system, skin, liver, kidney, and the nervous and respiratory systems;

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

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

(4) An assessment of obesity (body fatness), 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 Chapter VII, Section B-1.

(c) Periodic Medical Examinations

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

(d) Emergency Medical Care

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

(e) Information to be Provided to the Physician

The employer shall provide the following information to the examining physician 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.

(f) Physician's Written Opinion

The employer shall obtain a written opinion from the responsible physician which shall include:

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

(2) The physician's opinion as to whether the worker has any detected medical conditions which would increase the risk of material impairment of health from exposure to anticipated heat stress 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 of the results of the medical examination and any medical conditions which require further explanation or treatment.

The employer shall provide a copy of the physician's written opinion to the affected worker.

Section 3 - Surveillance of Heat-Induced Sentinel Health Events

(a) Definition

Surveillance of heat-induced Sentinel Health Events (SHE's) 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.

(b) 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-induced adverse effects shall be obtained and analyzed for each workplace.

Section 4 - Posting of Hazardous Areas

(a) 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 Ceiling Limit, there shall 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 shall 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-INDUCED FAINTING, HEAT EXHAUSTION, HEAT CRAMP,
HEAT RASH OR HEAT STROKE MAY OCCUR

(b) Emergency Situations

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

(c) Additional Requirements for Warning Signs

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

Section 5 - Protective Clothing and Equipment

Engineering controls and safe work practices shall be used to maintain worker exposure to heat stress at or below the applicable RAL or REL specified in Section 1. In addition, protective clothing and equipment (e.g., water-cooled garments, air-cooled garments, ice-packet vests, wetted-overgarments, heat-reflective aprons or suits) shall be provided by the employer to the workers when the total heat stress exceeds the Ceiling Limit.

Section 6 - Worker Information and Training

(a) 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, shall 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 VII),

(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.

(b) Continuing Education Programs

(1) The employer shall 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 (a) of this section. For each affected worker, the instructional program shall include adequate verbal and/or written communication of the specified information. The employer shall develop a written plan of the training program that includes a record of all instructional materials.

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

(c) Heat-Stress Safety Data Sheet

(1) The information specified in (a) of this section shall 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 shall contain:

(i) Emergency and first aid procedures, and

(ii) Notes to physician regarding classification, medical aspects, and prevention of heat injury and illness. These notes shall include information on the category and clinical features of each injury and illness, predisposing factors, underlying physiologic disturbance, treatment, and prevention procedures (see Table IV-1).

Section 7 - Control of Heat Stress

(a) General Requirements

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

(2) The employer shall 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.

(b) 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 III and VI). When the environmental heat exceeds the applicable RAL or REL, the following control requirements shall be used.

(a) When the air temperature exceeds the skin temperature, convective heat gain shall 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 shall 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 shall be reduced by: placing shielding or barriers, that 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 shall 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.

(c) Work and Hygienic Practices

(1) Work modifications and hygienic practices shall 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 shall be provided.

(d) Heat-Alert Program

A written Heat-Alert Program shall 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 Chapter VI, Section C.

Section 8 - Recordkeeping

(a) Environmental Surveillance

(1) The employer shall establish and maintain an accurate record of all measurements made to determine environmental and metabolic

heat exposures to workers as required in Section 1 of this recommended standard.

(2) Where the employer has determined that no metabolic heat measurements are required as specified in Section 1, Part (c)(2) of this recommended standard, the employer shall maintain a record of the screening estimates relied upon to reach the determination.

(b) Medical Surveillance

The employer shall establish and maintain an accurate record for each worker subject to medical surveillance as specified in Section 2 of this recommended standard.

(c) Surveillance of Heat-Induced Sentinel Health Events

The employer shall establish and maintain an accurate record of the data and analyses specified in Section 3 of this recommended standard.

(d) Heat-Induced Illness Surveillance

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

(e) Heat Stress Tolerance Augmentation

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

(f) Record Retention

In accordance with the requirements of 29 CFR 1910.20(d), the employer shall 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-induced SHE's, and

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

(g) Availability of Records

(1) The employer shall 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-induced SHE's, or records of heat stress tolerance augmentation that are required by this recommended standard shall 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.

(h) Transfer of Records

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

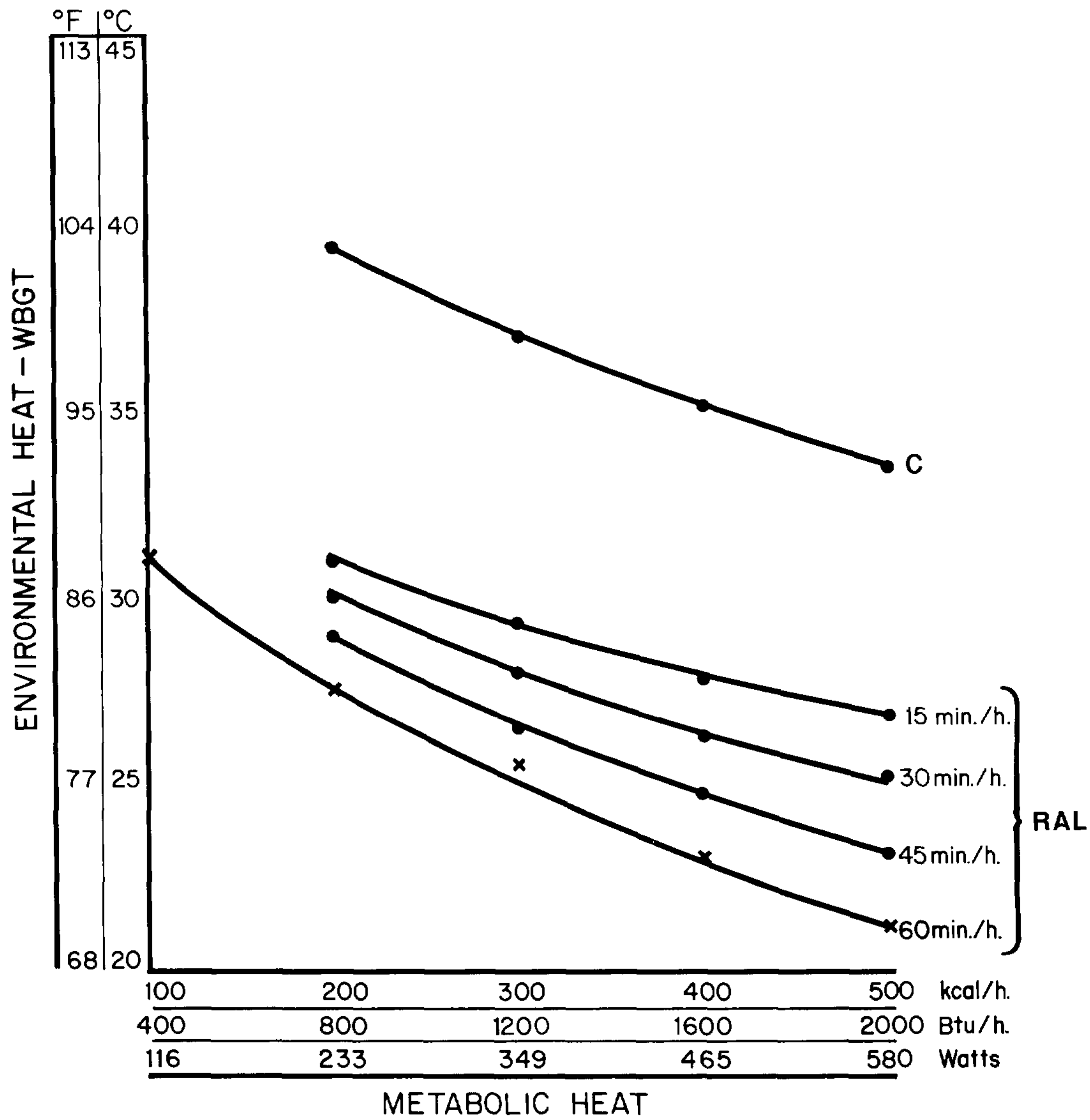

Figure 1. Recommended Heat-Stress Alert Limits
Heat-Unacclimatized Workers

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.
Based on References 2,3,4,5,6,7,8.

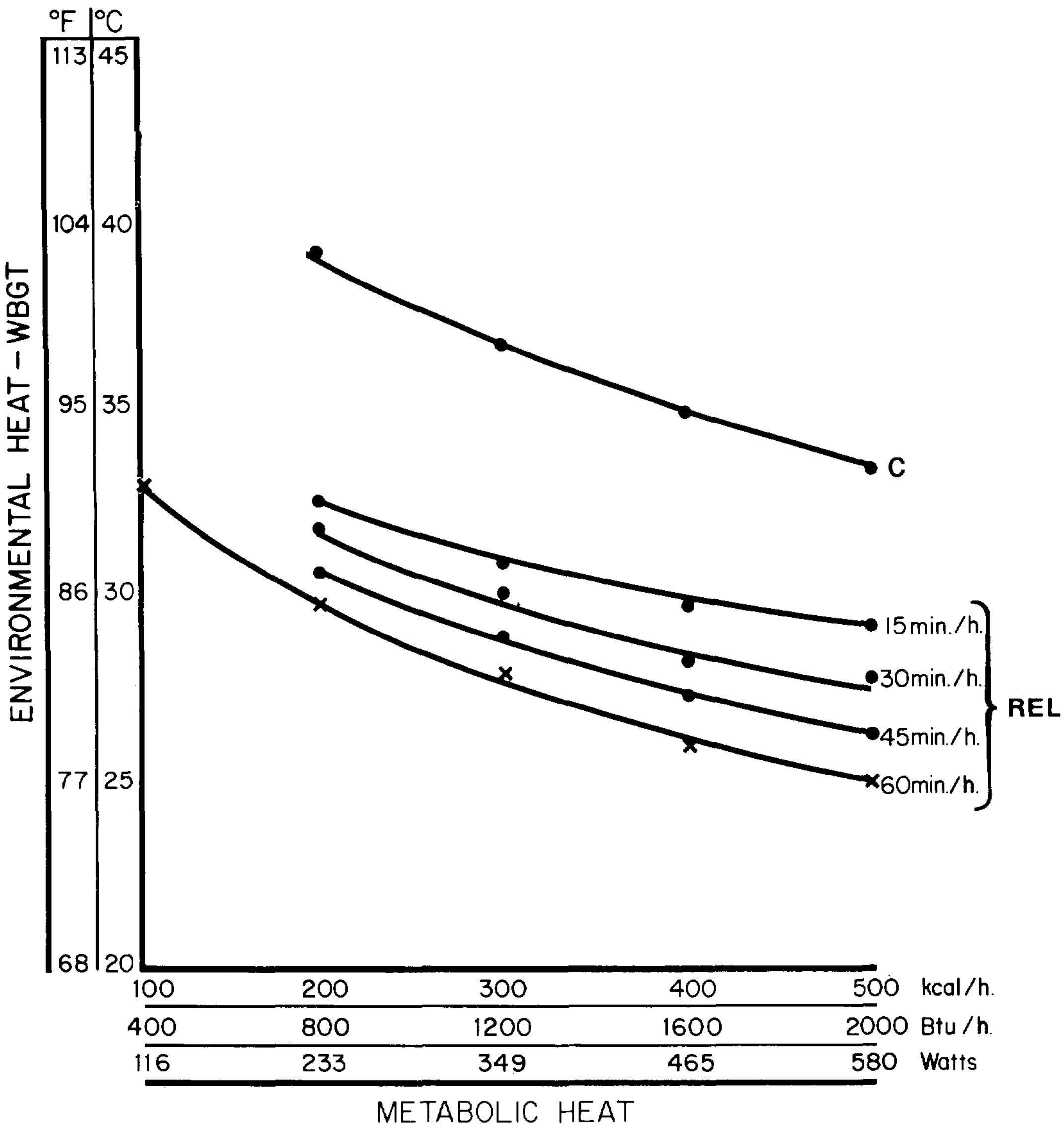

Figure 2. Recommended Heat-Stress Exposure Limits
Heat-Acclimatized Workers

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.
Based on References 2,3,4,5,6,7,8.

II. 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. In the Act, NIOSH is charged with developing criteria documents for toxic chemical substances and harmful physical agents which will describe exposure levels that are safe for various periods of employment including but not limited to the exposure levels at which no worker will suffer impaired health or functional capacities or diminished life expectancy as a result of any work experience. Environmental heat is a potentially harmful physical agent. This document presents the criteria and recommendations for a standard that were prepared to meet the need for preventing heat-induced health impairment resulting from exposure to occupational heat stress.

This document is an update of the Criteria for a Recommended Standard.... Occupational Exposure to Hot Environments (HSM-10269) published by NIOSH in January 1972 [9]. In June 1972, NIOSH sent the criteria document to the Occupational Safety and Health Administration (OSHA). In January 1973, the Assistant Secretary of Labor for Occupational Safety and Health appointed a 15 member Standards Advisory Committee on Heat Stress to review the NIOSH criteria document and develop a proposed standard. The committee submitted a proposed standard to the Assistant Secretary of Labor, OSHA, in January 1974 [7]. A standard on occupational exposure to hot environments was not promulgated. The updating of this document is based on the relevant scientific data and industry experience that have accrued since the original document was prepared. The document presents the criteria, techniques, and procedures for the assessment, evaluation, and control of occupational heat stress by engineering and preventive work practices and those for the recognition, treatment, and prevention of heat-induced illnesses and unsafe acts by medical supervision, hygienic practices, and training programs.

The recommended criteria were developed to ensure that adherence to them will (1) protect against the risk of heat-induced illnesses and unsafe acts, (2) be achievable by techniques that are valid, reproducible, and available, and (3) be attainable by 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 1 and 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 illnesses even in the least heat-tolerant workers.

Estimates of the number of industrial workers who are exposed to heat stress on the job are at best rough guesses. A review of the Statistical Abstracts of the United States, 105th edition 1985, for the number of workers in industries where heat stress is a potential safety and health hazard indicates that a conservative estimate would be 5 to 10 million workers [10].

A glossary of terms, symbols, abbreviations, and units of measure used in this document is presented in XII-A.

III. 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). To achieve 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.

A. 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 [2,7,11,12,13,14,15,16,17,18,19,20,21].

B. Modes of Heat Exchange

The major modes of heat exchange between man and the environment are convection, radiation, and evaporation. Other than for brief periods of body contact with hot tools, equipment, floors, etc., which may cause burns, conduction plays a minor role in industrial heat stress.

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 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 workshirt and trousers. The values are 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 [13]. The equations utilizing the SI units for heat exchange by C, R, and E are presented in Appendix B.

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.

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 [13]:

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

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 man" 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)

2. Radiation (R)

The radiative 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 $(T_w - T_{sk})^4$ but an acceptable approximation for the customary one-layer clothed individual is [13]:

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

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 °F

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

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 [13]:

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

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

C. 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 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 [22,23,24]. 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, radiative, and evaporative heat exchange.

Calculating heat exchange, when it must be modified by the F_{cl}, is a time consuming and complex task that requires the use of a hand held programmable calculator [133]. 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 [168]. 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 scientific 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 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) [169].

1. Clothing Insulation and Nonevaporative 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 (I_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 average man with 1.8 m^2 of surface area, the hourly heat exchange by radiation and convection (H_{R+C}) can be estimated as:

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

Thus, the 0.8 clo still air layer limits the heat exchange by radiation and convection for the nude standard individual 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 worker 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} [14].

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 [14].

The typical value for clothing insulation is 1.57 clo per centimeter of thickness (4 clo per inch). It is difficult to extend this generalization to very thin fabric layers or to fabrics which, like underwear, 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 [14,24,25]. Table III-1 presents a listing for the intrinsic insulation contributed by adding each of the listed items of civilian clothing.

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.

TABLE III-1.--Clo insulation units for individual items of clothing and formula for obtaining total insulation (I_{cl})

Clothing	Men	Clothing	Women
Underwear			
Sleeveless	0.06	Bra and Panties	0.05
T-shirt	0.09	Half slip	0.13
Underpants	0.05	Full slip	0.19
Torso			
Shirt		Blouse	
Light, short sleeve	0.14	Light	0.20[a]
long sleeve	0.22	Heavy	0.29[a]
Heavy, short sleeve	0.25	Dress	
long sleeve	0.29	Light	0.22[a,b]
(Plus 5% for tie or turtleneck)		Heavy	0.90[a,b]
Vest		Skirt	
Light	0.15	Light	0.10[b]
Heavy	0.29	Heavy	0.22[b]
Trousers		Slacks	
Light	0.26	Light	0.26
Heavy	0.32	Heavy	0.44
Sweater		Sweater	
Light	0.20[a]	Light	0.17[a]
Heavy	0.37[a]	Heavy	0.37[a]
Jacket		Jacket	
Light	0.22	Light	0.17
Heavy	0.49	Heavy	0.37
Footwear			
Socks		Stockings	
Ankle length	0.04	Any length	0.01
Knee-high	0.10	Panty hose	0.01
Shoes		Shoes	
Sandals	0.02	Sandals	0.02
Oxfords	0.04	Pumps	0.04
Boots	0.08	Boots	0.08

Total I_{cl} = 0.80 (individual items) plus the external air layer of 0.8

[a]Less 10% if short sleeve or sleeveless
[b]Plus 5% if below knee length, less 5% if above

Adapted from Reference 25.

In summary, insulation is generally a function of the thickness of the clothing ensemble, and this, 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; most three-layer systems are comparable, regardless of some rather major differences in fiber or fabric type [14].

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 <u>not</u> 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 man with 1.8 m^2 of surface area, as:

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

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 [14,20,26].

3. Physiologic Problems of Clothing

The percent of sweat-wetted skin surface area ($\underline{w}$) that will be required 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 exercise 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 with between 20% and 40% wetting of the body surface, and performance decrements can appear; 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 workers. 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 [20].

The physiologic problem with clothing, heat transfer, and 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 (b/min) (CO=SVxHR). 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. The blood supply (or cardiac output) is a function of HR times SV (HRxSV). 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.

Stroke volume 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 heart rate; the individual worker's maximum heart rate 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 heart rate is a function of age and can be roughly estimated by the relationship: 220 b/min minus age in years [27,28]. Given equivalent HR at rest (e.g., 60 b/min), a 20-year-old worker's HR has the capacity to increase by 140 b/min, i.e., (220-20)-60 while a 60-year-old worker can increase his HR only 100 b/min, 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 decrease in HR increase capacity 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 also is a function of the cardiac output. 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 cardiac output 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 (0.7°F), 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 [20,26].

Work under a heat-stress condition sets up a competition for cardiac output, 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 stroke volume to decrease; therefore, heart rate must increase to maintain the same cardiac output.

For a fit, young workforce, the average work heart rate should be limited to about 110 b/min if an 8-hour workshift is to be completed; an average heart rate of 140 b/min for a maximum work time of 4 hours or less, and 160 b/min should not be maintained for more than 2 hours [29]. If the intensity of work results in a heart rate 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 the inadequate blood supply to the brain; this occurs when cardiac output 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 heart rates approach their maxima.

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 $M+H_{R+C}>0$), but is limited either by high ambient water vapor pressure, low wind, or 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) are considered undesirable for an average industrial workforce. 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-induced illness. Finally, t_{re} levels above 41°C (105.8°F) are associated with heatstroke, a life-threatening major medical emergency. The competition for cardiac output is sorely exacerbated by hypohydration (limited stroke volume), by age (limited maximum heart rate), and by reduced physical fitness (compromised cardiac output). 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 [20,26].

IV. BIOLOGIC EFFECTS OF HEAT

A. Physiologic Responses to Heat

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. In general terms, the anterior hypothalamus operates as a 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.

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 [30]. These monoamine transmitters are important in the passage of appropriate information to the posterior hypothalamus. Another neuronal transmitter is acetylcholine. It is known that the "set point" in the posterior hypothalamus is regulated by ionic exchanges.

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. However, the "set-point" hypothesis has recently generated considerable controversy [31].

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.

The posterior hypothalamus, besides determining the "set-point," is also responsible for mobilizing the physiologic mechanisms required to maintain that temperature. In situations where the "set-point" temperature is exceeded, the circulation is controlled on a regional basis through the sympathetic nervous system to dilate the cutaneous vascular bed and thereby increase skin blood flow, and if necessary, the sweating mechanism is invoked. These mechanisms are designed to dissipate heat in an attempt to return the "set-point" to its original level.

A question that must be addressed is the difference between a physiologically raised body temperature and a fever During 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 "set-point" [30]. In contrast, during exercise in heat, which may result in an increase in body temperature, there is no change in "set-point" temperature, 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 "set-point."

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. However, even at rest, the muscles produce about 20-25% of the body's total heat production. 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 exercise can be much higher, all of which 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.

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 cardiac output which at levels of work of up to about 40% $\dot{V}O_2max$ is brought about by an increase in both stroke volume and heart rate. When maximum stroke volume is reached, additional increases in cardiac output can be achieved solely by increased heart rate (which itself has a maximum value). Further complexities arise when high work intensities are sustained for long periods, particularly when work is carried out in hot surroundings. 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 meet the oxygen needs of the working muscles completely.

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. Because of the lack of oxygen, the working muscles must then begin to draw on their anaerobic reserves, deriving energy from the oxidation of glycogen in the muscles. That event leads to the accumulation of lactic acid which may be associated with the development of muscular fatigue. As the proportion of $\dot{V}O_2max$ 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 [31,32].

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 $\dot{V}O_2max$ [18,33]. However, two individuals doing the same job and working at the same absolute load level and who have widely different $\dot{V}O_2max$ values will have quite different core temperatures. Currently, recommendations for an acceptable proportion of $\dot{V}O_2max$ for daily industrial work vary from 30-40% of the $\dot{V}O_2max$, which in comfortably cool surroundings [34] is associated with rectal temperatures of, respectively, 37.4° and 37.7°C (99.3°-99.9°F), while work at 50% $\dot{V}O_2max$ yields a rectal temperature of 38°C (100.4°F) in the absence of heat stress.

In addition to sex- and age-related variability, the interindividual variability of $\dot{V}O_2max$ is high; therefore, the range of $\dot{V}O_2max$ to include 95 of every 100 individuals will be ±20% of the mean $\dot{V}O_2max$ value. Differences in body weight (particularly the muscle mass) can account for about half that variability when $\dot{V}O_2max$ 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 $\dot{V}O_2max$ after peaking at about 20 years of age, and falling in healthy individuals by nearly 10% each decade after age 30. The decrease in $\dot{V}O_2max$ 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 [34]. 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, in sweat production, and in the ability to regulate electrolyte balance, each of which may be large.

Previously, work performance was comprehensively reviewed [35,36], and little or no new data have been published. 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 hypohydration itself (except for severe hypohydration) 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 hypohydration which may be associated with a reduction of sweat production and a concomitant rise in rectal temperature and heart rate. If the total heat load is high and the sweat rate is 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. Existing evidence supports the concept that as the body temperature increases in a hot working environment, the endurance for physical work is decreased. Similarly, as the environmental heat stress increases, many of the psychomotor, vigilance, and other experimental psychologic tasks show decrements in performance [37,38,39,40,41]. The decrement in performance may be at least partly related to increases in core temperature and hypohydration. When the rectal temperature is raised to 38.5°-39.0°C (101.3°-102.2°F), 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, prompting the unproven suggestion that cerebral anoxia (reduced oxygen supply to the brain) may be responsible [4,39,42].

3. Circulatory Regulation

The circulatory system is the transport mechanism responsible for delivering oxygen and foodstuffs to all tissues and for transporting unwanted metabolites and heat from the tissues. However, the heart cannot provide enough cardiac output 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, sympathetic 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, 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 1 liter of blood to be added to the circulating volume [36].

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 man's 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 stroke volume falls gradually, and the heart rate must increase to maintain the cardiac output. The effective circulatory volume also decreases, partly due to hypohydration 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 [36].

4. The Sweating Mechanism

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. Sweat production at rates of about 1 L/h has been recorded frequently in industrial work and represents a large potential source of cooling if all the sweat is evaporated; each liter of sweat evaporated from the skin surface represents a loss of approximately 580 kcal (2320 Btu or 675 W) of heat to the environment. Large losses of water by sweat also pose a potential threat to successful thermoregulation, because a progressive depletion of body water content occurs if the water lost is not replaced; hypohydration by itself affects thermoregulation and results in a rise of core temperature.

An important constituent of sweat is salt or sodium chloride. In most circumstances, a salt deficit does not readily occur, because our normal diet provides 8-14 g/d. However, the salt content of sweat in unacclimatized individuals may be as high as 4 g/L, while for the acclimatized individual it will be reduced to 1 g/L or less. 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 2 or 3 days of heat exposure [32]. 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 [43]. 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 physician's orders). 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 workers, who are unacclimatized, suddenly have to work hard in hot climates; marked depletion of potassium can lead to serious physiologic consequences including the development of heatstroke [4]. 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 [32]. Since diuretics cause potassium loss, workers taking such medication while working in a hot environment may require special medical supervision.

The rate of evaporation of sweat is controlled by the difference in water vapor pressure on the sweat-wetted skin surface and the air layer next to the skin and by the velocity of air movement over the skin. As a consequence, hot environments with increasing humidity limit the amount of sweat that can be evaporated. Sweat that is not evaporated drips from the skin and it does not result in any heat loss from the body. It is deleterious, because it does represent a loss of water and salt from the body.

a. 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 quarts 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 [4,32,35] so that progressive hypohydration results in a lower sweat production and a corresponding increase in body temperature, which is a dangerous situation.

Sweat lost in such 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 the 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 [44]. Because the normal thirst mechanism is not sensitive enough to ensure a sufficient water intake [32], every effort should be made to encourage individuals to drink water or low-sodium noncarbonated beverages. The fluid should be as palatable as possible at 10°-15°C or 50°-60°F. Small quantities taken at frequent intervals, about 150-200 mL or 5-7 ozs every 15-20 minutes, is a more effective regimen for practical fluid replacement than the intake of 750 mL or more once an hour. Communal drinking containers should be prohibited. 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. With suitable instruction concerning the problems of not drinking enough to replace water lost in sweat, most individuals will comply. Those who do not replace water loss while at work, will at least diminish the amount of water deficit they generate and will usually replenish that deficit in off-duty hours.

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. Aldosterone is released from the adrenal glands and reduces salt lost both in the kidney and in the sweat glands.

b. Dietary Factors

There is no reason to believe that a well-balanced diet for work in temperate environments should not suffice for hot climates.

A very high protein diet might increase the obligatory urine output for nitrogen removal, and thus increase water intake requirements [31,32]. 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 [45].

5. Acclimatization to Heat

When workers are unexpectedly exposed to hot work environments, they readily show signs of distress and discomfort; develop increased core temperatures and heart rates; complaints of headache, giddiness, or nausea; and suffer other symptoms of incipient heat exhaustion [4,8,39,44,46,47,48]. On first exposure, they may faint. On repeated exposure 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, so that after daily heat exposure for 7-10 days, the individuals perform the work with a much lower core temperature and heart rate and higher sweat rate (i.e., a reduced thermoregulatory strain) and with none of the distressing symptoms that were experienced at first. During that period there is at first 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 in excess of 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 [48,49]. However, acclimatization does not necessarily mean that the individuals can work above the Prescriptive Zone as effectively as below it (see Appendix A) [18].

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 h/d; 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 a continuous exposure of about 100 minutes daily [4,49]. 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, they find it hard to rest effectively in hot surroundings [44].

The level of acclimatization is relative to the initial level of individual physical fitness and the total heat stress experienced by the individual. 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.

Failure to replace the water lost in sweat will retard or even prevent the development of the physiologic adaptations described. In spite of the fact that acclimatization will be reasonably well maintained for a few days of nonheat exposure, absence from work in the heat for a week or more results in a significant loss in the beneficial adaptations. However, usually heat acclimatization can be regained in 2 to 3 days upon return to a hot job [47,49]. Heat acclimatization appears to be better maintained by individuals who are physically fit [50].

The total sweat production increases with acclimatization, and sweating begins at a lower skin temperature. The cutaneous circulation and circulatory conductance decreases with acclimatization, reflecting the reduction in the proportion of cardiac output that must be allocated for thermoregulation, because of the more efficient sweating mechanism. There is still no clear explanation of how these events are brought about and what the underlying mechanisms are that alter the cardiovascular and thermoregulatory responses so dramatically. 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 conserves the amount of water lost through the kidneys.

It is obvious from the foregoing description that sudden seasonal shifts in environmental temperature may result in thermoregulatory difficulties for exposed workers. At such times, cases of heat disorder 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.

6. Other Related Factors

a. 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 a curiously increased high 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 [18,27,28]. 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 [27,28]. 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 [51]. In analyzing the distribution of 5 years' accumulation of data on heatstroke in South African gold mines, Strydom [52] found a marked increase in heatstroke 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 heatstroke. 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 heatstroke in the older group.

b. Gender

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 VO_2max, the women perform either similarly or only slightly less well than men [53,54,55,56]. There seems to be little change in thermoregulatory capacities at different times during their menstrual cycles [57].

c. Body Fat

It is well established that obesity predisposes individuals to heat disorders [4]. 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. In addition, the body surface to body weight ratio (m^2 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 insulative 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 [58].

d. Drugs

(1) Alcohol

Alcohol has been commonly associated with the occurrence of heatstroke [4]. It is a drug which interferes with central and peripheral nervous function and is associated with hypohydration 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 illnesses.

(2) Therapeutic Drugs

Many drugs prescribed for therapeutic purposes can interfere with thermoregulation [59]. Some of these drugs are anticholinergic in nature or involve inhibition of monoamine oxidative reactions, but almost any drug that affects central nervous system (CNS) 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 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.

(3) Social Drugs

It is hard to separate drugs used therapeutically from those which are used socially. Nevertheless, there are many drugs other than alcohol which are used on social occasions. Some of those have been implicated in cases of heat disorder, sometimes leading to death [59].

e. Nonheat 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 [4,60,61,62]. In prolonged heat waves, the mortality is higher in the early phase of the heat wave [60,61]. While acclimatization may play a part in the decrease in mortality during the later 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.

f. 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 stress on different occasions. Such variations are not totally understood. It has been shown [47] 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 [63]. However, the degree of variability in tolerance to hot environments remains a vexing problem.

7. Heat-Related Health and Safety Effects

The incidence of work-related heat illness in the United States is not documented by an occupational injury/illness surveillance system. However, the Supplementary Data System (SDS) maintained by the U.S. Bureau of Labor Statistics (BLS) contains coded information from participating states about workers' heat illness compensation claims.

Those workers' compensation cases which were coded to indicate that the disorder was a heat illness which occurred during 1979 have been analyzed by Jensen [64]. The results indicate that the industries with the highest rate of reported compensation cases for heat illness per 100,000 workers are agriculture (9.16 cases/100,000 workers), construction (6.36/100,000), and mining (5.01/100,000). The other industrial divisions had case rates of fewer than 3 per 100,000 workers. Dinman et al. [65] reported an incidence rate of 6.2 per 1,000,000 man-hours in a study of three aluminum plants during a May-September observation period. Minard reported 1 per 1,000 workers had heat-related illnesses during a 5-month period in three aluminum and two steel plants (presumably the same plants reported by Dinman et al.) [66]. Janous, Horvath, and Horvath and Colwell also reported an increased incidence of heat illnesses in the iron and steel industry [67,68,69].

In 1979, the total U.S. incidence of work-related heat illnesses for which the worker lost at least one day of work following the day of onset (lost-workday cases) was estimated to be 1,432 cases [64]. The estimation is based on the assumption that the proportion of cases of a particular kind of injury in the SDS data base is equivalent to the proportion of cases for that kind of injury or lost-workday cases nationwide. It has been shown that when the thermal environmental conditions of the workplace exceed temperatures which are typically preferred by most people, the safety-related behavior of workers is detrimentally affected and increased exponentially with increasing heat load [70,71].

In an analysis by cause (chemical and physical agent) of the occupational illnesses and injuries reported in the 1973 State of California, Division of Labor Statistics and Research, Dukes-Dobos [71] found that 422 cases resulting in some lost time were the result of "heat and humidity," which was the most frequent physical agent cause. Forty-seven of these cases were hospitalized and three died. Chlorine was the most frequently cited chemical hazard with 529 lost-time cases; 48 were hospitalized, and there were no deaths. Other chemical and physical agents such as ammonia, trichloroethylene, noise, benzene, lead, and chromium were less frequently involved than heat. Janous [67] reported increased accidents in heat-exposed steelworkers.

B. Acute Heat Disorders

A variety of heat disorders can be distinguished clinically when individuals are exposed to excessive heat [4,18,72,73,74,75]. These disorders range from simple postural heat syncope (fainting) to the complexities of heatstroke. 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 then 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 treatment of heat illnesses is presented in Table IV-1. Recently, a new scheme for differential diagnosis of heat-induced illnesses has been published [72].

TABLE IV-1.--Classification, medical aspects, and prevention of heat illness

Category and clinical features	Predisposing factors	Underlying physiologic disturbance	Treatment	Prevention
1. Temperature Regulation Heatstroke				
Heatstroke: (1) Hot dry skin usually red, mottled or cyanotic; (2) t_{re}, 40.5°C (104°F) and over; (3) confusion, loss of consciousness, convulsions, t_{re} continues to rise; fatal if treatment delayed	(1) Sustained exertion in heat by unacclimatized workers; (2) Lack of physical fitness and obesity; (3) Recent alcohol intake; (4) Dehydration; (5) Individual susceptibility; and (6) Chronic cardiovascular disease	Failure of the central drive for sweating (cause unknown) leading to loss of evaporative cooling and an uncontrolled accelerating rise in t_{re}, there may be partial rather than complete failure of sweating	Immediate and rapid cooling by immersion in chilled water with massage or by wrapping in wet sheet with vigorous fanning with cool dry air, avoid overcooling, treat shock if present	Medical screening of workers, selection based on health and physical fitness, acclimatization for 5-7 days by graded work and heat exposure, monitoring workers during sustained work in severe heat
2. Circulatory Hypostasis Heat Syncope				
Fainting while standing erect and immobile in heat	Lack of acclimatization	Pooling of blood in dilated vessels of skin and lower parts of body	Remove to cooler area, rest recumbent position, recovery prompt and complete	Acclimatization, intermittent activity to assist venous return to heart
3. Water and/or Salt Depletion				
(a) Heat Exhaustion				
(1) Fatigue, nausea, headache, giddiness; (2) Skin clammy and moist; complexion pale, muddy, or hectic	(1) Sustained exertion in heat; (2) Lack of acclimatization; and (3) Failure to replace water lost in sweat	(1) Dehydration from deficiency of water; (2) Depletion of circulating blood volume; (3) Circulatory strain from	Remove to cooler environment, rest recumbent position, administer fluids by mouth, keep at rest	Acclimatize workers using a breaking-in schedule for 5 to 7 days, supplement dietary salt only

(continued)

TABLE IV-1.--Classification, medical aspects, and prevention of heat illness

Category and clinical features	Predisposing factors	Underlying physiologic disturbance	Treatment	Prevention
flush; (3) May faint on standing with rapid thready pulse and low blood pressure; (4) Oral temperature normal or low but rectal temperature usually elevated (37.5°-38.5°C) (99.5°-101.3°F); water restriction type: urine volume small, highly concentrated; salt restriction type: urine less concentrated, chlorides less than 3 g/L		competing demands for blood flow to skin and to active muscles	until urine volume indicates that water balances have been restored	during acclimatization, ample drinking water to be available at all times and to be taken frequently during work day
(b) Heat Cramps				
Painful spasms of muscles used during work (arms, legs, or abdominal); onset during or after work hours	(1) Heavy sweating during hot work; (2) Drinking large volumes of water without replacing salt loss	Loss of body salt in sweat, water intake dilutes electrolytes, water enters muscles, causing spasm	Salted liquids by mouth, or more prompt relief by I-V infusion	Adequate salt intake with meals; in unacclimatized workers supplement salt intake at meals
4. Skin Eruptions				
(a) Heat Rash (miliaria rubra; "prickly heat")				
Profuse tiny raised red vesicles (blister-like) on affected areas, pricking sensations during heat exposure	Unrelieved exposure to humid heat with skin continuously wet with unevaporated sweat	Plugging of sweat gland ducts with retention of sweat and inflammatory reaction	Mild drying lotions, skin cleanliness to prevent infection	Cool sleeping quarters to allow skin to dry between heat exposures

(continued)

TABLE IV-1.--Classification, medical aspects, and prevention of heat illness

Category and clinical features	Predisposing factors	Underlying physiologic disturbance	Treatment	Prevention
(b) 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 available for anhidrotic areas of skin, recovery of sweating occurs gradually on return to cooler climate	Treat heat rash and avoid further skin trauma by sunburn, periodic relief from sustained heat
5. Behavioral Disorders				
(a) Heat Fatigue--Transient				
Impaired performance of skilled sensorimotor, mental, or vigilance tasks, in heat	Performance decrement greater in unacclimatized and unskilled worker	Discomfort and physiologic strain	Not indicated unless accompanied by other heat illness	Acclimatization and training for work in the heat
(b) Heat Fatigue--Chronic				
Reduced performance capacity, lowering of self-imposed standards of social behavior (e.g., alcoholic overindulgence), inability to concentrate, etc.	Workers at risk come from temperate climates, for long residence in tropical latitudes	Psychosocial stresses probably as important as heat stress, may involve hormonal imbalance but no positive evidence	Medical treatment for serious cases, speedy relief of symptoms on returning home	Orientation on life in hot regions (customs, climate, living conditions, etc.)

Adapted from Reference 73.

1. Heatstroke

The classical description of heatstroke includes: (1) a major disruption of central nervous function (unconsciousness or convulsions); (2) a lack of sweating; and (3) a rectal temperature in excess of 41°C (105.8°F) [4,59,75,76]. The 41°C rectal temperature is an arbitrary value for hyperpyrexia, because the disorder has not been produced experimentally in humans so that observations are made only after the admission of patients to hospitals, which may vary in time from about 30 minutes to several hours after the event. In some heatstroke cases, sweating may be present [76]. The local circumstances of metabolic and environmental heat loads which give rise to the disorder are highly variable and are often difficult or impossible to reconstruct with accuracy. The period between the occurrence of the event and admission to a hospital may result in a quite different medical outcome from one patient to another depending on the knowledge, understanding, skill, and facilities available to those who render first aid in the intervening period. Recently, the sequence of biologic events in some fatal heatstroke cases have been described [77].

Heatstroke is a MEDICAL EMERGENCY, and any procedure from the moment of onset which will cool the patient improves the prognosis. Placing the patient in a shady area, removing outer clothing and wetting the skin, and increasing air movement to enhance evaporative cooling are all urgently needed until professional methods of cooling and assessment of the degree of the disorder are available. Frequently, by the time a patient is admitted to a hospital, the disorder has progressed to a multisystem lesion affecting virtually all tissues and organs [77]. 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 their development requires a combination of a given degree of elevated body temperature and a certain period for tissue or cellular damage to occur. 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. An ill worker should not be sent home or left unattended without a physician's specific order.

2. Heat Exhaustion

Heat exhaustion is a mild form of heat disorder which readily yields to prompt treatment. This disorder has been encountered frequently in experimental assessment of heat tolerance. Characteristically, it is sometimes but not always accompanied by a small increase in body temperature (38°-39°C or 100.4°-102.2°F). The symptoms of headache, nausea, vertigo, weakness, thirst, and giddiness are common to both heat exhaustion and the early stage of heatstroke. There is a wide interindividual 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 [78].

There are, of course, many variants in the development of heat disorders. Failure to replace water may predispose the individual to one or more of the heat disorders and may complicate an already complex situation. Therefore, cases of hyperpyrexia can be precipitated by hypohydration. It is unlikely that there is only one cause of hyperpyrexia without some influence from another. Recent data suggest that cases of heat exhaustion can be expected to occur some 10 times more frequently than cases of heatstroke [59].

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 copious intake of water without appropriate replacement of salt. Other electrolytes such as Mg^{++}, Ca^{++}, and K^{+} 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.

4. Heat Rashes

The most common heat rash is prickly heat (miliaria rubra), which appears as red papules, usually in areas where the 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 [21,79,80]. The papules may become infected unless they are treated.

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 with the formation of small to large watery vesicles which rapidly subside once sweating stops, and 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 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, the 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 of them carries the possibility of resulting patchy areas which are anhidrotic, and thereby adversely affects evaporative heat loss and thermoregulation. In experimentally induced miliaria rubra, sweating capacity recovers within 3-4 weeks [79,80]. Wet and/or damaged skin could absorb toxic chemicals more readily than dry unbroken skin.

C. Chronic Heat Disorders

Some long term effects from exposure to heat stress (based on anecdotal, historical, and some epidemiologic and experimental evidence) have been suggested. Recently, the evidence was reviewed by Dukes-Dobos who proposed a three-category classification of possible heat-related chronic health effects [77]. The three categories are Type I - those related to acute heat illnesses such as reduced heat tolerance following heatstroke or reduced sweating capacity; Type II - not clear clinical entities, but are similar to general stress reactions; and Type III - which includes anhidrotic heat exhaustion, tropical neurosthenia, and increased incidence of kidney stones. The primary references cited in the review are suggestive of some possible chronic heat effects. However, the available data do not contribute information of value in protecting workers from heat effects. Nevertheless, the concept of chronic health effects from heat exposure may merit further formal laboratory and hot industry investigations.

V. MEASUREMENT OF HEAT STRESS

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

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

A. Environmental Factors

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

1. Dry Bulb (Air) Temperature

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

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

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

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

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

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

a. Liquid-in-Glass Thermometers

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

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

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

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

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

Adapted from Reference 81.

b. Thermocouples

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

c. Resistance Thermometers

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

2. Humidity

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

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

a. Water Vapor Pressure

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

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

b. Natural Wet Bulb Temperature

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

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

c. Psychrometric Wet Bulb Temperature

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

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

d. Dew Point Temperature

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

3. Air Velocity

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

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

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

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

Adapted from Reference 81.

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

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

a. Vane Anemometers (swing and cup)

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

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

b. Thermoanemometers

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

4. Radiation

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

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

a. Artificial (Occupational) Radiation

(1) Black Globe Thermometers

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

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

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

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

where:

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

(2) Radiometers

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

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

b. Natural (Solar) Radiation

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

(1) Pyrheliometers

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

(2) Pyranometers

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

5. Microwaves

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

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

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

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

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

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

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

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

C. Metabolic Heat

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

1. Measurements of Metabolic Heat

a. Measurement of Metabolic Heat by Direct Calorimetry

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

b. Measurements of Metabolic Heat by Indirect Calorimetry

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

(1) Closed Circuit

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

(2) Open Circuit

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

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

2. Estimation of Metabolic Heat

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

a. Tables of Energy Expenditures

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

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

b. Task Analysis

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

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

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

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

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

C. Basal metabolism	**1.0**

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

* For standard worker of 70 kg body weight (154 lbs.) and 1.8 m^2 body surface (19.4 ft^2).
**Example of measuring metabolic heat production of a worker when performing initial screening.
Adapted from References 2,108,111,112.

VI. CONTROL OF HEAT STRESS

From a review of the heat balance equation [$H=(M-W)\pm C\pm R-E$], described in Chapter III, Section A, 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 VI-1 [113].

TABLE VI-1.--Checklist for controlling heat stress and strain

Item	Actions for consideration
I. Controls	
M, body heat production of task	reduce physical demands of the work; powered assistance for heavy tasks
R, radiative load	interpose line-of-sight barrier; furnace wall insulation, metallic reflecting screen, heat reflective clothing, cover exposed parts of body
C, convective load	if air temperature is above 35°C (95°F); reduce air temperature, reduce air speed across skin, wear clothing if air temperature is below 35°C (95°F); increase air speed across skin and reduce clothing
E_{max}, maximum evaporative cooling by sweating	increase by: decreasing humidity, increasing air speed
	decrease clothing
II. Work practices	shorten duration of each exposure; more frequent short exposures better than fewer long exposures schedule very hot jobs in cooler part of day when possible
exposure limit	self-limiting, based on formal indoctrination of workers and supervisors on signs and symptoms of overstrain
recovery	air-conditioned space nearby

(continued)

TABLE VI-1.--Checklist for controlling heat stress and strain

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 hypohydration 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 Reference 113.

A. Engineering Controls

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

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 ($\bar{t}_{sk}$ of 35°C or 95°F), heat is gained by convection. The rate of heat gain is dependent on temperature differential (t_a - $\bar{t}_{sk}$) and air velocity (V_a). Where t_a is below $\bar{t}_{sk}$, heat is lost from the body; the rate of loss is dependent on t_a - $\bar{t}_{sk}$ 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 $\bar{t}_{sk}$, 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 $\bar{t}_{sk}$ (convective heat gain), t_a should be reduced by bringing in cooler outside air or by evaporative or refrigerative cooling of the air, and 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 VI-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.

2. Radiant Heat Control

Radiant heat exchange between the worker and the 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.

3. Evaporative Heat Control

Heat is lost from the body when sweat is evaporated 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°-35°C (93.2°-95°F). 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 controls 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 (e.g., 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 [114].

B. Work and Hygienic Practices and Administrative Controls

Situations exist in industries where the complete control of heat stress by the application of engineering controls may be technologically impossible or impractical, where the level of environmental heat stress may be unpredictable and variable (as seasonal heat waves), and where the exposure time may vary with the task and with unforeseen critical events. Where engineering controls of the heat stress are not practical or complete, other solutions must be sought to keep the level of total heat stress on the worker within limits which will not be accompanied by an increased risk of heat 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 worker 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 physical fitness.

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.

- 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 rest-work regimen to permit more rest time.
- Provide cool areas for rest and recovery.
- Add extra personnel to reduce exposure time for each member of the crew.
- Permit freedom to interrupt work 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.

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. A design for rest-work cycles has been developed by Kamon [115]. 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),
- Increase of the work force.

3. Enhancing Tolerance to Heat

Stimulating the human heat adaptive mechanisms can significantly increase the capacity to tolerate work in heat. There is, however, a wide difference in the ability of people to adapt to heat which must be kept in mind when considering any group of workers.

a. 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 of heat-related illnesses and unsafe acts. Heat acclimatization can usually be induced in 5 to 7 days of exposure at the hot job. For workers who have had previous experience with the job, the acclimatization regimen should be exposure for 50% on day 1, 60% on day 2, 80% on day 3, and 100% on day 4. For new workers the schedule should be 20% on day 1 and a 20% increase on each additional day.

b. Being physically fit for the job will enhance (but not replace heat acclimatization) heat tolerance for both heat-acclimatized and unacclimatized workers. The time required to develop heat acclimatization in unfit individuals is about 50% greater than in the physically fit.

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

d. Electrolyte balance in the body fluids must be maintained to prevent some of the heat-induced illnesses. For heat-unacclimatized workers who may be on a restricted salt diet, additional salting of the food, with a physician's concurrence, during the first 2 days of heat exposure may be required to replace the salt lost in the sweat. The acclimatized worker loses relatively little salt in the sweat; therefore, salt supplementation of the normal U.S. diet is usually not required.

4. Health and Safety Training

Prevention of serious sequelae from heat-induced illnesses is dependent on early recognition of the signs and symptoms of impending heat illnesses and the initiation of first aid and/or corrective procedures at the earliest possible moment.

a. Supervisors and other personnel should be trained in recognizing the signs and symptoms of the various types of heat-induced illnesses, e.g., heat cramps, heat exhaustion, heat rash, and heatstroke, and in administering first-aid procedures (see Table IV-1).

b. All personnel exposed to heat should receive basic instruction on the causes and recognition of the various heat illnesses and personal care procedures that should be exercised to minimize the risk of their occurrence.

c. All personnel who use heat protective clothing and equipment should be instructed in their proper care and use.

d. All personnel working in hot areas should be instructed on the effects of nonoccupational factors (drugs, alcohol, obesity, etc.) on tolerance to occupational heat stress.

e. A buddy system which depends on the instruction of workers on hot jobs to recognize the early signs and symptoms of heat illnesses should be initiated. 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 any of the early symptoms of a developing heat illness are present. If a worker exhibits signs and symptoms which may be indicative of an impending heat illness, the worker should be sent to the dispensary or first-aid station for more complete evaluation of the situation and to initiate the medical or first-aid treatment procedures. 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. Contingency plans for treatment, e.g., cool rest area and transportation to hospital, should be in place.

5. Screening for Heat Intolerance

The ability to tolerate heat stress varies widely even between individuals within a group of normal healthy individuals with similar heat exposure experiences [5,6,116]. One way to reduce the risk of incurring heat illnesses and disorders within a heat-exposed workforce is to reduce or eliminate the exposure to heat stress of the heat-intolerant individuals. Identification of heat-intolerant individuals without the need for performing a strenuous, time-consuming heat-tolerance test would be 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. None of the individuals with a maximum work capacity of 2.5 liters of oxygen per minute (L/min) or above were heat intolerant, while 63% of those with $\dot{V}O_2max$ below 2.5 L/min were heat intolerant. It has also been shown that heat-acclimatized individuals with a $\dot{V}O_2max$ less than 2.5 L/min had a 5% risk of reaching heatstroke levels of body temperature (40°C or 104°F) while those with a $\dot{V}O_2max$ above 2.5 L/min had only a 0.05% risk [5,6].

Because tolerance to physical work in a hot environment is related to physical work capacity, heat tolerance might be predictable from physical fitness tests. A simple physical fitness test which could be administered in a physician's office or a plant first-aid room has been suggested [116,117]. However, such tests have not as yet been proven to have predictive validity for use in hot industries.

Medical screening for heat intolerance in otherwise healthy normal workers should include a history of any previous incident of heat illness. Workers who have experienced a heat illness may be less heat tolerant [4].

C. Heat-Alert Program - Preventing Emergencies

In some plants where heat illnesses and disorders occurred mainly during hot spells in the summer, a Heat-Alert Program (HAP) has been established for preventive purposes. Although such programs differ in detail from one plant to another, the main idea behind them is identical, i.e., to take advantage of the weather forecast of the National Weather Service. If a hot spell 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 safety departments. An effective HAP is described below [77].

1. Each year, early in the spring, establish a Heat-Alert Committee consisting of an industrial physician or nurse, industrial hygienist, safety engineer, operation engineer, and a high ranking manager. Once established, this committee takes care of the following options:

a. Arrange a training course for all involved in the HAP, dealing with procedures to follow in the event a Heat Alert is declared. In the course, special emphasis is given to the prevention and early recognition of heat illnesses and first-aid procedures when a heat illness occurs.

b. By memorandum, instruct the supervisors to:

(1) Reverse winterization of the plant, 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 repair is performed, that these facilities 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 case of a heat 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 35°C (95°F) or above or a maximum of 32°C (90°F) if the predicted maximum is 5°C (9°F) above the maximum reached in any of the preceding 3 days.

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

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

b. Increase the number of workers in 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 which 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. The physician's permission to return to work must be given in writing.

j. Restrict overtime work.

D. Auxiliary Body Cooling and Protective Clothing

When unacceptable levels of heat-stress occur, there are generally only four approaches to a solution: (1) modify the worker by heat acclimatization; (2) modify the clothing or equipment; (3) modify the work; or (4) modify the environment. 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 the protective clothing, should be in good physical condition, and should be encouraged to drink as much water as necessary to compensate for sweat water loss.

If these modifications of the individual (heat acclimatization and physical fitness enhancement) are not enough to alleviate the heat stress and reduce the risk of heat illnesses, only the latter three solutions are left to deal with the problem. It may be possible to redesign ventilation systems for occupied spaces to avoid interior humidity and temperature buildup. 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 mobile individuals afoot 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 1 and 2.

Auxiliary cooling systems can range from such simple approaches as an ice vest, prefrozen and worn under the clothing, to more complex systems; however, cost of logistics and maintenance are considerations of varying magnitude in all of these systems. In all, four auxiliary cooling approaches have been evaluated: (1) water-cooled garments, (2) an air-cooled vest, (3) an ice packet vest, and (4) a wettable cover. Each of these cooling approaches might be applied in alleviating risk of severe heat stress in a specific industrial setting [14,26].

1. Water-cooled Garments

Water-cooled garments include (1) a water-cooled hood which provides cooling to the head, (2) a water-cooled vest which provides cooling to the head and torso, (3) a short, water-cooled undergarment which provides cooling to the torso, arms, and legs, and (4) a long, water-cooled undergarment which provides cooling to the head, torso, arms, and legs. None of these water-cooled systems provide cooling to the hands and feet.

Water-cooled garments and headgear require a battery driven circulating pump and container where the circulating fluid is cooled by the ice. The weight of the batteries, container, and pump will limit the amount of ice that can be carried. The amount of ice available will determine the effective use time of the water-cooled garment.

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.

2. Air-cooled Garments

Air-cooled suits and/or hoods which distribute cooling air next to the skin are available. The total heat exchange from a completely sweat wetted skin when cooling air is supplied to the air-cooled suit 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, should be considered as a simple cooled air source.

3. Ice Packet Vest

The available ice packet vests may contain as many as 72 ice packets; each packet has a surface area of approximately 64 cm^2 and contains about 46 grams of water. These ice packets are generally secured to the vest by tape. The cooling provided by each individual ice packet 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. Solid carbon dioxide in plastic packets can be used instead of ice packets in some models.

In environments of 29.4°C (84.9°F) at 85% rh and 35.0°C (95°F) at 62% rh, an ice packet vest can still provide some cooling up to 4 hours of operation (about 2 to 3 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 3 hours of operation. With 60% of the ice packets in place in the vest, the cooling provided may be negligible after 2 hours of operation. Since the ice packet vest does not provide continuous and regulated cooling over an indefinite time period, exposure to a hot environment would require redressing with backup frozen vests every 2 to 4 hours. Replacing an ice packet vest would obviously 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 ice packet vest is also relatively cheaper than other cooling approaches.

4. Wetted Overgarments

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 can be a simple and effective auxiliary cooling garment.

Predicted values of supplementary cooling and of the minimal water requirements to maintain the cover wet in various combinations of air temperature, relative humidity, and wind speed can be calculated. 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 to use.

E. Performance Degradation

A variety of options for auxiliary cooling to reduce the level of heat stress, if not totally eliminate it under most environmental conditions both indoors and outdoors, have been prescribed. However, the elimination of serious heat-stress problems will not totally resolve the 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 [78]. The majority of the decrements result from mechanical barriers to sensory inputs to the wearer and from barriers to communication between individuals. Overall, 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 [78].

VII. PREVENTIVE MEDICAL PRACTICES

With proper attention to health and safety considerations, a hot work environment can be a safe place within which to work. A primary responsibility for preventing heat illness resides with the engineer and/or industrial hygienist who recommends procedures for heat-stress controls and monitors workplace environmental conditions. Continuous industrial hygiene characterization of environmental conditions, obtained via either continuous monitoring of the environment or algorithms that relate workplace temperature and humidity to ambient climatic conditions and to the work activity itself, must be available to these personnel. However, because of the complexities of anticipating and preventing heat illness in the individual worker, the physician must be intimately involved in efforts to protect workers exposed to potentially hazardous levels of heat stress in the workplace.

Since an environment that exceeds the Recommended Alert Limit (RAL) for an unacclimatized or the Recommended Exposure Limit (REL) for an acclimatized worker poses a potential threat to workers, the supervising health professional must possess a clear understanding of the peculiar complexities of heat stress. In particular, the physician must be aware of the following:

- The REL represents the most extreme heat-stress condition to which even the healthiest and most acclimatized worker may be safely exposed for prolonged periods of time.

- Among workers who do not have medical conditions that impair heat tolerance, some may be at risk of developing heat illness when exposed to levels below the RAL. In addition, some workers cannot acclimatize to heat-stress levels above the RAL. Empirical data suggest that fewer than 5% of the workers cannot adequately acclimatize to heat stress (see Chapter IV).

- The RAL and REL are TWA values with permissible short-term excursions above the levels; however, the frequency and extent to which such brief excursions may be safely permitted are not known.

Thus, sound judgment and vigilance by the physician, the workers, and their supervisors are essential to the prevention and early recognition of adverse heat-induced health effects.

The physician's role in protecting workers in a hot environment should include the following:

- <u>Work environment not exceeding the RAL</u> In a work environment in which the heat stress experienced by the worker approaches but is kept below the RAL by engineering controls, work practices, and/or personal protective equipment, the physician's primary responsibilities are (1) preplacement evaluation (detection of a worker with a medical condition that would warrant exclusion of the worker from the work setting), (2) supervision during initial days of exposure of the worker to the hot environment (detection of apparently "healthy" workers who cannot tolerate heat stress), and

(3) detection of evidence of heat-induced illness (a sentinel health event [SHE]) in one or more workers that would indicate a failure of control measures to prevent heat-induced illness and related injuries at levels below the RAL).

- Work environment that exceeds the RAL In a work environment in which only acclimatized individuals can work safely because the level of heat stress exceeds the RAL, the physician bears a more direct responsibility for ensuring the health and safety of the workers. Through the preplacement evaluation and the supervision of heat acclimatization, the physician may detect a worker who is incapable of heat acclimatization or who has another medical condition that precludes placing that worker in a hot environment. While a single incident of heat illness may be a SHE indicating a failure of control measures, it may also signify a transient or long-term loss of heat tolerance or a change in the health status of that worker. The onset of heat-induced illness in more than one worker in a heat-acclimatized workforce is a SHE that indicates a failure of control measures. The physician must be cognizant of each of these possibilities.

The following discussion is directed toward the protection of workers in environments exceeding the RAL. However, it also provides the core of information required to protect all workers in hot environments.

A. Protection of Workers Exposed to Heat in Excess of the RAL

The medical component of a program which protects workers who are exposed to heat stress in excess of the RAL is complex. In order to ascertain a worker's fitness for placement and/or continued work in a particular environment, numerous characteristics of the individual worker (e.g., age, gender, weight, social habits, chronic or irreversible health characteristics, and acute medical conditions) must be assessed in the context of the extent of heat stress imposed in a given work setting. Thus, while many potential causes of impaired heat tolerance may be regarded as "relative contraindications" to work in a hot environment, the physician must assess the fitness of the worker for the specific job and should not interpret potential causes of impaired heat tolerance as "absolute contraindications" to job placement.

A preplacement medical evaluation followed by proper acclimatization training will reduce the likelihood that a worker assigned to a job that exceeds the RAL will incur heat injury. However, substantial differences exist between individuals in their abilities to tolerate and adapt to heat; such differences cannot necessarily be predicted prior to actual trial exposures of suitably screened and trained individuals.

Heat acclimatization signifies a dynamic state of conditioning rather than a permanent change in the worker's innate physiology. The phenomenon of heat acclimatization is well established, but for an individual worker, it can be documented only by demonstrating that, after completion of an acclimatization regimen, the worker can indeed work without excessive physiologic heat strain in an environment that an unacclimatized worker could not withstand. The ability of such a worker to tolerate elevated heat stress requires integrity of cardiac, pulmonary, and renal function; the sweating mechanism; the body's fluid and electrolyte balances; and the central nervous system's heat-regulatory mechanism. Impairment or diminution of any of these functions may interfere with the worker's capacity to acclimatize to the heat or to perform strenuous work in the heat once acclimatized. Chronic illness, the use or misuse of pharmacologic agents, a suboptimal nutritional state, or a disturbed water and electrolyte balance may reduce the worker's capacity to acclimatize. In addition, an acute episode of mild illness, especially if it entails fever, vomiting, respiratory impairment, or diarrhea, may cause abrupt transient loss of acclimatization. Not being exposed to heat stress for a period of a few days, as may occur during a vacation or an alternate job assignment away from heat, may also disrupt the worker's state of heat acclimatization. Finally, a worker who is acclimatized at one level of heat stress may require further acclimatization if the total heat load is increased by the imposition of more strenuous work, increased heat and/or humidity, a requirement to carry and use respiratory protection equipment, or a requirement to wear clothing that compromises heat elimination.

A physician who is responsible for workers in hot jobs (whose jobs exceed the RAL) must be aware that each worker is confronted each day by workplace conditions that may pose actual (as opposed to potential) risks if that worker's capacity to withstand heat is acutely reduced or if the degree of heat stress increases beyond the heat-acclimatized tolerance capacity of that worker. Furthermore, a physician who will not be continuously present at the worksite bears a responsibility to ensure the education of workers, industrial hygienists, medical and health professionals, and on-site management personnel about the early signs and symptoms of heat intolerance and injury. Biologic monitoring of exposed workers may assist the physician in assuring protection of workers (biologic monitoring is discussed in Chapter IV).

B. Medical Examinations

The purpose of preplacement and periodic medical examinations of persons applying for or 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 in jeopardy. Examinations should be performed that assess the physical, mental, psychomotor, emotional, and clinical qualifications of such individuals. These examinations entail two parts which relate, respectively, to overall health promotion (regardless of workplace or job placement) and to workplace-specific medical issues. This section focuses only on the latter and only with specific regard to heat stress. However, because tolerance to heat stress depends upon the integrity of multiple organ systems and can be jeopardized by the insidious onset of common medical conditions such as hypertension, coronary artery disease, decreased pulmonary function, diabetes, and impaired renal function, workers exposed to heat stress require a comprehensive medical evaluation.

Prior to the preplacement examination, the physician should obtain a description of the job itself, a description of chemical and other environmental hazards that may be encountered at the worksite, the anticipated level of environmental heat stress, an estimate of the physical and mental demands of the job, and a list of the protective equipment and clothing that is worn. This information will provide the examining physician a guide for determining the scope and comprehensiveness of the physical examination. Specific factors important in determining the individual's level of heat tolerance, the abilities to perform work in hot environments, and the medical problems associated with a failure to meet the demands of the work in hot jobs have been discussed in Chapter IV. A discussion of health factors and medications that affect heat tolerance in a nonworker population can be found in Kilbourne et al. [62].

The use of information from the medical evaluation should be directed toward understanding the potential maximum total heat stress likely to be experienced by the worker on the job, i.e., the sum of the metabolic demands of the work and of using respirators and other personal protective equipment or clothing; the environmental heat load; and the consequences of impediments to heat elimination, such as high humidity, low air movement (enclosed spaces or unventilated buildings), or protective clothing that impedes the evaporation of sweat. The environmental heat load and the physical demands of the job can be measured, calculated, or estimated by the procedures described previously in Chapters III and V. For such measurements the expertise of an industrial hygienist may be required; however, the physician must be able to interpret the data in terms of the stresses of the job and the worker's physical, sensory, psychomotor, and mental performance capabilities to meet the demands [73,118,119].

1. Preplacement Physical Examination

The preplacement physical examination is usually designed for new workers or workers who are transferring from jobs that do not involve exposure to heat. Unless demonstrated otherwise, it should be assumed that such individuals are not acclimatized to work in hot environments.

a. The physician should obtain:

(1) A medical history that addresses the cardiac, vascular, respiratory, neurologic, renal, hematologic, gastrointestinal, and reproductive systems and includes information on specific dermatologic, endocrine, connective tissue, and metabolic conditions that might affect heat acclimatization or the ability to eliminate heat [120,121].

(2) A complete occupational history, including years of work in each job, the physical and chemical hazards encountered, the physical demands of these jobs, 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 in nonoccupational activities [120].

(3) A list of all prescribed and over-the-counter medications used by the worker. In particular, the physician should consider the possible impact of medications that potentially can affect cardiac output, electrolyte balance, renal function, sweating capacity, or autonomic nervous system function including: diuretics, antihypertensive drugs, sedatives, antispasmodics, anticoagulants, psychotropics, anticholinergics, and drugs that may alter the thirst (haloperidol) or sweating mechanism (phenothiazines and antihistamines).

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

(5) Data on height, weight, gender, and age (see discussion in Chapter IV).

b. The direct 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), 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.

c. More detailed medical evaluation may be warranted. Communication between the physician performing the preplacement evaluation and the worker's own physician may be appropriate and should be encouraged. For instance:

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

(2) For a worker who uses prescribed medications that might interfere with heat tolerance or acclimatization, 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) Hypertension per se is not to be an "absolute" contraindication to working under heat stress (see VII-B-3). However, the physician should consider the possible effects of

antihypertensive medications on heat tolerance. In particular, for workers who follow a salt-restricted diet or who take diuretic medications that affect serum electrolyte levels, it may be prudent to monitor blood electrolyte values, especially during the initial phase of acclimatization to heat stress.

(4) For workers who must wear respiratory protection or other personal protective equipment, pulmonary function testing and/or a submaximal stress electrocardiogram may be appropriate. Furthermore, the physician must assess the worker's ability to tolerate the <u>total</u> heat stress of a job, which will include the metabolic burdens of wearing and using protective equipment.

(5) For workers with 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.

(6) Insofar as obesity can interfere with heat tolerance (see Chapter IV), a specific measurement of percent body fat may be warranted for an individual worker. An individual should not be disqualified from a job solely on this basis, but such a worker may merit special supervision during the acclimatization period.

(7) Women having childbearing potential (or who are pregnant) and workers with a history of impaired reproductive capacity (male or female) should be apprised of the overall uncertainties regarding the effects on reproduction of working in a hot environment (see VII-B-4).

2. Ongoing Medical Evaluation

a. Medical supervision of workers following job placement involves two primary sets of responsibilities:

(1) The monitoring of individual workers for changes in individual health that might affect heat tolerance or for evidence suggesting failure to maintain a safe working environment. The evaluation of these data in aggregate form permits surveillance of the work population as a whole for evidence of heat-related injury that is suggestive of failure to maintain a safe working environment.

(2) The ability to respond to heat injuries that do occur within the workforce.

b. On an annual basis, the physician should update the information gathered in the preplacement examination (see Chapter VII-B-1-a and b) for all persons working in a hot environment. In addition, the physician should ensure that workers who may have been transferred into a hot environment have been examined and are heat acclimatized. A more complete examination may be advisable if indicated by the updated medical history and laboratory data.

Special attention should be directed to the cardiovascular, respiratory, nervous, and musculoskeletal systems and the skin.

3. Hypertension

Limited human data are available that relate to the relationship of hypertension to heat strain. The capacity to tolerate exercise in heat was compared in a group of workers with essential hypertension (resting arterial pressure 150/97 mmHg) with a group of normotensives of equal age, $\dot{V}O_2max$, weight, body fat content, and surface area (resting arterial pressure 115/73 mmHg). During exercise in heat (38°C (91.4°F) t_a and 28°C (82.4°F) t_{wb} at work rates of 85-90 W), there was no significant intergroup difference in t_{re}, $\bar{t}_{sk}$, calculated heat-exchange variables, heart rate, or sweat rate. The blood pressure difference between the two groups was maintained [122]. The study of mortality of steelworkers employed in hot jobs conducted by Redmond et al. on a cohort of 59,000 steelworkers showed no increase in relative risk of death from all cardiovascular diseases or from hypertensive heart disease as a function of the level of the heat stress; however, for workers who had worked for 6 months or less at the hot jobs, the relative risk of death from arteriosclerotic heart disease was 1.78 as compared to those who worked at the hot jobs longer than 6 months [123].

4. Considerations Regarding Reproduction

a. Pregnancy

The medical literature provides little data on potential risks for pregnant women or for fertile men and fertile noncontracepting women with heavy work and/or added heat stress within the permissible limits, e.g., where t_{re} does not exceed 38°C (100.4°F) (see Chapter IV). However, because the human data are limited and because research data from animal experimentation indicate the possibility of heat-induced 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 physician.

b. Infertility

Heat exposure has been associated with temporary infertility in both females and males, with the effects being more pronounced in the male [124,125]. Available data are insufficient to assure that the REL protect against such effects. Thus, the examining physician should question workers exposed to high heat loads about their reproductive histories, whether they use contraceptive methods, type of contraceptive methods used, whether they have ever tried to have children, and whether female workers have ever been pregnant. In addition, the worker should be questioned about any history of infertility, including possible heat-related infertility. Because the heat-related infertility is usually temporary, reduction in heat exposure or job transfer should result in recovery.

c. Teratogenicity and Heat-induced Abortion

The body of experimental evidence reviewed by Lary [126] 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 central nervous system, 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.

The evidence for teratogenic effects of hyperthermia in humans is less convincing, in part, because it is based mainly on self-reported data obtained months or years after a pregnancy in which increased body temperature occurred during pathologic processes (e.g., acute infection during early pregnancy). However, recent 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) [126]. Based on the animal experimental data and the human retrospective studies, it appears prudent 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.

C. Surveillance

To ensure that the control practices provide adequate protection to workers in hot areas, the plant physician or nurse 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 health-related absences. These events may lead the physician 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.

D. Biologic Monitoring of Workers Exposed to Heat Stress

To assess the capacity of the workforce and individual workers to continue working on a particular hot job, physiologic monitoring of each worker or randomly selected workers while they are working in the heat should be considered as an adjunct to environmental and metabolic monitoring. A recovery heart rate, taken during the third minute of seated rest following a normal work cycle, of 90 beats per minute (b/min) or higher, and recovery heart rate taken during the first minute of seated rest minus the third minute recovery heart rate of 10 b/min or fewer, and/or an oral temperature of 38°C (100.4°F) or above indicate excessive heat strain [127,128]. Both oral temperature and pulse rate should be measured again at the end of the rest period before the worker returns to work to determine whether the rest time has been sufficient for recovery to occur. Measurements should be taken at appropriate intervals covering a full 2-hour period for the hottest part of the day and again at the end of the workday. Baseline oral temperatures and pulse rates taken before the workers begin the first task in the morning can be used as a basis for deciding whether individual workers are fit to continue work that day. If excessive heat strain is indicated, the work situation will require reexamination, preferably by the physician and industrial hygienist to determine whether it is a case of worker intolerance or excessive job-related heat stress.

VIII. BASIS FOR THE RECOMMENDED STANDARD

The research data and industry experience information upon which the recommendations for this standard are based were derived from (a) an analysis of the published scientific literature; (b) the many techniques 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.

The scientific basis for the recommendations has been discussed in Chapters III through VII. In Chapter VIII some special considerations which heavily influenced the form and emphasis of the final recommended criteria for this standard for work in hot environments are discussed.

A. Estimation of Risks

The ultimate objective of a recommended heat-stress standard is to limit the level of health risk (level of strain and the danger of incurring heat-related illnesses or injuries) associated with the total heat load (environmental and metabolic) imposed on a worker in a hot environment. The level of sophistication of risk estimation has improved during the past few years but still lacks a high level of accuracy. The earlier estimation techniques were usually qualitative or at best only semiquantitative.

One of the earlier semiquantitative procedures for estimating the risk of adverse health effects under conditions of heat exposure was designed by Lee and Henschel [129]. 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 was 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 the earlier attempts to develop procedures for estimating risk was the lack of sufficient reliable industry experience data to validate the estimates.

A large amount of empirical data on the relationship between heat stress and strain (including death from heatstroke) has accumulated over the past 40 years in the South African deep hot mines. From data derived from laboratory studies, a series of curves has been prepared to predict the probability of a worker's body temperature reaching dangerous levels when working under various levels of heat stress [130,131]. Based on these data and on epidemiologic data on heatstroke from 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 the worker is in imminent danger of fatal or irreversible heatstroke, the estimated probability of reaching this body temperature is 10^{-6} for workers exposed to an effective temperature (ET) of 34.6°C (94.3°F), 10^{-4} at 35.3°C (95.5°F), 10^{-2} at 35.8°C (96.4°F), and $10^{-0.5}$ at 36.6°C (97.9°F). If a body temperature of 38.5°-39.0°C (101.3°-102.2°F) is accepted as the critical temperature, the ET at which the probability of the body temperature reaching 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 humidities has not been proven. Probabilities of body temperature reaching designated levels at various ET values are also presented for unacclimatized men [5,130,131]. 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 38°C (100.4°F) in prolonged daily exposure to heavy work. In closely controlled conditions the deep body temperature may be allowed to rise to 39°C (102.2°F)" [48]. This does not mean that when a worker's t_{re} reaches 38°C (100.4°F) or even 39°C (102.2°F), the worker will necessarily become a heat casualty. If, however, the t_{re} exceeds 38°C (100.4°F), the risk of heat casualties occurring increases. The 38°C (100.4°F) 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 load are assessed.

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 [70]. 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 WBGT's of 17°-23°C (62.6°-73.4°F). Unsafe behavior also increased as the level of physical work of the job increased [70].

B. Correlation Between Exposure and Effects

The large amount of published data obtained during 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 generality 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 relates to the level of heat acclimatization and of physical work capacity. The individual variability may be large; however, with extreme heat stress, the variability decreases as the limits on 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-induced strain using computer programs encompassing the many variables.

Sophisticated models designed to predict physiologic strain as a function of heat load and as modified by a variety of confounding factors are available. These models range from graphic presentations of relationships to programs for handheld and desk calculators and computers [132,133]. 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 which 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 can be applied as a modified form of risk prediction. However, they do not, as presently designed, provide information on the level of heat stress when one worker in 10, or in 1,000, or in 10,000, will incur heat exhaustion, heat cramps, or heatstroke.

C. Physiologic Monitoring of Heat Strain

When the first NIOSH Criteria for a Recommended Standard....Occupational Exposure to Hot Environments document was prepared in 1972, 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, recently it has been proposed that monitoring body temperature and/or work and recovery heart rate of workers exposed to work environment conditions in excess of the ACGIH TLV could be a safe and relatively simple approach [117,127,128]. 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-induced 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), 1-1/2 to 2 minutes (P_2), and 2-1/2 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 b/min 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 b/min. 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 b/min the work-heat-stress conditions are satisfactory; if the P_3 approximates 90 b/min and/or the P_1-P_3 recovery is approximately 10 b/min, it indicates that the work level is high but there is little increase in body temperature; if P_3 is greater than 90 b/min and/or P_1-P_3 is less than 10 b/min, it indicates a no-recovery pattern and the heat-work stress exceeds acceptable levels; corrective actions should be taken to prevent heat injury or illness [127,128]. The corrective actions may be of several types (engineering, work practices, etc.).

In practice, obtaining recovery heart rates at 1- or 2-hour intervals or at the end of several workcycles during the hottest part of the workday of the summer season may present logistical problems, but available technology may allow these problems to be overcome. The pulse rate recording wristwatch that is used by some joggers, if proved sufficiently accurate and reliable, may permit automated heart rate measurements. With the advent of the single use disposable oral thermometer, measuring oral temperatures of workers at hourly intervals should be 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 at the end of 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.

Assessment of heat strain by monitored physiologic responses of heart rate and/or body temperature using radiotelemetry has been advocated. Such monitoring systems can be assembled from off-the-shelf electronic components and transducers and have been used in research in fire fighting and steel mills and are routinely used in the space flight program [134,135]. However, at present they are not applicable to routine industrial situations.

The obvious advantage of such an automated system would be that data could be immediately observed and trends established from which actions can be initiated to prevent excessive heat strain. The obvious disadvantages are that it requires time to attach the transducers to the worker at the start and remove them from the worker 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; electronic components require careful maintenance for proper operations. Also, the telemetric signals are often disturbed by the electromagnetic fields that may be generated by the manufacturing process.

D. Recommendations of U.S. Organizations and Agencies

1. The American Conference of Governmental Industrial Hygienists (ACGIH)

The American Conference of Governmental Industrial Hygienists (ACGIH) TLVs 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" [2]. The TLVs are based on the assumptions that the (1) workers are acclimatized to the work-associated heat stress present at the workplace, (2) workers are clothed in usual work clothing, (3) workers have adequate water and salt intake, (4) workers should be capable of functioning effectively, and (5) the TWA deep body temperature will not exceed 38°C (100.4°F). Those workers who are more tolerant to work in the heat than the average 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. The TLV permissible heat-exposure values consider both the environmental heat factors and the metabolic heat production. The environmental factors are expressed as the WBGT and are measured with the dry bulb, natural wet bulb, and black globe thermometers. The metabolic heat production is expressed as work-load category: light work = <200 kcal/h (<800 Btu/h or 230 W); moderate work = 200-350 kcal/h (800-1400 Btu/h or 230-405 W); and heavy work = >350 kcal/h (>1400 Btu/h or 405 W). The ranking of the job may be measured directly by the worker's metabolic rate while doing the job or estimated by the use of the work-load assessment procedure where both body position and movement and type of work are taken into consideration. For continuous work and exposure, a WBGT limit value is set for each level of physical work with a decreasing permissible WBGT for increasing levels of metabolic heat production.

The TLV permissible heat-exposure values range from a WBGT of 30°C (86°F) for light work, 26.7°C (80°F) for moderate work, to 25°C (77°F) for heavy work for continuous exposure based on a 1-hour TWA for WBGT and work load. These values are comparable to those in the ISO Standard 7243 [3]. In addition to the permissible heat-exposure threshold limit values for continuous work, the ACGIH Heat Stress TLV contains values for various rest-work regimens: 75% work, 25% rest each hour; 50% work, 50% rest each hour; and 25% work, 75% rest each hour for light, moderate, and heavy work, respectively. These TLVs assume that the rest environment is approximately the same as that at work. Appendix B of the ISO 7243 contains a similar set of values for rest-work regimens where the rest environment is similar to the work environment.

The ACGIH TLVs for heat stress which were adopted in 1974 forms the basis for the ISO standard on Heat Stress of 1982 (discussed in Chapter VIII-E).

2. Occupational Safety and Health Administration (OSHA) Standards Advisory Committee on Heat Stress (SACHS)

In January 1973, the Assistant Secretary of Labor for Occupational Safety and Health (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 working employees" [7]. The purpose of the standard was to minimize the risk of heat disorders and illnesses of workers exposed to hot environments so that the worker's well-being and health would not be impaired. 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 no longer considered for inclusion in the recommendations. The recommendations establish the threshold WBGT values for continuous exposure at the 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 are similar to the ACGIH TLVs. 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 do not satisfactorily reflect the advantage gained by the worker when air velocity is increased beyond 300 fpm. Data presented by Kamon et al. [136], however, questioned the assumption, because the clothing worn by the worker reduced the cooling effect of increased air velocity. However, under conditions where 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.

The recommendations of the SACHS contain a list of work practices that are to be initiated whenever the environmental conditions and work load exceed the threshold WBGT values. The threshold WBGT values and work levels are based on a 120-minute TWA. Also included are directions for medical surveillance, training of workers, and workplace monitoring.

The threshold WBGT values recommended by the OSHA SACHS are in substantial agreement with the ACGIH TLVs and the ISO standard. The OSHA SACHS recommendations have not, however, been promulgated into an OSHA heat-stress standard. Following any one of the three procedures would provide equally reliable guidance for ensuring worker health and well-being in hot occupational environments [137].

3. American Industrial Hygiene Association (AIHA)

The American Industrial Hygiene Association (AIHA) publication Heating and Cooling for Man in Industry, Chapter 2, "Heat Exchange and Human Tolerance Limits" contains a table of "Industrial Heat Exposure Limits" for industrial application [138]. The limits of heat exposure are expressed as WBGT values for light, moderate, and heavy work when the exposure is continuous for 50 minutes of each hour for an 8-hour day and for intermittent work-rest when each work period of 3 hours, 2 hours, 1 hour, 30 minutes, or 20 minutes is followed by 1 hour of rest. In establishing the heat-exposure limits for intermittent work-rest, it was assumed that the worker would rest in an environment that was cooler than the work area. It is also emphasized in the report that under conditions of severe heat where the work periods are limited to 20 or 30 minutes, experienced workers set their own schedules and work rate so that individual tolerances are not exceeded.

The maximum heat exposure limits for each of the work categories are, for continuous work, comparable to the TLVs and the ISO standard described in Chapter VIII-E.

For intermittent work, direct comparisons are difficult because of the differences in assumed rest area temperatures. However, when corrections for these differences are attempted, the ISO and the ACGIH TLV values for 75/25 and 50/50 work-rest regimens are not very different from the AIHA values. These limits support the generalizations that workable heat-stress exposure limits, based on the WBGT and metabolic heat-production levels, are logical and practical for use for industrial guidance [137].

4. The Armed Services

The 1980 publication (TBMED 507, NAVMED P-5052-5 and AFP 160-1) of the Armed Services, "Occupational and Environmental Health, Prevention, Treatment, and Control of Heat Injury" [139], addresses in detail the procedures for the assessment, measurement, evaluation, and control of heat stress and the recognition, prevention, and treatment of heat illnesses and injuries. Except for the part in which problems specific to military operations are discussed, the document is applicable to industrial-type settings.

The WBGT index is used for the measurement and assessment of the environmental heat load. It is emphasized that the measurements must be taken as close as possible to the location where the personnel are exposed. The threshold levels of WBGT for instituting proper hot weather practices are given for the various intensities of physical work (metabolic heat production). The WBGT and metabolic rates are calculated for a 2-hour TWA. The threshold WBGT values of 30°C (86°F) for light work, 28°C (82.4°F) for moderate work, and 25°C (77°F) for heavy work are about the same as those of the ISO standard and the ACGIH TLVs. However, these are the thresholds for instituting hot weather practices rather than limiting values. The mean metabolic rates (kcal/h or W) for light, moderate, and heavy work cited in this Armed Services document are expressed as TWA mean metabolic rates and are lower than the values generally used for each of the work categories.

Except for the problem of the metabolic rates, this document is an excellent, accurate, and easily used presentation. Engineering controls and the use of protective clothing and equipment are not extensively discussed; however, on balance it serves as a useful guide for the prevention, treatment, and control of heat-induced injuries and illnesses. In addition, it is in general conformity with the ISO standard, the ACGIH TLVs, and most other recommended heat-stress indices based on the WBGT.

5. American College of Sports Medicine (ACSM)

In July 1984, the American College of Sports Medicine (ACSM) published a position statement on "Prevention of Heat Injuries During Distance Running" [140]. 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-induced injuries and illnesses, the ACSM has prepared a list of recommendations which would serve as advisory guidelines to be followed during distance running when the environmental heat load exceeds specific values. These recommendations include (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 2-3 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 developing heat illness; and (7) provision should be made for the care of heat-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 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" is moderate risk with a WBGT of 18°-23°C (64.4°-73.4°F). It is assumed that the air temperature and humidity and solar radiation are likely to increase during the day.

E. International Standards and Recommendations

1. The International Organization for Standardization (ISO)

In 1982 the International Organization for Standardization (ISO) adopted and published an international standard on "Hot Environments - Estimation of the Heat Stress on Working Man Based on the WBGT Index (Wet Bulb Globe Temperature)" [3]. The standard, as published, was approved by the member bodies of 18 of the 25 countries who responded to the request for review of the document. Only two member bodies disapproved. Several of the member bodies who approved the documents have official or unofficial heat-stress standards in their own countries, i.e., France, Republic of South Africa, Germany, and Sweden. The member bodies of the United States and the U.S.S.R. were among those who neither approved nor disapproved the document. The vote of each member body is supposedly based on a consensus of the membership of its Technical Advisory Group. Although the U.S. group did not reach a consensus, several of the guidelines in the ISO standard were recommended by the NIOSH workshop [141] to be included in an updated criteria document.

The ISO heat-stress standard in general resembles the ACGIH TLV for heat stress adopted in 1974. The basic premise upon which both are based is that no worker should be exposed to any combination of environmental heat and physical work which would cause the worker's body core temperature to exceed 38°C (100.4°F). The 38°C is based on the recommendations of the World Health Organization's report of 1969 on health factors involved in working under conditions of heat stress [48]. In addition, the ISO standard is based on the WBGT index for expressing the combination of environmental factors and on reference tables (or direct oxygen consumption measurements) for estimating the metabolic heat load. The ISO standard includes a table for the classification of metabolic heat with examples of activities characteristic of each of the five metabolic rates (rest, low metabolic rate, moderate metabolic rate, high metabolic rate, and very high metabolic rate). The upper permissible WBGT value for each of these work categories is presented for both the heat-acclimatized and for the heat-unacclimatized worker. For the heavy and very heavy work categories, the WBGT values are further subdivided into "no sensible air movement" and for "sensible air movement" categories.

The ISO standard index values, as do most other recommended heat-stress limit values, assume that the worker is a normal healthy individual, physically fit for the level of activity being done, and wearing standard summer weight workclothing with a thermal insulation value of about 0.6 clo (not including the still air layer insulation). Deviations in health status, physical fitness, and type and characteristics of clothing worn will require a modification of the permissible WBGT index values. The ISO WBGT index values are also based on the hypothesis that the environment in which any rest periods are taken is essentially the same as the worksite environment, and that the worker spends most of the workday in this environment.

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.

The ISO standard brings together, on an international level, heat-stress guidelines which are component parts of the many official and unofficial standards and guidelines set forth nationally. Basically a general conformity between the many proposed standards.

A disturbing aspect of the ISO standard is that the "reference values correspond to exposures to which almost all individuals can be ordinarily exposed without harmful effect, provided that there is no preexisting pathological condition." This statement implies that in the specified nonpathologic population exposed to the standard index values of heat stress, some individuals could incur heat illnesses. What proportion of the population is "almost all?" How many heat illnesses are acceptable before corrective actions are taken? How are these less tolerant workers identified?

The problem of how to identify those few individuals whose low heat tolerance places them at high risk before their health and safety are jeopardized in a hot work environment is not addressed. The ISO standard does not address the problem of using biologic monitoring as an adjunct approach to reducing the risk of heat-induced illnesses.

The ISO standard includes one condition that is not addressed in some of the other standards or recommendations. A correction factor for air velocity during high metabolic heat production is introduced to compensate for the effect of air velocity on sweat evaporation rate. When there is no perceptible air movement, the WBGT index value is 1°C (1.8°F) lower than where there is a perceptible air movement for high metabolic rate (200-260 W/m^2) and 2°C (3.6°F) lower for very high metabolic rate (>260 W/m^2). This appears to be a reasonable correction; however, rarely in industrial situations does a "no sensible air movement" occur except possibly in confined enclosures. The movement of the torso and the limbs, especially during hard work, in itself will create an effective air movement. Consequently, it may be questioned whether an air movement correction is really necessary.

2. ISO Proposed Analytical Method

The ISO Working Group for the Thermal Environment has prepared a draft document "Analytical Determination of Thermal Stress" which, if adopted, would provide an alternative procedure for assessing the stressfulness of a hot industrial environment [142]. The method is based on a comparison between the required sweat production as a result of the working conditions and the maximum physiologically achievable skin wettedness and sweat production. The standard requires (1) calculating the sweat evaporation rate required to maintain body thermal balance, (2) calculating the maximum sweat evaporation rate permitted to the ambient environment, and (3) calculating the sweat rate required to achieve the needed skin wettedness. The cooling efficiency of sweat as modified by the clothing worn is included in the calculation of required skin wettedness.

The data required for making the calculations include dry bulb air temperature, wet bulb temperature, radiant temperature, air velocity, metabolic heat production, vapor and wind permeability, and insulation value of the clothing worn. From these, the convective, radiative, and evaporative heat exchange can be calculated using the thermodynamic constants. Finally, E_{req}/E_{max} can be expressed as sweat production required to wet the skin to the extent necessary (skin wettedness required). This approach basically is similar to the new effective temperature (ET*) proposed by the scientists at the Pierce Foundation Laboratories [143].

The computer program for calculating the required sweat rate and the allowable exposure time is written in BASIC computer language. It may require adaptation of the program to fit a particular user computer system. The major disadvantages with this proposed approach to a standard are essentially the same as those of other suggested approaches based on detailed calculations of heat exchange. The separate environmental factors, especially effective air velocity, are difficult to measure with required accuracy under conditions of actual industrial work situations. Air velocity, in particular, may vary widely from time to time at a workplace and at any time between short distances at a workplace. For routine industrial use, this proposed procedure appears to be too complicated. Furthermore, a number of assumptions must be made for the variables needed to solve the equation, because the variables cannot or are not easily measured directly, e.g., mean skin temperature is assumed to be 35°C (95°F) but may be lower or higher, and the convective and radiant heat transfer coefficients, which are assumed to be constant, vary with body posture. These and other assumed values detract from the usefulness of the predictions of heat strain.

On the positive side, the equations are well suited for deciding on the most efficient approach to reducing total heat load (e.g., environmental vs. metabolic heat). The ISO draft standard recommends limits in terms of hourly TWA values and 8 hours of exposure. The criterion for the 8-hour exposure is the amount of body water that can be lost by sweating and can be replaced without excessive hypohydration. These 8-hour values, expressed as total sweat production, are 3,250 mL for unacclimatized and 5,200 mL for acclimatized workers. An 8-hour sweat production of 2,500 mL and 3,900 mL, respectively, for the unacclimatized and the acclimatized workers are considered to represent a level of heat stress at which some countermeasures should be initiated. Hourly limits based on these 8-hour recommended action limits would be reduced by about 35%. If workers were exposed to heat each hour at the maximum hourly level in terms of the required sweat index, they would reach the 8-hour sweating limit after about 5 hours of exposure. These recommendations are supported by data from several western and eastern countries and from the United States, including the NIOSH studies.

The suggested physiologic strain criteria for thermal exposure limits based on average values are summarized in Table VIII-1.

TABLE VIII-1.--Criteria for thermal limits based on average values

	Heat (nonacclimatized) Alert	Danger	Heat (acclimatized) Alert	Danger
Heat storage kcal	58	70	58	70
Rectal temp increase °C (°F)	0.8 (1.4)	1 (1.8)	0.8 (1.4)	1 (1.8)
Skin temp increase °C (°F)	2.4 (4.3)	3 (5.4)	2.4 (4.3)	3 (5.4)
Sweat rate, max rest g/h	260	390	520	780
Sweat rate, max work g/h	520	650	780	1040
Max 8h sweat production to prevent excessive dehydration	2.60	3.25	3.90	5.20
Skin wettedness, rest	0.85		1.0	
Skin wettedness, work	0.50		0.85	

Adapted from Reference 16.

F. 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.

1. Finland

A heat-stress limits guide has been recommended which is not, however, an official national standard for Finland. The guide conforms to the ACGIH TLV for heat stress [144]. To evaluate the heat exposure, the WBGT method was used, because it was considered to be the best internationally documented procedure, and because it is simple and suitable for use in the field.

The limits presented in the Finnish guidelines are (as are the ACGIH TLV) based on the assumption that the worker is healthy, heat acclimatized, properly clothed, and provided with adequate water and salt. Higher levels of heat exposure are permitted for workers who show unusually high heat tolerance.

2. Sweden

The Department of Occupational Safety, General Bureau TAA 3, Collection of Reports AFS 198X, Report No. 4, 1981-09-11, Ventilation of Work Rooms [145], although mainly concerned with workroom heating, cooling, and ventilation to achieve thermal comfort and no health hazards, does specify "highest permissible heat exposure" which should not be exceeded. The maximum heat exposure is based on an hourly TWA for each of the various levels of physical activity: sitting, light, medium heavy, and heavy. For each activity level, the maximum environmental heat load is expressed in WBGT units: 28°, 25°, and 23°C (82°, 77°, and 73°F) for the light, medium heavy, and heavy activity levels, respectively. The activity levels in watts or kcal/h are not given. Consequently, it is difficult to compare exactly the presented maximum heat exposure levels with those of the ISO or ACGIH TLV.

If it is assumed that the activity levels are comparable to those of the ISO and ACGIH TLV, then the Swedish maximum heat-stress levels are about 2°C (3.6°F) lower for each activity. The Swedish WBGT (SWBGT) for air velocities less than 0.5 m/sec is calculated from the formula $SWBGT = 0.7t_{wb}+0.3t_a+2$. The added 2 is a correction factor when the psychrometric wet bulb temperature is used instead of the natural wet bulb temperature.

3. Romania

Chapter X, "Microclimate, Ventilation and Heating" of the Occupational Health Protection Standards of the Romanian Republic [146] provides data on air movement requirement and average maximum acceptable air temperature (t_a) for various levels of physical work (light = 150 kcal/h, average = 151-300 kcal/h, heavy = >300 kcal/h) and various levels of radiant heat load (600, 1200, 1800 kcal/h); relative humidity should not exceed 60%. In addition, several engineering controls, work practices, and types of personal protective equipment are listed. These control procedures are comparable to those provided in other heat-stress standards and recommendations. The maximum listed air temperatures and required wind speeds range from 28°C (82.4°F) and 1 m/sec for light work and low radiant heat to 22°C (71.6°F) and 3 m/sec for heavy physical work and high radiant heat. To convert the t_a, V_a, and the various levels of radiant heat and the metabolic heat load into WBGT, CET or comparable indices for direct comparison with other standards and recommendations would require considerable manipulation. The standard specifies that the microclimatic conditions at the worksite must be such that the worker can maintain thermal equilibrium while performing normal work duties. The body temperature accepted for thermal equilibrium is not specified. No mention was made of state of acclimatization, health status, clothing worn, etc., as factors to be considered in setting the heat stress values.

4. U.S.S.R.

The U.S.S.R. heat-stress standard CH245-68, 1963 [147] defines acceptable combinations of air temperature, humidity, air speed, and radiant temperatures for light, medium heavy, and heavy work loads. In general format, the U.S.S.R. and Romanian standards are comparable. They differ, however, in several points: (1) for medium heavy work the U.S.S.R. uses 150-245 kcal/h while Romania uses 150-300 kcal/h; (2) for heavy work the values are >250 kcal/h for the U.S.S.R. and >300 kcal/h for Romania; (3) for light work and radiant heat <600 kcal/m^2/h the U.S.S.R. t_a is 22°-24°C (71.6°-75.2°F) at air velocity of 0.5-1 m/sec while the Romanian t_a is 28°C (82.4°F) at air velocity of 1 m/sec; (4) for the heavy work and radiant heat >1200 kcal/h the U.S.S.R. t_a is 16°C (60.8°F) with air velocity of 3 m/sec while the Romanian t_a is 22°C (71.6°F) at air velocity of 3 m/sec; and (5) for all combinations of work and radiant heat loads in between these extremes the U.S.S.R. t_a is consistently 2°C (3.6°F) or more below the Romanian t_a at comparable air velocities. The U.S.S.R. standard suggests that for high heat and work load occupations, the rest area for the workers be kept at "optimum conditions." For radiant heat sources above 45°C (113°F), radiation shielding must be provided. State of acclimatization, physical fitness, health status, clothing worn, provision of water, etc., are not addressed as factors that were considered in establishing the heat-stress limits.

5. Belgium

The Belgium Royal Decree [148] concerning workplace environments contains a section on maximum permissible temperature in indoor workplaces acceptable for very light (90 kcal/h), light (150 kcal/h), semiheavy (250 kcal/h), and heavy work (350 kcal/h). The work category energies are comparable to those used in the ISO standard. It is specified that if the workers are exposed to radiant heat, the environmental heat load should be measured with a wet globe thermometer or any other method that will give similar effective temperature values. The maximum temperatures established for the various work intensities are the same as those of the ISO and the ACGIH TLV, but the values are stated in terms of ET.

Based on the advice of an industrial physician and agreement of the workers' representative to the Committee of Safety, Health and Improvement of the Workplace, the maximum permissible temperature may be exceeded if (1) exposure is intermittent, (2) a cool rest area is available, and (3) adequate means of protection against excessive heat are provided. The decree also provides that for outside work in the sun, the workers should be protected from solar radiation by an adequate device.

The industrial physician is given the responsibility for ensuring heat acclimatization of the worker, selection and use of protective devices, establishing rest times, and informing workers of the need for an adequate fluid intake. The employer is responsible for providing engineering controls for convective heat by ventilation and radiant heat by shielding, reflective protective clothing, or clothing with incorporated cooling.

If engineering controls are not adequate, a reduction in exposure time to the excessive heat is recommended. This reduction in exposure is accomplished by varying the work-rest cycle. The rest area temperature must be below 30°C (86°F). A table is provided for work-rest cycles for various environmental heat loads at each of the levels of physical work. For 10 minutes of rest in each 2-hour work period, the maximum effective temperatures are 30.1°, 26.8°, and 25.1°C (86.1°, 80.23°, and 77.2°F) for light, semiheavy, and heavy work, respectively. At the other extreme, only 5 minutes of work is permitted when the effective temperature is 33°, 32°, and 31.5°C (91.9°, 89.6°, and 88.7°F) for light, semiheavy, and heavy work, respectively. These values are relatively comparable to the WBGT values listed in the ACGIH TLVs for similar work loads.

6. Australia

Rule 1 of the Factories (Health and Safety) Regulations, Factories and Shops Act of 1960-1973, as revised by order of Council, November 1973, sections (8)(b) through (8)(d), (9), and (10) [149] contain general statements pertaining to temperature, air movement, and humidity for hot working areas in factories. In those factories that are not air conditioned, the inside globe temperature shall not exceed 25°C (77°F) when the outside temperature is 22.2°C (72°F) or below, or the inside globe temperature shall not exceed the outside temperature by more than 2.8°C (5°F) when the outside temperature is above 22.2°C (72°F).

Minimum air movement is specified only for dressing and dining areas, and humidities are specified only for areas that are air conditioned. These Australian rules are very general but do contain a provision that if in the opinion of an inspector "the temperature and humidity is likely to be injurious to the health of a worker, the inspector may require that remedial measures shall be taken." These remedial measures include plant alterations and engineering controls. Recently, however, the Australian member body of ISO voted for the adoption of the ISO standard. Recently, the Victorian Trade Hall Council published guidelines on working in heat [150]. The suggested guidelines which closely follow the ACGIH TLVs for heat stress [2] included a summary of (1) what is heat stress, (2) effects of heat stress, (3) heat illnesses, (4) measurement of heat stress, (5) protective measurements against heat stress, (6) medical requirements under heat-stress conditions, (7) acclimatization to heat, and (8) regulations governing hot work. The Australian Health and Medical Research Council also adopted these guidelines. An unusual feature is the recommendation that "hazard money" should not be an acceptable policy but that "a first priority is the elimination of the workplace hazards or dangers and the refusal to accept payment for hazardous or unsafe work."

7. Japan

The Recommendations on Maximum Allowable Concentrations of Toxic Substances and Others in the Work Environment, 1982 published by the Japanese Association of Industrial Health contains a section on "Maximum Allowable Standards for High Temperatures" [151]. These recommendations are designed as guidelines for protecting the worker from health hazards in the hot work environment but do not have official governmental endorsement. In this way they are comparable to the ACGIH TLVs.

The section on maximum allowable standards for high temperatures sets the environmental heat-stress limits in WBGT and Corrected Effective Temperature (CET) units for five intensities of physical work ranging from extremely light (130 kcal/h) to heavy (370 kcal/h). When the permissible maximum allowable WBGT values are compared to the ACGIH TLVs for similar levels of physical work, they are essentially equal and are also comparable to the ISO recommended heat-stress limits.

IX. INDICES FOR ASSESSING HEAT STRESS AND STRAIN

During the past half century 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 psychologic 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 and 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.

A. Direct Indices

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°-25.5°C (71.6°-77.9°F) are considered comfortable by most people. If work intensity is increased to moderate or heavy work, the comfort air temperature is decreased about 1.7°C (3°F) 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 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 [14].

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 heatstroke occurring in South African and German mines [130].

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.

B. Rational Indices

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.

2. Belding-Hatch Heat-Stress Index

The Belding and Hatch Heat-Stress Index (HSI) [152] 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_{req}) 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 1 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 8 liters per 8-hour day of sweat production is too high, and as the 8-hour sweat production exceeds 5 liters, more and more workers will dehydrate more than 1.5% of the body weight, thereby increasing the risk of heat illness and accidents. 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, dry and hot, 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_{req} 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 at best is 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 as a result of observations on clothed subjects, by McKarns and Brief [153]. 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.

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 [16,22,26,136,143,154].

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.

C. Empirical Indices

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

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 heating effect of radiant heat 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 relative humidity in place of the 100% reference rh for the ET and CET. The ET* has all the liabilities 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 26.5°C (79.7°F) for hard work. For the fully heat-acclimatized individuals, the tolerable limits are increased about 2°C (3.6°F).

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 27.7°C (81.9°F) (at 100% rh with minimal air motion) which is approximately the reported threshold for the onset of fatal heatstroke during hard work [5,6]. 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.

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. For indoor use only two measurements are needed: natural wet bulb and black globe temperatures. For outdoors in sunshine, the air temperature also must be measured. The calculation of the WBGT for indoors is:

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

for outdoors:

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

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 a 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 [155]. 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 [9] 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 [156]. The WBGT was used as the index for expressing environmental heat load in the ACGIH TLVs - Heat Stress adopted in 1974 [2]. 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 the Heat Stress on Working Man Based on the WBGT Index (Wet Bulb Globe Temperature) 1982 [3] (see Chapter VIII 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 worktime 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.

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 [157]. 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)).

During the past few years, the WGT has been used in many laboratory studies and field situations where it has been compared with the WBGT [158,159,160,161,162]. 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 7°C (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 good 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.

D. 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 illness or accidents and (2) to provide a basis for recommending control procedures. The physiologic responses to an increasing heat load include an increase in heart rate, an increase in body temperature, an increase in skin temperature, and an increase in 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 [48,127,128]. It, therefore, 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 predesignated 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 [127,128]. However, several of the physiologic strain monitoring procedures are either invasive (radio pill) or socially unacceptable (rectal catheter) or interfere with communication (ear thermometer). Physiologic monitoring requires medical supervision and the consent of the worker.

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 workcycle or at specified times during the workday [29]. At the end of a workcycle, 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 P_1 exceeds 110 beats per minutes (b/min), and/or the P_1-P_3 is fewer than 10 b/min, the heat and work stress is assumed to be above acceptable values. These values are for 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 [127,128] as a basis for monitoring the strain of working at hot jobs. The ultimate criterion of high heat strain is an oral temperature exceeding 37.5°C (99.5°F). The heart rate recovery pattern is used to assist in the evaluation. If the P_3 is 90 b/min or fewer, the job situation is satisfactory; if the P_3 is about 90 b/min and the P_1-P_3 is about 10 b/min, 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 b/min and the P_1-P_3 is fewer than 10 b/min, the stress (heat + work) is too high for the individual and corrective actions should be introduced. These individuals should be examined by a physician, and the work schedule and work environment should be evaluated.

The field data reported by Jensen and Dukes-Dobos [163] 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 5 minutes will not seriously interfere with the work sequence; in addition, the instrumentation required (a stopwatch at a minimum) can be simple and inexpensive. Certainly the recovery and work heart rate 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.

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 38°C (100.4°F) or oral temperature of 37.5°C (99.5°F). 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) although not a complicated procedure does present the serious problem of being generally socially unacceptable to the workers.

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). There is no reason why, with worker permission, monitoring body temperature cannot be applied in many hot industrial jobs. Evaluation of the significance of any oral temperature must follow established medical and occupational hygiene guidelines.

3. Skin Temperature

The use of skin temperature 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 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 [14,15,20,22,164,165]. 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.

4. Hypohydration

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 to prevent hypohydration. If hypohydration 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 [32]. When hypohydration exceeds 5%, it may lead to collapse and to hypohydration heat illness. Since the feeling of thirst is not an adequate guide for water replacement, workers in hot jobs should be encouraged to take a drink of water every 15 to 20 minutes. The water should be cool 10°-15°C (50°-59°F), but neither warm nor cold. Drinking from disposable drinking cups is preferable to using drinking fountains. The amount of hypohydration 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 water drinking schedule is usually satisfactory.

X. RESEARCH NEEDS

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

A. 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 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?

B. 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" [48], 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-induced 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 1 hour of exposure as when reached after more than 1 hour of exposure?

C. 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.

D. Identifying Heat Intolerant Workers

Most humans when exposed to heat stress will develop, by the processes of heat acclimatization, a remarkable ability to tolerate the heat. In any worker population, some will be able to tolerate heat better than others, and a few, for a variety of reasons, will be relatively heat intolerant. At present, the heat-tolerant individual cannot be easily distinguished from the heat-intolerant individual except by the physiologic responses to exposure to high heat loads or on the basis of $\dot{V}O_2max$ (<2.5 L/m). However, waiting until an individual becomes a heat casualty to determine heat intolerance is an unacceptable procedure. A short and easily administered screening test which will reliably predict degree of heat tolerance would be very useful.

E. 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 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 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 [77]. 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.

F. Circadian Rhythm of Heat Tolerance

The normal daily variation in body temperature from the high point in the early afternoon to the low point in the early morning hours is about 1°C (1.8°F). 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) [48]. 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?

G. Heat-Strain Monitoring

The heat-stress indices and strain prediction techniques are useful for estimating what the level of strain is likely to be for a given heat-stress situation and a given worker population, but they do not permit a prediction of which individual or individuals will become heat casualties. Because of the wide interindividual tolerance to heat stress, predictions of when and under what circumstances an individual may reach unacceptable levels of physiologic and psychologic strain cannot be made with a high degree of accuracy. One solution to this dilemma might be an individual heat-load dosimeter or a physiologic strain monitor (e.g., body or skin temperature or heart rate). A physiologic strain monitor would remove the necessity for measuring and monitoring the thermal environment and estimating the metabolic heat production. Monitoring the body temperature of a worker on a hot job once an hour and removing the worker from the heat if the body temperature reaches a previously agreed upon level would eliminate the risk of incurring a heat-related illness or injury. A small worker-worn packet containing a sensor, signal converter, display, and alarm to monitor body temperature and/or heart rate is technically feasible. The problem, however, is worker acceptance of the sensors.

H. Accidents and Heat Stress

Are accidents more prevalent in hot industries and in the hotter months of the year? There are data [70,71] that show a relationship between industrial accidents and heat stress, but there are not enough data to establish heat stress limits for accident prevention in hot industries. Field evaluations, as well as laboratory studies, are required to correlate accident probability or frequency with environmental and job heat-stress values in order to determine with statistical validity the role of heat stress in industrial accidents.

I. Effects of Heat on Reproduction

It is a well-documented phenomenon in mammals that spermatogenesis is very sensitive to testicular temperature [125]. Raising testicular temperature to deep body temperature inhibits spermatogenesis and results in relative infertility. A recent study of male foundry workers suggests that infertility is higher among couples where the male member is a foundry worker exposed to high temperatures than it is among the general population [124]. There are many industrial situations, including jobs where impermeable or semipermeable protective clothing must be worn, in which the testicular temperature would be expected to approximate body temperature. If a degree of male infertility is associated with heat exposure, data are required to prove the relationship, and remedial or preventive methods must be devised. Whether heat acts as a teratogenic agent in humans, as it apparently does in animals, is another problem that requires more research.

J. 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.

K. Effects of Clothing and Benefits of Cooling Garments

There are several versions of effective cooling clothing and equipment commercially available. All versions, although very useful in special hot situations, have one or more of the following disadvantages: (1) limited operating time, (2) restrictions of free movement of the worker, (3) additional weight that must be carried, (4) limited dexterity and movement of the hands, arms, head, and legs, (5) increased minimal space within which the individual can work, and (6) use with other protective clothing and equipment (e.g., for protection against chemical hazards). The maximum efficiency and usability of such systems have not been achieved. Research on systems that will minimize the disadvantages while maximizing the efficiency of the cooling- and heat-exchange capacities is needed.

L. Medical Screening and Biologic Monitoring Procedures

Data to substantiate the degree of effectiveness of medical screening and biologic monitoring in reducing the risk of heat-induced illnesses among workers in hot industries are, at present, not systematically recorded nor are they readily available in the open literature. Such data, however, must be made available in sufficient quantity and detail to permit an epidemiologic and medical assessment of their health and safety, as well as economic feasibility for health and safety control procedures in hot industries. Standardized procedures for reporting incidences of heat-related health and safety problems, as well as environmental and work-heat loads, assessment of control procedures in use, medical screening practices, and biologic monitoring procedures, if routinely followed and reported, would provide an objective basis for assessing the usefulness of medical screening and biologic monitoring as preventive approaches to health.

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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
$\eth$	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. Radiation (R) SI Units

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

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

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 $\underline{E}_{sk}$ 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 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. <u>Evaporation (E) SI Units</u>

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 ($m^2kP_a\ W^{-1}$). 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.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1994: 550-147/00020