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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 122, *Ergonomics*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 7933:2004), which has been technically revised.

The main changes are as follows:

— The maximum sweat rate S_{Wmax} described in B.4 has been corrected, i.e. it is no longer adjusted for metabolic rate.

— As the model has not been extensively validated for conditions with unsteady environmental parameters, metabolic rate and/or clothing, a caution has been added for cases where these parameters vary substantially with time.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 15265 describes the assessment strategy for the prevention of discomfort or health effects in any thermal working condition, while ISO 8025[1)] recommends specific practices concerning hot working environments. For these hot environments, these standards propose relying on the wet bulb globe temperature (WBGT) heat stress index described in ISO 7243 as a screening method for establishing the presence or absence of heat stress, and on the more elaborate method presented in this document, to make a more accurate estimation of stress, to determine the allowable durations of work in these conditions and to optimize the methods of protection. This method, based on an analysis of the heat exchange between a person and the environment, is intended to be used directly when it is desirable to carry out a detailed analysis of working conditions in heat.

This document makes it possible to predict the evolution of a few physiological parameters (skin and rectal temperatures, as well as sweat rate) over time for a person working in a hot environment. This prediction is made according to the climatic parameters, the energy expenditure of the person and his or her clothing. This prediction is made for an average person and should be used to assess the risk of heat stress for a group of people; it cannot predict a particular person's responses.

This document 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.

Occupational health specialists are responsible for evaluating the risk encountered by a given individual, taking into consideration their specific characteristics that can differ from those of a standard person. ISO 9886 describes how physiological parameters are used to monitor the physiological behaviour of a particular person and ISO 12894 describes how medical supervision is organized.

1) Under preparation. Stage at the time of publication: ISO/DIS 8025:2023.

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

1 Scope

This document describes a model [the predicted heat strain (PHS) model] for the analytical determination and interpretation of the thermal stress (in terms of water loss and rectal temperature) experienced by an average person in a hot environment and determines the maximum allowable exposure times within which the physiological strain is acceptable for 95 % of the exposed population (the maximum tolerable rectal temperature and the maximum tolerable water loss are not exceeded by 95 % of the exposed people).

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 average person. In this way, this document makes it possible to determine which parameter or group of parameters can be changed, and to what extent, in order to reduce the risk of excessive physiological strain.

In its present form, this method of assessment is not applicable to cases where special protective clothing (e.g. fully reflective clothing, active cooling and ventilation, impermeable coveralls) is worn.

This document does not predict the physiological response of an individual person, but only considers average persons in good health and fit for the work they perform. It is therefore intended to be used by, among others, ergonomists and industrial hygienists, as the outcomes can require expert interpretations. Recommendations about how and when to use this model are given in ISO 8025.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 13731, *Ergonomics of the thermal environment — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13731 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

4 Symbols

For the purposes of this document, the symbols and units listed in Table 1 apply.

Table 1 — Symbols and units

Symbol	Term	Unit
α	fraction of the body mass at the skin temperature	—
α_i	fraction of the body mass at the skin temperature at time t_i	—
α_{i-1}	fraction of the body mass at the skin temperature at time t_{i-1}	—
β_{im}	correction factor for the static moisture permeability index	—
β_{Ia}	correction factor for the static boundary layer thermal insulation	—
β_{Icl}	correction factor for the static clothing thermal insulation	—
β_{IT}	correction factor for the static total clothing thermal insulation	—
$\varepsilon_{\mathrm{cl}}$	emissivity of outer clothing surface, assuming this is non-reflective	—
$\varepsilon_{\mathrm{cl,r}}$	emissivity of outer clothing surface	—
θ	angle between walking direction and wind direction	—
A_{Du}	DuBois body area surface	$\mathrm{m^2}$
A_{p}	fraction of the body surface covered by the reflective clothing	—
A_{r}	effective radiating area of a body	$\mathrm{m^2}$
C	convective heat flow	$\mathrm{W{\cdot}m^{-2}}$
c_{e}	water latent heat of vaporization	$\mathrm{J{\cdot}kg^{-1}}$
c_{p}	specific heat of dry air at constant pressure	$\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$
$c_{\mathrm{p,b}}$	specific heat of the body	$\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$
C_{res}	respiratory convective heat flow	$\mathrm{W{\cdot}m^{-2}}$
D_{lim}	allowable exposure time	min
$\mathrm{D}_{\mathrm{lim,tcr}}$	allowable exposure time for heat storage	min
$D_{\mathrm{lim,loss}}$	allowable exposure time for water loss, 95 % of the working population	min
D_{max}	maximum water loss	g
E_{max}	maximum evaporative heat flow at the skin surface	$\mathrm{W{\cdot}m^{-2}}$
E_{p}	predicted evaporative heat flow at the skin surface	$\mathrm{W{\cdot}m^{-2}}$
E_{req}	required evaporative heat flow at the skin surface	$\mathrm{W{\cdot}m^{-2}}$
E_{res}	respiratory evaporative heat flow	$\mathrm{W{\cdot}m^{-2}}$
f_{cl}	clothing area factor	—
F_{r}	reflection coefficients for different special materials	—
h_{c}	convective heat transfer coefficient	$\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$
h_{r}	radiative heat transfer coefficient	$\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$
$I_{\mathrm{a,r}}$	resultant boundary layer thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
I_{a}	static (or basic) boundary layer thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
$I_{\mathrm{cl,r}}$	resultant clothing thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
I_{cl}	static (or basic) clothing thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
$i_{\mathrm{m,r}}$	resultant moisture permeability index	—
i_{m}	static (or basic) moisture permeability index	—
$I_{\mathrm{T,r}}$	resultant total clothing thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
I_{T}	static (or basic) total clothing thermal insulation	$\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$
K	conductive heat flow	$\mathrm{W{\cdot}m^{-2}}$
k_{Sw}	time constant of the increase of the sweat rate	min
k_{tcr}	time constant of the variation of the core temperature as function of the metabolic rate	min
k_{tsk}	time constant of the variation of the skin temperature	min
M	metabolic rate	$\mathrm{W{\cdot}m^{-2}}$

Table 1 *(continued)*

Symbol	Term	Unit
p_a	water vapour partial pressure at air temperature	kPa
$Q_{tot,i}$	heat storage during the last time increment at time t_i	W·m^{-2}
$Q_{eq,i}$	heat storage during the last time increment at time t_i, due to the increase of core temperature associated with the metabolic rate	W·m^{-2}
R	radiative heat flow	W·m^{-2}
$R_{e,T,r}$	resultant clothing total water vapour resistance	m^2·Pa·W^{-1}
r_{req}	required evaporative efficiency of sweating	—
S	body heat storage rate	W·m^{-2}
S_{eq}	body heat storage for increase of core temperature associated with the metabolic rate	W·m^{-2}
S_{Wmax}	maximum sweat rate capacity	W·m^{-2}
S_{Wp}	predicted sweat rate	W·m^{-2}
$S_{Wp,i}$	predicted sweat rate at time t_i	W·m^{-2}
$S_{Wp,i-1}$	predicted sweat rate at time t_{i-1}	W·m^{-2}
S_{Wreq}	required sweat rate	W·m^{-2}
t	time	min
t_a	air temperature	°C
t_{cl}	clothing surface temperature	°C
t_{cr}	core temperature	°C
$t_{cr,eq\ i}$	core temperature as a function of the metabolic rate at time t_i	°C
$t_{cr,eq\ i-1}$	core temperature as a function of the metabolic rate at time t_{i-1}	°C
$t_{cr,eqm}$	steady-state value of core temperature as a function of the metabolic rate	°C
$t_{cr,i}$	core temperature at time t_i	°C
$t_{cr,i-1}$	core temperature at time t_{i-1}	°C
t_{ex}	expired air temperature	°C
t_r	mean radiant temperature	°C
t_{re}	rectal temperature	°C
$t_{re,max}$	maximum rectal temperature	°C
$t_{re,i}$	rectal temperature at time t_i	°C
$t_{re,i-1}$	rectal temperature at time t_{i-1}	°C
t_{sk}	skin temperature	°C
$t_{sk,eq}$	steady-state mean skin temperature	°C
$t_{sk,eq,cl}$	steady-state mean skin temperature for clothed person	°C
$t_{sk,eq,nu}$	steady-state mean skin temperature for nude person	°C
$t_{sk,i}$	mean skin temperature at time t_i	°C
$t_{sk,i-1}$	mean skin temperature at time t_{i-1}	°C
V_{ex}	expired volume flow rate	L·min^{-1}
v_a	air velocity	m·s^{-1}
v_{ar}	relative air velocity	m·s^{-1}
v_w	walking speed	m·s^{-1}
W	effective mechanical power	W·m^{-2}
W_a	humidity ratio of inhaled air	kg_{water}/kg_{air}
W_b	body mass	kg
W_{ex}	humidity ratio of expired air	kg_{water}/kg_{air}

Table 1 *(continued)*

Symbol	Term	Unit
w	skin wettedness	—
w_{max}	maximum skin wettedness	—
w_p	predicted skin wettedness	—
w_{req}	required skin wettedness	—

5 Principles of the predicted heat strain (PHS) model

WARNING — The model has not been extensively validated for conditions with unsteady environmental parameters, metabolic rate and/or clothing and therefore must be used cautiously in cases where these parameters vary substantially with time. It does not enable users to determine validly the duration of time needed for an average person whose rectal temperature has risen to 38 °C or more to recover a rectal temperature of 36,8 °C.

The PHS model is based on the thermal energy balance of the body, which requires the values of the following parameters:

a) the parameters of the thermal environment as measured or estimated according to ISO 7726:

— air temperature, t_a;

— mean radiant temperature, t_r;

— water vapour partial pressure, p_a;

— air velocity, v_a.

b) the metabolic rate, M, as measured or estimated using ISO 8996 or other methods of equal or greater accuracy;

c) the static clothing thermal characteristics, as measured or estimated using ISO 9920 or other methods of equal or greater accuracy.

Clause 6 describes the principles of the calculation of the different heat exchanges occurring in the heat balance equation, as well as those of the sweat loss necessary for the maintenance of the thermal equilibrium of the body. The mathematical expressions given in Annex A shall be used for these calculations.

Clause 7 describes the method for interpreting the results from Clause 6, which leads to the determination of the predicted sweat rate, the predicted rectal temperature and the allowable exposure times. The determination of the allowable exposure times is based on two strain criteria: maximum allowable rectal temperature and maximum allowable body water loss, given in Annex B.

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

6 Main steps of the calculation

6.1 Heat balance equation

6.1.1 General

The thermal energy balance of the human body can be written as Formula (1):

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

This equation expresses that the internal heat production of the body, which corresponds to the metabolic rate, M, minus the effective mechanical power, W, are 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.

If the balance is not satisfied, some excess energy is stored in the body, S.

The different terms of Formula (1) are successively reviewed in 6.1.2 to 6.1.11 in terms of the principles of calculation (normative expressions for the computations are provided in Annex A).

6.1.2 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.

6.1.3 Effective mechanical power, W

In most industrial situations, the effective mechanical power is small and can be ignored, i.e. $W = 0$.

6.1.4 Heat flow by respiratory convection, C_{res}

The heat flow by respiratory convection is expressed, in principle, by Formula (2):

$$C_{res} = 0{,}000\,02 c_p \times V_{ex} \times \left(\frac{t_{ex} - t_a}{A_{Du}} \right) \qquad (2)$$

6.1.5 Heat flow by respiratory evaporation, E_{res}

The heat flow by respiratory evaporation is expressed, in principle, by Formula (3):

$$E_{res} = 0{,}000\,02 c_e \times V_{ex} \times \left(\frac{W_{ex} - W_a}{A_{Du}} \right) \qquad (3)$$

6.1.6 Heat flow by conduction, K

Heat flow by thermal conduction occurs on the body surfaces in contact with solid objects. It is usually quite small and ignored.

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

6.1.7 Heat flow by convection, *C*

The heat flow by convection on the bare skin is expressed by Formula (4):

$$C = h_c \times (t_{sk} - t_a) \tag{4}$$

For clothed people, the heat flow by convection occurs at the surface of the clothing and is expressed by Formula (5):

$$C = h_c \times f_{cl} \times (t_{cl} - t_a) \tag{5}$$

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

6.1.8 Heat flow by radiation, *R*

The heat flow by radiation is expressed by Formula (6):

$$R = h_r \times f_{cl} \times (t_{cl} - t_a) \tag{6}$$

where h_r is the radiative heat transfer coefficient and takes into account the clothing characteristics (e.g. emissivity and the presence of reflective clothing) and the effective radiating area of the person related to the posture (e.g. standing, seated, crouching person).

6.1.9 Heat flow by evaporation, *E*

The maximum evaporative heat flow, E_{max}, is that which can be achieved in the hypothetical case of the skin being completely wetted. In these conditions, Formula (7) applies:

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{e,T,r}} \tag{7}$$

where the dynamic clothing total water vapour resistance, $R_{e,T,r}$, takes into account the clothing characteristics as well as the movements of the person and the air.

The actual evaporation heat flow, *E*, depends upon the fraction, *w*, of the skin surface wetted by sweat and is given by Formula (8):

$$E = w \times E_{max} \tag{8}$$

6.1.10 Heat storage for increase of core temperature associated with the metabolic rate, Q_{eqi}

Even in a neutral environment, the core temperature rises towards a steady-state value, $t_{cr,eq}$, as a function of the metabolic rate.

The core temperature reaches this steady-state temperature exponentially with time. The heat storage associated with the increase from time t_{i-1} to time t_i, Q_{eqi} does not contribute to the onset of sweating and should therefore be deducted from Formula (1).

6.1.11 Heat storage, *S*

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