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Ergonomics of the thermal environment — Analytical determination and interpretation of heat stress using calculation of the predicted heat strain

Ergonomie des ambiances thermiques — Détermination analytique et interprétation de la contrainte thermique fondées sur le calcul de l'astreinte thermique prévisible

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 7933 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*.

This second edition cancels and replaces the first edition (ISO 7933:1989), which was based on the Required Sweat Rate index. In order to avoid any confusion and, as extensive modifications are brought to the prediction model, the name of the index has been changed to Predicted Heat Strain (PHS).

Introduction

Other International Standards of this series describe how the parameters influencing the human thermoregulation in a given environment must be estimated or quantified. Others specify how these parameters must be integrated in order to predict the degree of discomfort or the health risk in these environments. The present document was prepared to standardize the methods that occupational health specialists should use to approach a given problem and progressively collect the information needed to control or prevent the problem.

The method of computation and interpretation of thermal balance is based on the latest scientific information. Future improvements concerning the calculation of the different terms of the heat balance equation, or its interpretation, will be taken into account when they become available. In its present form, this method of assessment is not applicable to cases where special protective clothing (reflective clothing, active cooling and ventilation, impermeable, with personal protective equipment) is worn.

In addition, occupational health specialists are responsible for evaluating the risk encountered by a given individual, taking into consideration his specific characteristics that might differ from those of a standard subject. ISO 9886 describes how physiological parameters must be used to monitor the physiological behaviour of a particular subject and ISO 12894 describes how medical supervision must be organized.

Ergonomics of the thermal environment — Analytical determination and interpretation of heat stress using calculation of the predicted heat strain

1 Scope

This International Standard specifies a method for the analytical evaluation and interpretation of the thermal stress experienced by a subject in a hot environment. It describes a method for predicting the sweat rate and the internal core temperature that the human body will develop in response to the working conditions.

The various terms used in this prediction model, and in particular in the heat balance, show the influence of the different physical parameters of the environment on the thermal stress experienced by the subject. In this way, this International Standard makes it possible to determine which parameter or group of parameters should be modified, and to what extent, in order to reduce the risk of physiological strains.

The main objectives of this International Standard are the following:

a) the evaluation of the thermal stress in conditions likely to lead to excessive core temperature increase or water loss for the standard subject;

b) the determination of exposure times with which the physiological strain is acceptable (no physical damage is to be expected). In the context of this prediction mode, these exposure times are called "maximum allowable exposure times".

This International Standard does not predict the physiological response of individual subjects, but only considers standard subjects in good health and fit for the work they perform. It is therefore intended to be used by ergonomists, industrial hygienists, etc., to evaluate working conditions.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7726, *Ergonomics of the thermal environment — Instruments for measuring physical quantities*

ISO 8996, *Ergonomics of the thermal environment — Determination of metabolic rate*

ISO 9886, *Ergonomics — Evaluation of thermal strain by physiological measurements*

ISO 9920, *Ergonomics of the thermal environment — Estimation of the thermal insulation and evaporative resistance of a clothing ensemble*

3 Symbols

For the purposes of this document, the symbols and abbreviated terms, designated below as “symbols” with their units, are in accordance with ISO 7726.

However, additional symbols are used to for the presentation of the Predicted Heat Strain index.

A complete list of symbols is presented in Table 1.

Table 1 — Symbols and units

Symbol	Term	Unit
–	code = 1 if walking speed entered, 0 otherwise	–
–	code = 1 if walking direction entered, 0 otherwise	–
α	fraction of the body mass at the skin temperature	dimensionless
α_i	skin-core weighting at time t_i	dimensionless
α_{i-1}	skin-core weighting at time t_{i-1}	dimensionless
ε	emissivity	dimensionless
θ	angle between walking direction and wind direction	degrees
A_{Du}	DuBois body surface area	square metre
A_{p}	fraction of the body surface covered by the reflective clothing	dimensionless
A_{r}	effective radiating area of a body	dimensionless
C	convective heat flow	watts per square metre
c_{e}	water latent heat of vaporization	joules per kilogram
$C_{\mathrm{orr,cl}}$	correction for the dynamic total dry thermal insulation at or above 0,6 clo	dimensionless
$C_{\mathrm{orr,Ia}}$	correction for the dynamic total dry thermal insulation at 0 clo	dimensionless
$C_{\mathrm{orr,tot}}$	correction for the dynamic clothing insulation as a function of the actual clothing	dimensionless
$C_{\mathrm{orr,E}}$	correction for the dynamic permeability index	dimensionless
c_{p}	specific heat of dry air at constant pressure	joules per kilogram of dry air kelvin
C_{res}	respiratory convective heat flow	watts per square metre
c_{sp}	specific heat of the body	watts per square meter per kelvin
D_{lim}	maximum allowable exposure time	minutes
$D_{\mathrm{lim\ tre}}$	maximum allowable exposure time for heat storage	minutes
$D_{\mathrm{limloss50}}$	maximum allowable exposure time for water loss, mean subject	minutes
$D_{\mathrm{limloss95}}$	maximum allowable exposure time for water loss, 95 % of the working population	minutes
D_{max}	maximum water loss	grams
D_{max50}	maximum water loss to protect a mean subject	grams
D_{max95}	maximum water loss to protect 95 % of the working population	grams
DRINK	1 if workers can drink freely, 0 otherwise	dimensionless

Symbol	Term	Unit
dS_i	body heat storage during the last time increment	watts per square metre
dS_{eq}	body heat storage rate for increase of core temperature associated with the metabolic rate	watts per square meter
E	evaporative heat flow at the skin	watts per square metre
E_{max}	maximum evaporative heat flow at the skin surface	watts per square metre
E_p	predicted evaporative heat flow	watts per square metre
E_{req}	required evaporative heat flow	watts per square metre
E_{res}	respiratory evaporative heat flow	watts per square metre
f_{cl}	clothing area factor	dimensionless
$F_{cl,R}$	reduction factor for radiation heat exchange due to wearing clothes	dimensionless
F_r	emissivity of the reflective clothing	dimensionless
H_b	body height	meters
h_{cdyn}	dynamic convective heat transfer coefficient	watts per square metre kelvin
h_r	radiative heat transfer coefficient	watts per square metre kelvin
$I_{a\ st}$	static boundary layer thermal insulation	square meters kelvin per watt
$I_{cl\ st}$	static clothing insulation	square meters kelvin per watt
I_{cl}	clothing insulation	clo
$I_{tot\ st}$	total static clothing insulation	square meters kelvin per watt
$I_{a\ dyn}$	dynamic boundary layer thermal insulation	square meters kelvin per watt
$I_{cl\ dyn}$	dynamic clothing insulation	square meters kelvin per watt
$I_{tot\ dyn}$	total dynamic clothing insulation	square meters kelvin per watt
i_{mst}	static moisture permeability index	dimensionless
i_{mdyn}	dynamic moisture permeability index	dimensionless
$incr$	time increment from time t_{i-1} to time t_i	minutes
k_{Sw}	fraction k of predicted sweat rate	dimensionless
K	conductive heat flow	watts per square metre
M	metabolic rate	watts per square meter
p_a	water vapour partial pressure	kilopascals
$p_{sk,s}$	saturated water vapour pressure at skin temperature	kilopascals
R	radiative heat flow	watts per square metre
r_{req}	required evaporative efficiency of sweating	dimensionless
R_{tdyn}	dynamic total evaporative resistance of clothing and boundary air layer	square metres kilopascals per watt
S	body heat storage rate	watts per square metre
S_{eq}	body heat storage for increase of core temperature associated with the metabolic rate	watts per square metre
Sw_{max}	maximum sweat rate	watts per square metre
Sw_p	predicted sweat rate	watts per square metre
$Sw_{p,i}$	predicted sweat rate at time t_i	watts per square metre

Symbol	Term	Unit
$Sw_{p,i-1}$	predicted sweat rate at time t_{i-1}	watts per square metre
Sw_{req}	required sweat rate	watts per square metre
t	time	minutes
t_a	air temperature	degrees celsius
t_{cl}	clothing surface temperature	degrees celsius
t_{cr}	core temperature	degrees celsius
$t_{cr,eqm}$	steady state value of core temperature as a function of the metabolic rate	degrees celsius
$t_{cr,eq}$	core temperature as a function of the metabolic rate	degrees celsius
$t_{cr,eq\ i}$	core temperature as a function of the metabolic rate at time t_i	degrees celsius
$t_{cr,eq\ i-1}$	core temperature as a function of the metabolic rate at time t_{i-1}	degrees celsius
$t_{cr,i}$	core temperature at time t_i	degrees celsius
$t_{cr,i-1}$	core temperature at time t_{i-1}	degrees celsius
t_{ex}	expired air temperature	degrees celsius
t_r	mean radiant temperature	degrees celsius
t_{re}	rectal temperature	degrees celsius
$t_{re,\ max}$	maximum acceptable rectal temperature	degrees celsius
$t_{re,i}$	rectal temperature at time t_i	degrees celsius
$t_{re,i-1}$	rectal temperature at time t_{i-1}	degrees celsius
$t_{sk,eq}$	steady state mean skin temperature	degrees celsius
$t_{sk,eq\ nu}$	steady state mean skin temperature for nude subjects	degrees celsius
$t_{sk,eq\ cl}$	steady state mean skin temperature for clothed subjects	degrees celsius
$t_{sk,i}$	mean skin temperature at time t_i	degrees celsius
$t_{sk,i-1}$	mean skin temperature at time t_{i-1}	degrees celsius
V	respiratory ventilation rate	litres per minute
v_a	air velocity	metres per second
v_{ar}	relative air velocity	metres per second
v_w	walking speed	metres per second
w	skin wettedness	dimensionless
W	effective mechanical power	watts per square metre
W_a	humidity ratio	kilograms of water per kilogram of dry air
W_b	body mass	kilograms
W_{ex}	humidity ratio for the expired air	kilograms of water per kilogram of dry air
w_{max}	maximum skin wettedness	dimensionless
w_p	predicted skin wettedness	dimensionless
w_{req}	required skin wettedness	dimensionless

4 Principles of the method of evaluation

The method of evaluation and interpretation calculates the thermal balance of the body from

a) the parameters of the thermal environment:

- air temperature, t_a;
- mean radiant temperature, t_r;
- partial vapour pressure, p_a;
- air velocity, v_a;

(These parameters are estimated or measured according to ISO 7726.)

b) the mean characteristics of the subjects exposed to this working situation:

- the metabolic rate, M, estimated on the basis of ISO 8996;
- the clothing thermal characteristics estimated on the basis of ISO 9920.

Clause 5 describes the principles of the calculation of the different heat exchanges occurring in the thermal balance equation, as well as those of the sweat loss necessary for the maintenance of the thermal equilibrium of the body. The mathematical expressions for these calculations are given in Annex A.

Clause 6 describes the method of interpretation which leads to the determination of the predicted sweat rate, the predicted rectal temperature, and the maximum allowable exposure times and work-rest regimens to achieve the predicted sweat rate. This determination is based on two criteria: maximum body core temperature increase and maximum body water loss. Maximum values for these criteria are given in Annex B.

The precision with which the predicted sweat rate and the exposure times are estimated is a function of the model (i.e. of the expressions proposed in Annex A) and the maximum values, which are adopted. It is also a function of the accuracy of estimation and measurement of the physical parameters and of the precision with which the metabolic rate and the thermal insulation of the clothing are estimated.

5 Main steps of the calculation

5.1 General heat balance equation

5.1.1 General

The thermal balance equation of the body may be written as:

$$M - W = C_{res} + E_{res} + K + C + R + E + S \qquad (1)$$

This equation expresses that the internal heat production of the body, which corresponds to the metabolic rate (M) minus the effective mechanical power (W), is balanced by the heat exchanges in the respiratory tract by convection (C_{res}) and evaporation (E_{res}), as well as by the heat exchanges on the skin by conduction (K), convection (C), radiation (R), and evaporation (E), and by the eventual balance, heat storage (S), accumulating in the body.

The different terms of Equation (1) are successively reviewed in terms of the principles of calculation (detailed expressions are shown in Annex A).

5.1.2 Metabolic rate, M

The estimation or measurement of the metabolic rate is described in ISO 8996.

Indications for the evaluation of the metabolic rate are given in Annex C.

5.1.3 Effective mechanical power, W

In most industrial situations, the effective mechanical power is small and can be neglected.

5.1.4 Heat flow by respiratory convection, C_{res}

The heat flow by respiratory convection may be expressed, in principle, by the equation

$$C_{res} = 0{,}072\ c_p \times V \times \frac{t_{ex} - t_a}{A_{Du}} \quad (2)$$

5.1.5 Heat flow by respiratory evaporation, E_{res}

The heat flow by respiratory evaporation may be expressed, in principle, by the equation

$$E_{res} = 0{,}072\ c_e \times V \times \frac{W_{ex} - W_a}{A_{Du}} \quad (3)$$

5.1.6 Heat flow by conduction: K

As this International Standard deals with the risk of whole-body dehydration and hyperthermia, the heat flow by thermal conduction at the body surfaces in contact with solid objects may be quantitatively assimilated to the heat losses by convection and radiation which would occur if these surfaces were not in contact with any solid body. In this way, the heat flow by conduction is not directly taken into account.

ISO 13732-1 deals specifically with the risks of pain and burns when parts of the body contact hot surfaces.

5.1.7 Heat flow by convection at the skin surface, C

The heat flow by convection at the skin surface may be expressed by the equation

$$C = h_{cdyn} \times f_{cl} \times (t_{sk} - t_a) \quad (4)$$

where the dynamic convective heat transfer coefficient between the clothing and the outside air, h_{cdyn}, takes into account the clothing characteristics, the movements of the subject and the air movements.

Annex D provides some indications for the evaluation of the clothing thermal characteristics.

5.1.8 Heat flow by radiation at the surface of the skin, R

The heat flow by radiation may be expressed by the equation

$$R = h_r \times f_{cl} \times (t_{sk} - t_r) \quad (5)$$

where the radiative heat transfer coefficient between the clothing and the outside air, h_r, takes into account the clothing characteristics, the movements of the subject and the air movements.

5.1.9 Heat flow by evaporation at the skin surface, E

The maximum evaporative heat flow at the skin surface, E_{max}, is that which can be achieved in the hypothetical case of the skin being completely wetted. In these conditions

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{tdyn}} \quad (6)$$

where the total evaporative resistance of the limiting layer of air and clothing, R_{tdyn}, takes into account the clothing characteristics, the movements of the subject and the air movements.

In the case of a partially wetted skin, the evaporation heat flow, E, in watts per square metre, is given by

$$E = w \times E_{max} \quad (7)$$

5.1.10 Heat storage for increase of core temperature associated with the metabolic rate, dS_{eq}

Even in neutral environment, the core temperature rises towards a steady state value $t_{cr,eq}$ as a function of the metabolic rate relative to the individual's maximal aerobic power.

The core temperature reaches this steady state temperature exponentially with time. The heat storage associated with this increase, dS_{eq}, does not contribute to the onset of sweating and must therefore be deducted from the heat balance equation.

5.1.11 Heat storage, S

The heat storage of the body is given by the algebraic sum of the heat flows defined previously.

5.2 Calculation of the required evaporative heat flow, the required skin wettedness and the required sweat rate

Taking into account the hypotheses made concerning the heat flow by conduction, the general heat balance Equation (1) can be written as

$$E + S = M - W - C_{res} - E_{res} - C - R \quad (8)$$

The required evaporative heat flow, E_{req}, is the evaporation heat flow required for the maintenance of the thermal equilibrium of the body and, therefore, for the heat storage to be equal to zero. It is given by

$$E_{req} = M - W - C_{res} - E_{res} - C - R - dS_{eq} \quad (9)$$

The required skin wettedness, w_{req}, is the ratio between the required evaporative heat flow and the maximum evaporative heat flow at the skin surface:

$$w_{req} = \frac{E_{req}}{E_{max}} \quad (10)$$

The calculation of the required sweat rate is made on the basis of the required evaporative heat flow, but taking account of the fraction of sweat that trickles away because of the large variations in local skin wettedness. The required sweat rate is given by

$$Sw_{req} = \frac{E_{req}}{r_{req}} \quad (11)$$

NOTE The sweat rate in watts per square meter represents the equivalent in heat of the sweat rate expressed in grams of sweat per square metre of skin surface and per hour. 1 W·m^{-2} corresponds to a flow of 1,47 g·m^{-2} h^{-1} or 2,67 g·h^{-1} for a standard subject (1,8 m^2 of body surface).