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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

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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	$W \cdot m^{-2}$
$Q_{eq,i}$	heat storage during the last time increment at time t_i, due to the increase of core temperature associated with the metabolic rate	$W \cdot m^{-2}$
R	radiative heat flow	$W \cdot m^{-2}$
$R_{e,T,r}$	resultant clothing total water vapour resistance	$m^2 \cdot Pa \cdot W^{-1}$
r_{req}	required evaporative efficiency of sweating	—
S	body heat storage rate	$W \cdot m^{-2}$
S_{eq}	body heat storage for increase of core temperature associated with the metabolic rate	$W \cdot m^{-2}$
S_{Wmax}	maximum sweat rate capacity	$W \cdot m^{-2}$
S_{Wp}	predicted sweat rate	$W \cdot m^{-2}$
$S_{Wp,i}$	predicted sweat rate at time t_i	$W \cdot m^{-2}$
$S_{Wp,i-1}$	predicted sweat rate at time t_{i-1}	$W \cdot m^{-2}$
S_{Wreq}	required sweat rate	$W \cdot m^{-2}$
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	$L \cdot min^{-1}$
v_a	air velocity	$m \cdot s^{-1}$
v_{ar}	relative air velocity	$m \cdot s^{-1}$
v_w	walking speed	$m \cdot s^{-1}$
W	effective mechanical power	$W \cdot m^{-2}$
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):

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

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):

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

6.1.5 Heat flow by respiratory evaporation, E_{res}

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

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

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.

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

Because conduction (K) is ignored as it is a non-significant avenue of heat exchange, the general Formula (1) can be written as Formula (9):

$$E + S = M - W - C_{\mathrm{res}} - E_{\mathrm{res}} - C - R \tag{9}$$

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 body heat storage rate to be equal to zero. It is given by Formula (10):

$$E_{\mathrm{req}} = M - W - C_{\mathrm{res}} - E_{\mathrm{res}} - C - R \tag{10}$$

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, as in Formula (11):

$$w_{\mathrm{req}} = \frac{E_{\mathrm{req}}}{E_{\mathrm{max}}} \tag{11}$$

The calculation of the required sweat rate, S_{Wreq}, is made on the basis of the required evaporative heat flow, but taking account of the evaporative efficiency of the sweating, r_{req}, as in Formula (12):

$$S_{\mathrm{Wreq}} = \frac{E_{\mathrm{req}}}{r_{\mathrm{req}}} \tag{12}$$

NOTE The sweat rate in W·m^{-2} represents the equivalent in heat of the sweat rate expressed in g·m^{-2} h^{-1}. 1 W·m^{-2} corresponds to a flow of sweat of 1,47 g·m^{-2} h^{-1} or 2,67 g·h^{-1} for a standard person (1,8 m^2 of body surface).

7 Interpretation of required sweat rate

7.1 Basis of the method of interpretation

7.1.1 General

The interpretation of the values calculated by the recommended analytical method is based on:

- two stress criteria (see 7.1.2):
  - the maximum skin wettedness, w_{max};
  - the maximum sweat rate, S_{Wmax};
- two strain criteria (see 7.1.3):
  - the maximum rectal temperature, $t_{\mathrm{re,\,max}}$;
  - the maximum water loss, D_{max}.

7.1.2 Stress criteria

The required sweat rate, S_{Wreq}, cannot exceed the maximum sweat rate, S_{Wmax}, achievable by the person. The required skin wettedness, w_{req}, cannot exceed the maximum skin wettedness, w_{max}, achievable by the person. These two maximum values are a function of the acclimatization of the person.

7.1.3 Strain criteria

In the case of non-equilibrium of the thermal balance, the rectal temperature increase should be limited at a maximum value, $t_{re,max}$, such that the probability of any acute pathological effect due to heat stress is extremely limited. Finally, whatever the thermal balance, the water loss should be restricted to a value, D_{max}, compatible with fluid and electrolyte maintenance by the body.

7.1.4 Reference values

Annex B includes reference values for the stress criteria (w_{max} and S_{Wmax}) and the strain criteria ($t_{re, max}$ and D_{max}). w_{max}, S_{Wmax} and D_{max} values are a function of the acclimatization state of the person.

7.2 Analysis of the work situation

Heat exchanges are computed at time t_i, from the body conditions existing at the previous computation time, t_{i-1}, and as a function of the climatic parameters, the metabolic rate and clothing conditions during the time increment.

The steps are:

— the required evaporative heat flow, E_{req}, skin wettedness, w_{req}, and sweat rate, S_{Wreq}, are first computed;

— from these, the predicted sweat rate, S_{Wp}, skin wettedness, w_p, and evaporative heat flow, E_p, are computed considering the stress criteria (E_{max}, w_{max} and S_{Wmax}) as well as the exponential response of the sweating system;

— the rate of heat storage is estimated by the difference between the required and predicted evaporative heat flow;

— the stored heat contributes to the increase or decrease in skin and core temperatures and these are estimated;

— from these values, the heat exchanges during the time increment are computed.

The evolutions of S_{Wp}, t_{cr} and t_{re} are in this way iteratively computed.

7.3 Determination of allowable exposure time, D_{lim}

The allowable exposure time, D_{lim}, is reached when either the predicted rectal temperature (t_{re}) or the predicted cumulated water loss reaches the corresponding maximum values.

Special precautionary measures need to be taken and individual physiological supervision of the persons is recommended in work situations in which:

— the maximum evaporative heat flow at the skin surface, E_{max}, is negative, leading to condensation of water vapour on the skin; or

— the estimated allowable exposure time is less than 30 min.

The conditions for carrying out this surveillance and the measuring techniques to be used are described in ISO 9886.

A computer program in BASIC is given in Annex E, which allows for the calculation and the interpretation of any condition where the metabolic rate, the clothing thermal characteristics and the climatic parameters are known.

Annex F provides some data (input data and results) that shall be used for the validation of any computer program developed on the basis of the model presented in Annex A.

Annex A
(normative)

Data necessary for the computation of thermal balance

A.1 Ranges of validity

The numerical values and the formulae given in this annex conform to the state of knowledge at the time of publication. Some are likely to be amended in the light of increased knowledge.

The algorithms described in this annex were validated on a database of 747 laboratory experiments and 366 field experiments from eight European research institutions.[15] Table A.1 gives the ranges of conditions for which the PHS model can be considered to be validated. When one or more parameters are outside this range, this model should be used with care and special attention given to the people exposed.

Table A.1 — Ranges of validity of the PHS model

Parameters	Units	Minimum	Maximum
t_a	°C	15	50
p_a	kPa	0,5	4,5
$t_r - t_a$	°C	0	60
v_a	ms^{-1}	0	3
M	$W \cdot m^{-2}$	56	250
I_{cl}	clo	0,1	1,0

The time increment used during this validation study was equal to 1 min. The model has not been validated for times in excess of 480 min.

A.2 Determination of the heat flow by respiratory convection, C_{res}

The heat flow by respiratory convection can be estimated by Formula (A.1):

$$C_{res} = 0{,}001\,52\, M\, (28{,}56 - 0{,}885\, t_a + 0{,}641\, p_a) \tag{A.1}$$

A.3 Determination of the heat flow by respiratory evaporation, E_{res}

The heat flow by respiratory evaporation can be estimated by Formula (A.2):

$$E_{res} = 0{,}001\,27\, M\, (59{,}34 + 0{,}53\, t_a - 11{,}63\, p_a) \tag{A.2}$$

A.4 Determination of the steady-state mean skin temperature

In climatic conditions for which this document is applicable, the steady-state mean skin temperature can be estimated as a function of the parameters of the working situation, using Formulae (A.3) and (A.4).

— For $I_{cl} \leq 0{,}2$ clo:

$$t_{sk,eq,nu} = 7{,}19 + 0{,}064\, t_a + 0{,}061\, t_r - 0{,}348\, v_a + 0{,}198\, p_a + 0{,}616\, t_{re} \tag{A.3}$$

— For $I_{cl} \geq 0{,}6$ clo:

$$t_{\text{sk,eq,}cl} = 12{,}17 + 0{,}02\ t_{\text{a}} + 0{,}04\ t_{\text{r}} - 0{,}253\ v_{\text{a}} + 0{,}194\ p_{\text{a}} + 0{,}005\ 35\ M + 0{,}513\ t_{\text{re}} \quad \text{(A.4)}$$

For I_{cl} values between 0,2 and 0,6, the steady-state skin temperature is interpolated between these two values using Formula (A.5):

$$t_{\text{sk,eq}} = t_{\text{sk,eq,nu}} + 2{,}5 \times (t_{\text{sk,eq,cl}} - t_{\text{sk,eq,nu}}) \times (I_{\text{cl,st}} - 0{,}2) \quad \text{(A.5)}$$

A.5 Determination of the instantaneous value of skin temperature

The skin temperature, $t_{\text{sk},i}$, at time t_i can be estimated from:

— the skin temperature, $t_{\text{sk},i-1}$, at time $t_{i\text{-}1}$ one minute earlier;

— the steady-state skin temperature, $t_{\text{sk,eq}}$, predicted from the conditions existing during the last minute by Formula (A.5).

The time constant of the response of the skin temperature being equal to 3 min, Formulae (A.6) and (A.7) are used:

$$t_{\text{sk},i} = k_{\text{tsk}} \times t_{\text{sk},i-1} + (1 - k_{\text{tsk}}) \times t_{\text{sk,eq}} \quad \text{(A.6)}$$

$$k_{\text{tsk}} = \exp(-1/3) \quad \text{(A.7)}$$

A.6 Determination of the heat accumulation associated with the metabolic rate, Q_{eqi}

In a neutral environment, the core temperature increases as a function of metabolic rate. For an average person, equilibrium core temperature is related to metabolic rate according to Formula (A.8):

$$t_{\text{cr,eq}} = 0{,}003\ 6(M - 55) + 36{,}8 \quad \text{(A.8)}$$

The core temperature reaches this equilibrium core temperature following a first-order system with a time constant equal to 10 min. At time i, it is estimated using Formulae (A.9) and (A.10):

$$t_{\text{cr,eq},i} = k_{\text{tcr}} \times t_{\text{cr,eq},i\text{-}1} + (1 - k_{\text{tcr}}) \times t_{\text{cr,eq}} \quad \text{(A.9)}$$

$$k_{\text{tcr}} = \exp(-1/10) \quad \text{(A.10)}$$

The heat storage associated with this increase is given by Formula (A.11):

$$Q_{\text{eqi}} = c_{\text{p,b}} \times W_{\text{b}} / (A_{\text{Du}} \times 60) \times (t_{\text{cr,eq},i} - t_{\text{cr,eq},i\text{-}1}) \times (1 - \alpha_{i\text{-}1}) \quad \text{(A.11)}$$

A.7 Determination of the static insulation characteristics of clothing

For a nude person and in static conditions without movements either of the air (<0,2 m·s^{-1}) or of the person, the sensible heat exchanges ($C + R$) can be estimated by Formula (A.12):

$$C+R=\frac{t_{\mathrm{sk}}-t_{\mathrm{a}}}{I_{\mathrm{T}}} \qquad \text{(A.12)}$$

For a clothed person, this static heat resistance, I_{T}, can be estimated using Formula (A.13):

$$I_{\mathrm{T}}=I_{\mathrm{cl}}+\frac{I_{\mathrm{a}}}{f_{\mathrm{cl}}} \qquad \text{(A.13)}$$

where

— I_{a} can be estimated as 0,111 m^2 K·W^{-1};

— the clothing area factor, f_{cl}, is given by Formula (A.14):

$$f_{\mathrm{cl}} = 1 + 1{,}97 \cdot I_{\mathrm{cl}} \qquad \text{(A.14)}$$

A.8 Determination of the resultant (or dynamic) insulation characteristics of clothing

Activity and ventilation modify the insulation characteristics of the clothing and the adjacent air layer.

Because both wind and movement reduce the insulation, this needs to be corrected. The correction factor β_{IT} can be estimated with Formulae (A.15) and (A.16):

— for a nude person ($I_{\mathrm{cl,st}} = 0$):

$$\beta_{\mathrm{IT}}=\beta_{\mathrm{Ia}}=e^{[(0{,}047v_{\mathrm{ar}}-0{,}472)v_{\mathrm{ar}}+(0{,}117v_{\mathrm{w}}-0{,}342)v_{\mathrm{w}}]} \qquad \text{(A.15)}$$

— for a person wearing clothes with $I_{\mathrm{cl,st}} > 0{,}6$ clo:

$$\beta_{\mathrm{IT}}=\beta_{\mathrm{cl}}=e^{[0{,}043+(0{,}066v_{\mathrm{ar}}-0{,}398)v_{\mathrm{ar}}+(0{,}094v_{\mathrm{w}}-0{,}378)v_{\mathrm{w}}]} \qquad \text{(A.16)}$$

When the walking speed is undefined or the person is stationary, the value for v_{w} can be calculated with Formula (A.17):

$$v_{\mathrm{w}} = 0{,}005\,2\,(M - 58) \qquad \text{(A.17)}$$

where $v_{\mathrm{w}} \leq 0{,}7$ m·s^{-1}.

When the walking speed v_w is known, but the direction varies, the relative air velocity is taken as the largest of the two velocities v_{a} and v_{w}.

When a walking direction θ is kept relative to the air velocity, the relative air velocity is given by Formula (A.18):

$$v_{\mathrm{ar}} = |v_{\mathrm{a}}+v_{\mathrm{w}}\cos(\pi\theta/180)| \qquad \text{(A.18)}$$

In all cases, the relative air velocity, v_{ar}, is limited to 3 m·s^{-1} and the walking speed, v_{w}, limited to 1,5 m·s^{-1}.

For conditions with I_{cl} between 0 and 0,6 clo, the correction factor is estimated by interpolation between these two values by Formulae (A.19) to (A.22):

$$\beta_{IT} = [(0{,}6 - I_{cl}) \times \beta_{Ia} + I_{cl} \times \beta_{cl}]/0{,}6 \tag{A.19}$$

In any case, this correction factor is limited to 1.

Finally, resultant (or dynamic) thermal insulation values are calculated as:

$$I_{a,r} = \beta_{Ia} \times I_a \tag{A.20}$$

$$I_{T,r} = \beta_{IT} \times I_T \tag{A.21}$$

$$I_{cl,r} = I_{T,r} - \frac{I_{a,r}}{f_{cl}} \tag{A.22}$$

A.9 Estimation of the heat exchanges through convection and radiation

The dry heat exchanges can be estimated using Formulae (A.23) to (A.27). Formulae (A.23) describes the heat exchanges between the clothing and the environment:

$$C + R = f_{cl} \times [h_c \times (t_{cl} - t_a) + h_r \times (t_{cl} - t_r)] \tag{A.23}$$

Formulae (A.24) describes the heat exchanges between the skin and the clothing surface:

$$C + R = \left(\frac{t_{sk} - t_{cl}}{I_{cl,r}} \right) \tag{A.24}$$

The convective heat transfer coefficient, h_c, can be estimated as the greatest value of:

$$2{,}38|t_{cl} - t_a|^{0{,}25} \tag{A.25}$$

$$3{,}5 + 5{,}2v_{ar} \tag{A.26}$$

$$8{,}7{v_{ar}}^{0{,}6} \tag{A.27}$$

The radiative heat exchange coefficient, h_r, can be estimated using Formula (A.28):

$$h_r = \varepsilon_{cl,r} \times \sigma \times \frac{A_r}{A_{Du}} \times \frac{(t_{cl} + 273)^4 - (t_r + 273)^4}{t_{cl} - t_r} \tag{A.28}$$

where

σ is the Stefan-Boltzmann constant equal to $5{,}67 \cdot 10^{-8}$ W·m^{-2}·K^{-4};

A_r/A_{Du} is the fraction of surface of the body involved in heat exchange by radiation, equal to 0,67 for a crouching person, 0,70 for a seated person and 0,77 for a standing person;

$\varepsilon_{cl,r}$ is the emissivity of the outer clothed surface;

$\varepsilon_{cl,r} = \varepsilon_{cl}$ is the emissivity of the outer surface of ordinary clothing when no reflective clothes are used, which is taken to be 0,97.

When clothing with a reflection coefficient F_r is worn on a fraction A_p smaller than 50 % of the body surface, the emissivity in Formula (A.28) should be calculated using Formula (A.29):

$$\varepsilon_{cl,r} = (1 - A_p)\,\varepsilon_{cl} + A_p\,(1-F_r) \tag{A.29}$$

As stated in Clause 1, this method of assessment is not applicable to cases where special protective clothing, such as fully reflective clothing, is worn.

Both Formula (A.23) and Formula (A.24) should be solved iteratively in order to derive t_{cl}.

A.10 Estimation of the maximum evaporative heat flow at the skin surface, E_{max}

The maximum evaporative heat flow at the skin surface is given by Formula (A.30):

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{e,T,r}} \tag{A.30}$$

The resultant (or dynamic) clothing total water vapour resistance, $R_{e,T,r}$, is estimated from Formulae (A.31) to (A.33):

$$R_{e,T,r} = \frac{I_{T,r}}{16{,}7 i_{m,r}} \tag{A.31}$$

where the dynamic clothing permeability index, $i_{m,r}$, is equal to the static clothing permeability index, i_m, corrected for the influence of air and body movement.

$$i_{m,r} = i_m \times \beta_{im} \tag{A.32}$$

$$\beta_{im} = 2{,}6\,\beta_{IT}^2 - 6{,}5\,\beta_{IT} + 4{,}9 \tag{A.33}$$

where $i_{m,r}$ is limited to 0,9.

A.11 Estimation of the required evaporation rate, E_{req}, and the required sweat rate, S_{Wreq}

At time *i*, the required evaporation rate can be estimated by Formula (A.34), from the heat exchanges and the heat accumulation associated with the metabolic rate, Q_{eqi}, during the last time increment.

$$E_{req} = M - W - C_{res} - E_{res} - C - R - Q_{eqi} \tag{A.34}$$

The required skin wettedness is given by E_{req} divided by E_{max} as detailed in 6.2.

A greater skin wettedness is associated with (in fact, is the result of) a lower evaporative efficiency. The required evaporative efficiency decreases from 100 % to 50 % as the skin wettedness increases to 100 %. When the required evaporative heat flow, E_{req}, is greater than the maximum evaporative heat flow at the skin surface, the required wettedness, w_{req}, is greater than 1, and the evaporation efficiency, r_{req}, is expected to become lower than 0,5.

r_{req} is then computed from w_{req} using the following expressions:

— for $w_{req} \leq 1$, the efficiency is given by Formula (A.35):

$$r_{req} = 1 - w_{req}^2/2 \tag{A.35}$$

— for $w_{req} > 1$, the efficiency is given by Formula (A.36):

$$r_{req} = (2 - w_{req})^2/2 \tag{A.36}$$

— if $r_{req} < 0,05$, r_{req} is set to 0,05.

The required sweat rate, S_{Wreq}, is calculated as E_{req} divided by r_{req}.

In all cases, the required sweat rate, S_{Wreq}, may not be greater than S_{Wmax}.

A.12 Determination of the predicted sweat rate, S_{Wp}, and the predicted evaporative heat flow at the skin surface, E_p

The flow chart in Figure A.1 shows how the evaluations are performed. It requires the following explanations:

The sweat rate response can be described by a first-order system with a time constant of 10 min.

Therefore, the predicted sweat rate at time t_i is given by Formulae (A.37) and (A.38):

$$S_{Wp,i} = k_{Sw} \times S_{Wp,i-1} + (1 - k_{Sw}) \times S_{Wreq} \tag{A.37}$$

$$k_{SW} = \exp(-1/10) \tag{A.38}$$

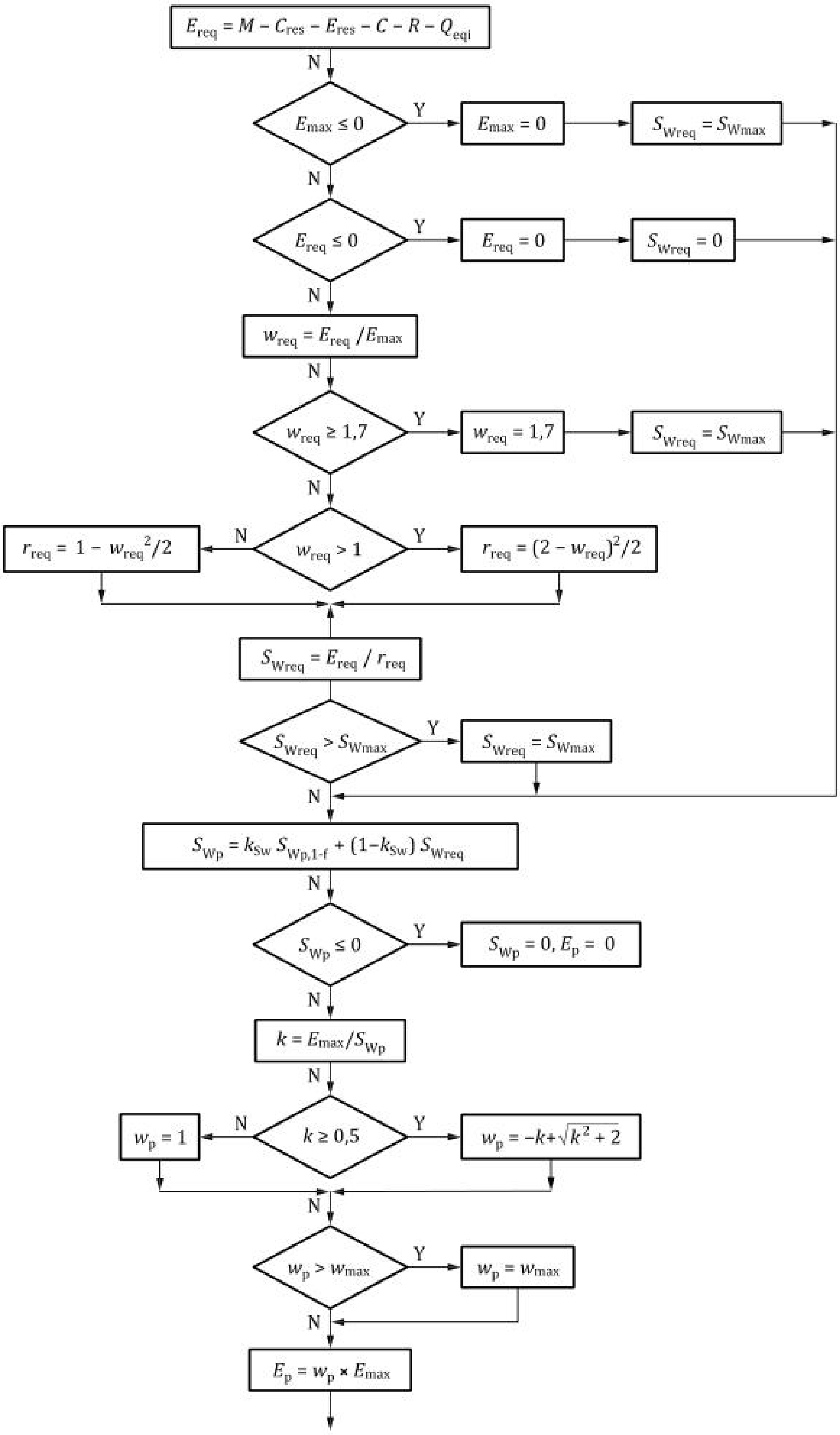

Figure A.1 — Flow chart for the determination of the predicted sweat rate, S_{Wp}, and the predicted evaporative heat flow rate, E_p

A.13 Evaluation of the rectal temperature

The heat storage during the last time increment at time t_i is given by Formula (A.39):

$$Q_{tot,i} = E_{req} - E_p + Q_{eqi} \tag{A.39}$$

This heat storage leads to an increase in core temperature, taking into account the increase in skin temperature. The fraction of the body mass at the mean core temperature is given by Formula (A.40):

$$(1 - \alpha) = 0{,}7 + 0{,}09\ (t_{cr} - 36{,}8) \tag{A.40}$$

This fraction is limited to:

— 0,7 for $t_{cr} \leq 36{,}8$ °C;

— 0,9 for $t_{cr} \geq 39{,}0$ °C.

Then, the core temperature at time i can be computed using Formula (A.41):

$$t_{cr,i} = \frac{1}{1-\frac{\alpha_i}{2}}\left[\frac{Q_{tot,i} \times A_{du} \times 60}{c_{sp} \times W_b} + t_{cr,i-1} - \frac{t_{cr,i-1} - t_{sk,i-1}}{2}\alpha_{i-1} - t_{sk,i}\frac{\alpha_i}{2}\right] \tag{A.41}$$

The rectal temperature is estimated according to Formula (A.42):

$$t_{re,i} = t_{re,i-1} + \frac{2t_{cr,i} - 1{,}926t_{re,i-1} - 1{,}31}{9} \tag{A.42}$$

Annex B
(informative)

Criteria for estimating acceptable exposure time in a hot work environment

B.1 General

The physiological criteria used for determining the maximum allowable exposure time are:

— acclimatized and unacclimatized persons in good health and fit for assigned duties;

— a maximum skin wettedness, w_{max};

— a maximum sweat rate capacity, S_{Wmax};

— protection of 95 % of the working population based on predicted rectal temperature and dehydration;

— a maximum water loss, D_{max};

— a maximum acceptable rectal temperature, $t_{re,max}$.

B.2 Acclimatized and unacclimatized persons

Acclimatized persons are able to sweat more abundantly, more uniformly on their body surface and earlier than unacclimatized persons. In a given work situation, this results in lower heat storage (lower core temperature) and lower cardiovascular strain (lower heart rate). In addition, acclimatized persons are known to lose less salt through sweating and therefore are able to endure a greater water loss.

This distinction between acclimatized and unacclimatized is therefore essential. Acclimatization state is accounted for in w_{max} and S_{Wmax}.

When the state of acclimatization is uncertain, the person is assumed to be unacclimatized.

B.3 Maximum skin wettedness, w_{max}

The maximum skin wettedness is set to 0,85 for an unacclimatized person and 1,0 for an acclimatized person.

B.4 Maximum sweat rate, S_{Wmax}

For this document, maximum sweat rate capacity is 400 $W \cdot m^{-2}$ for unacclimatized persons and 500 $W \cdot m^{-2}$ for acclimatized persons. This corresponds to possible productions of 1 l and 1,25 l maximum of sweat per hour, respectively.

B.5 Maximum dehydration and water loss

A 3 % dehydration induces an increased heart rate and depressed sweating sensitivity and is therefore adopted as the maximum dehydration for occupational exposures (not for specially trained persons in the military and sports).

For exposures lasting 4 h to 8 h, the rehydration is greater than 40 % in 95 % of cases.[19]

Based on these values, the maximum allowable water loss to protect 95 % of the working population (D_{max}) is set at 5 % of the body mass when people can drink freely. If no water is provided, the total water loss should be limited to 3 %.

B.6 Maximum value of rectal temperature

The WHO technical report No. 412 (1969)[10] underlined the importance of limiting deep body temperature. During the development of PHS, a 38 °C prediction criterion was confirmed as a population-based goal.[14] When the average rectal temperature is equal to 38 °C for a group of persons in given working conditions, it can be estimated that the probability for a particular individual to reach higher rectal temperatures is limited as follows:

— for 42,0 °C: less than 10^{-7} (less than once every 4 years among 10 000 persons) (250 workdays per year);

— for 39,2 °C: less than 10^{-4} (less than one person at risk among 10 000 shifts).

When this limit value of 38,0 °C was used in the validation study, it was confirmed that 95 % of the exposures resulted in observed rectal temperatures below 39 °C.[15]

Annex C
(informative)

Metabolic rate

ISO 8996 describes methods for estimating the metabolic rate. These methods are classified in four levels of increasing accuracy.

Level 1, screening: a simple method to quickly classify as light, moderate, high or very high the mean workload according to the kind of activity.

Level 2, observation: a time-and-motion study to characterize, on average, a working situation at a specific time. This method can be used by people with full knowledge of the working conditions but without necessarily any training in ergonomics.

Level 3, analysis: a method to estimate the metabolic rate from a heart rate recording over a representative period of time. This method is addressed to people trained in occupational health and ergonomics of the thermal environment.

Level 4, expertise: three methods requiring very specific measurements made by experts:

— oxygen consumption measurement;

— doubly labelled water method;

— direct calorimetry method.

While the screening method described in ISO 7243 (WBGT index) for establishing the presence or absence of heat stress in a given thermal environment can settle for the method of level 1 for estimating the metabolic rate, only methods of higher accuracy are compatible with the PHS model described in this document.

The use of the level 3 method based on heart rate recordings, including the mandatory correction for thermal effects on heart rate, is highly recommended.

It should be noted that, while the methods presented in ISO 8996 make it possible to evaluate the metabolic rate in watts, the PHS model calculates the heat exchanges in watts per square metre of body surface. The metabolic rate to be used in the formulae in Annex A should therefore be the value given in watts by the procedures from ISO 8996 divided by the body surface area, A_{Du}.

Annex D
(informative)

Clothing thermal characteristics

D.1 General

The thermal characteristics of the clothing to be considered are:

— thermal insulation;

— reflection of thermal radiation;

— permeability to water vapour.

D.2 Clothing thermal insulation

The clothing thermal insulation unit used in this document is $m^2 \cdot K \cdot W^{-1}$. However, the clothing insulation is often more conveniently expressed in clo, 1 clo being equal to 0,155 $W \cdot m^2 \cdot K^{-1}$.

Table D.1 gives the static (or basic) clothing thermal insulation values in clo for selected garment ensembles.

Table D.1 — Static (or basic) insulation values for selected garment ensembles

Garment ensembles	I_{cl} clo
Briefs, short-sleeve shirt, fitted trousers, calf-length socks, shoes	0,5
Underpants, shirt, fitted trousers, socks, shoes	0,6
Underpants, coverall, socks, shoes	0,7
Underpants, shirt, coverall, socks, shoes	0,8
Underpants, shirt, trousers, smock, socks, shoes	0,9
Briefs, undershirt, underpants, shirt, overalls, calf-length socks, shoes	1,0
Underpants, undershirt, shirt, trousers, jacket, vest, socks, shoes	1,1

The resultant (or dynamic) clothing thermal insulation is used in the calculation. The formulae for determination of the resultant (or dynamic) insulation characteristics of clothing are provided in A.8.

D.3 Reflection of thermal radiation

Table D.2 gives the reflection coefficients, F_r, for different special materials coated with aluminium to reflect thermal radiation.

Table D.2 — Reflection coefficients, F_r, for different special materials

Material	Treatment	F_r
Cotton	with aluminium paint	0,58
Viscose	with glossy aluminium foil	0,81
Aramid	with glossy aluminium foil	0,86
Wool	with glossy aluminium foil	0,87
Cotton	with glossy aluminium foil	0,96
Viscose	vacuum metallized with aluminium	0,94
Aramid	vacuum metallized with aluminium	0,96
Wool	vacuum metallized with aluminium	0,95
Cotton	vacuum metallized with aluminium	0,95
Glass fibre	vacuum metallized with aluminium	0,93

The reduction of radiative heat exchanges only occurs for the part of the body covered by the reflective clothing. Table D.3 provides information to estimate the fraction, A_p, of the area of the body concerned.

Table D.3 — Ratio of the area of a part of the body to the total body surface

Area	A_p
Head and face	0,07
Thorax and abdomen	0,175
Back	0,175
Arms	0,14
Hands	0,05
Thighs	0,19
Legs	0,13
Feet	0,07

D.4 Permeability to water vapour

The evaporative resistance of the clothing is strongly influenced by the permeability to water vapour of the material, which can be defined by the static moisture permeability index, i_m. For validation of this method, a value of i_m = 0,38, typical of woven clothing, was used.

Annex E
(informative)

Computer program for the computation of the predicted heat strain model

E.1 General

The correspondence between the symbols given in Table 1 and those used in the computer program in E.2 are detailed in Table E.1.

Table E.1 — Correspondence between some symbols in Table 1 and those used in the computer program

Symbol in the program	Symbol in Table 1
Ardu	A_r/A_{Du}
Conv	C
ConstSW	k_{Sw}
ConstTeq	k_{tcr}
ConstTsk	k_{tsk}
CORcl	β_{Icl}
CORe	β_{im}
CORia	β_{Ia}
CORtot	β_{IT}
dStorage	$Q_{tot,i}$
dStoreq	Q_{eqi}
Eclr	$\varepsilon_{cl,r}$
Eveff	r_{req}
Iadyn	$I_{a,r}$
Iast	I_a
Icl	I_{cl}
Icldyn	$I_{cl,r}$
imdyn	$i_{m,r}$
imst	i_m
Itotdyn	$I_{T,r}$
Itotst	I_T
ConstTsk	k_{tsk}
ConstTeq	k_{tcr}
ConstSw	k_{Sw}
Met	M
Rad	R
Rtdyn	$R_{e,T,r}$
SWp0	$S_{Wp,i-1}$
Tcr	$t_{cr,i}$
Tcr0	$t_{cr,i-1}$

Table E.1 *(continued)*

Symbol in the program	Symbol in Table 1
Tcreq	$t_{cr,eq\ i}$
Tcreq0	$t_{cr,eq,i-1}$
Tcreqm	$t_{cr,eqm}$
Texp	t_{ex}
Theta	θ
Tre	$t_{re,i}$
Tre0	$t_{re,i-1}$
Tsk	$t_{sk,i}$
Tsk0	$t_{sk,i-1}$
Tskeq	$t_{sk,eq}$
Tskeqcl	$t_{sk,eq,cl}$
Tskeqnu	$t_{sk,eq,nu}$
TskTcrwg	α_i
TskTcrwg0	α_{i-1}
Walksp	v_w
Weight	W_b
Work	W

E.2 Program

The model can predict a steady-state rectal temperature near the 38 °C limit. The thermal stress is obviously the same whether this steady-state value is just below 38 °C (in which case there is no limitation of the duration of exposure for heat accumulation) or slightly above (in which case the allowable exposure time can be short). In order to allow the user to be aware of these borderline situations and to make professional judgements regarding the duration of exposure, it is strongly recommended that programs not only provide the final values of accumulated water loss and rectal temperature but also make it possible to analyse, graphically or otherwise, the evolution of these parameters over time. This becomes essential when the exposure is variable over time.

```
' Predicted Heat Strain (PHS) model
' EXPONENTIAL AVERAGING CONSTANTS
    ConstTeq = Exp(-1 / 10):  ' Core temperature as a function of M: time constant: 10 min
    ConstTsk = Exp(-1 / 3):   ' Skin Temperature: time constant: 3 min
    ConstSW = Exp(-1 / 10):   ' Sweat rate: time constant: 10 min
' INPUT OF THE MEAN CHARACTERISTICS OF THE PERSONS
' The user must make sure at this point in the programme that the following parameters are
available.
' Standard values must be replaced by actual values.
    Weight = 75:      ' Body mass kilogrammes
    Height = 1.8:     ' Body height   metres
    Accl = 1:         ' = 1 if acclimatized person, = 0 otherwise
    Drink = 1:        ' Water replacement: = 1 if the persons can drink freely, = 0
otherwise
' COMPUTATION OF DERIVED PARAMETERS
    Adu = 0.202 * Weight ^ 0.425 * Height ^ 0.725:  ' Body surface area m2
    aux = 3490 * Weight / Adu:     ' Heat for 1 °C increase of the body per m2 of body
surface
    SWmax = 400:    If Accl = 1 Then SWmax = 500:  ' Maximum evaporative capacity
    wmax = 0.85:    If Accl = 1 Then wmax = 1:  ' Maximum wettedness
    Dmax = 0.05 * Weight * 1000:                ' Maximum water loss in grams
        If Drink = 0 Then Dmax = 0.03 * Weight * 1000:   ' if no free drinking
' INPUT OF THE PRIMARY PARAMETERS
' The user shall make sure that, at this point in the programme, the following parameters
are available.
' In order for the user to test rapidly the programme, the data for the first case in
```



```
Annex F of ISO 7933 (2020) are introduced.
    Duration = 480:    ' Duration of the work sequence, in minutes
    Ta = 40:           ' Air temperature, in °C
    Tg = 40:           ' Black globe temperature, in °C
    Diam = 15:         ' Diameter of the black globe, in cm
    Va = 0.3:          ' Air velocity, in metres per second
        Tr = ((Tg + 273) ^ 4 + 1.1579 * 10 ^ 8 / 0.95 / (Diam / 100) ^ 0.4 * Va ^ 0.6 *
(Tg - Ta)) ^ 0.25 - 273
    RH = 35:     ' Relative humidity
' Partial water vapour pressure kilopascals
        Pa = 0.6105 * Exp(17.27 * Ta / (Ta + 237.3)) * RH / 100:
    M = 300:     ' Metabolic rate, in watts
        Met = M / Adu:      ' Metabolic rate, in watts per square metre
    Work = 0:     ' Effective mechanical power, in watts per square metre
    Icl = 0.5:    ' Static thermal insulation, in clo
    imst = 0.38:  ' Static moisture permeability index

' Effective radiating area of the body
    Posture = 1:      ' Posture = 1 standing, = 2 sitting, = 3 crouching
        If Posture = 1 Then Ardu = 0.77
        If Posture = 2 Then Ardu = 0.7
        If Posture = 3 Then Ardu = 0.67
' Reflective clothing
    Ap = 0.54:        ' Fraction of the body surface covered by the reflective clothing
    Fr = 0.42      ' Reflection coefficient for different special materials
    Ecl = 0.97:        ' Emissivity of the clothed body surface (by default: Ecl = 0.97)
' Displacements
    defspeed = 0:     ' = 1 if walking speed entered, = 0 otherwise
    Walksp = 0:       ' Walking speed, m/s
    defdir = 0:       ' = 1 if walking direction entered, 0 otherwise
    THETA = 0:        ' Angle between walking direction and wind direction degrees
' CLOTHING INFLUENCE ON EXCHANGE COEFFICIENTS
    Iclst = Icl * 0.155:     ' Static clothing insulation
    fcl = 1 + 0.28 * Icl:    ' Clothing area factor
    Iast = 0.111:   ' Static boundary layer thermal insulation in quiet air
    Itotst = Iclst + Iast / fcl:     ' Total static insulation
' Relative velocities due to air velocity and movements
    If defspeed > 0 Then
        If defdir = 1 Then
            Var = Abs(Va - Walksp * Cos(3.14159 * THETA / 180)):    ' Unidirectional
walking
        Else
            If Va < Walksp Then Var = Walksp Else Var = Va:         'Omni-directional
walking
        End If
    Else
        Walksp = 0.0052 * (Met - 58)
            If Walksp > 0.7 Then Walksp = 0.7:  'Stationary or undefined speed
        Var = Va
    End If
' Dynamic clothing insulation
    Vaux = Var:  If Var > 3 Then Vaux = 3
    Waux = Walksp:  If Walksp > 1.5 Then Waux = 1.5
' Clothing insulation correction for wind (Var) and walking (Walksp)
    CORcl = 1.044 * Exp((0.066 * Vaux - 0.398) * Vaux + (0.094 * Waux - 0.378) * Waux)
        If CORcl > 1 Then CORcl = 1
    CORia = Exp((0.047 * Vaux - 0.472) * Vaux + (0.117 * Waux - 0.342) * Waux)
        If CORia > 1 Then CORia = 1
    CORtot = CORcl
        If Icl < = 0.6 Then CORtot = ((0.6 - Icl) * CORia + Icl * CORcl) / 0.6
    Itotdyn = Itotst * CORtot
    Iadyn = CORia * Iast
    Icldyn = Itotdyn - Iadyn / fcl
' Dynamic evaporative resistance
' Correction for wind and walking
    CORe = (2.6 * CORtot - 6.5) * CORtot + 4.9
    imdyn = imst * CORe: If imdyn > 0.9 Then imdyn = 0.9
    Rtdyn = Itotdyn / imdyn / 16.7
' INITIALISATION OF THE VARIABLES OF THE PROGRAMME
    Tre = 36.8:       ' Initial rectal temperature, °C
    Tcr = 36.8:       ' Initial core temperature, °C
```

```
    Tsk = 34.1:        ' Initial skin temperature, °C
    Tcreq = 36.8:      ' Initial core temperature associated to M, °C
    TskTcrwg = 0.3:    ' Initial skin - core weighting
    SWp = 0:           ' Initial sweat rate, W/m2
    SWtot = 0:         ' Initial total sweat rate, W/m2
    Dlimtcr = 999:     ' Allowable exposure time due to increase in temperature, min
    Dlimloss = 999:    ' Allowable exposure time due to excessive water loss, min
' ITERATION OF THE PROGRAMME
For Time = 1 To Duration
' Initialisation min per min
' value at beginning of time i = final value at time (i-1)
    Tre0 = Tre: Tcr0 = Tcr: Tsk0 = Tsk: Tcreq0 = Tcreq: TskTcrwg0 = TskTcrwg
' Equilibrium core temperature associated to the metabolic rate
    Tcreqm = 0.0036 * Met + 36.6
' Core temperature at this minute, by exponential averaging
    Tcreq = Tcreq0 * ConstTeq + Tcreqm * (1 - ConstTeq)
' Heat storage associated with this core temperature increase during the last minute
    dStoreq = aux/60 * (Tcreq - Tcreq0) * (1 - TskTcrwg0)
' SKIN TEMPERATURE PREDICTION
' Skin Temperature in equilibrium
' Clothed model
    Tskeqcl = 12.165 + 0.02017 * Ta + 0.04361 * Tr + 0.19354 * Pa - 0.25315 * Va
    Tskeqcl = Tskeqcl + 0.005346 * Met + 0.51274 * Tre
' Nude model
    Tskeqnu = 7.191 + 0.064 * Ta + 0.061 * Tr + 0.198 * Pa - 0.348 * Va
    Tskeqnu = Tskeqnu + 0.616 * Tre
' Value at this minute, as a function of the clothing insulation
        If Icl > = 0.6 Then Tskeq = Tskeqcl: GoTo Tsk
        If Icl < = 0.2 Then Tskeq = Tskeqnu: GoTo Tsk
' Interpolation between the values for clothed and nude person, if 0.2 < clo < 0.6
    Tskeq = Tskeqnu + 2.5 * (Tskeqcl - Tskeqnu) * (Icl - 0.2)
' Skin Temperature at this minute, by exponential averaging
Tsk:
    Tsk = Tsk0 * ConstTsk + Tskeq * (1 - ConstTsk)
        If Time = 1 Then Tsk = Tskeq
' Saturated water vapour pressure at the surface of the skin
    Psk = 0.6105 * Exp(17.27 * Tsk / (Tsk + 237.3))
' Mean temperature of the clothing: Tcl
    Z = 3.5 + 5.2 * Var
        If Var > 1 Then Z = 8.7 * Var ^ 0.6
    auxR = 0.0000000567 * Ardu
    Eclr = (1 - Ap) * Ecl + Ap * (1-Fr)
    Tcl = Tr + 0.1
Tcl:
' convection coefficient
    Hc = 2.38 * Abs(Tcl - Ta) ^ 0.25
        If Z > Hc Then Hc = Z
' Radiation coefficient
    HR = Eclr * auxR * ((Tcl + 273) ^ 4 - (Tr + 273) ^ 4) / (Tcl - Tr)
    Tcl1 = ((fcl * (Hc * Ta + HR * Tr) + Tsk / Icldyn)) / (fcl * (Hc + HR) + 1 / Icldyn)
    If Abs(Tcl - Tcl1) > 0.001 Then Tcl = (Tcl + Tcl1) / 2:     GoTo Tcl
' HEAT EXCHANGES
    Texp = 28.56 + 0.115 * Ta + 0.641 * Pa:    ' Temperature of the expired air
    Cres = 0.001516 * Met * (Texp - Ta):       ' Heat exchanges through respiratory
convection
    Eres = 0.00127 * Met * (59.34 + 0.53 * Ta - 11.63 * Pa):   ' through respiratory
evaporation
    Conv = fcl * Hc * (Tcl - Ta):      ' Heat exchange through convection
    Rad = fcl * HR * (Tcl - Tr):       ' Heat exchange through radiation
    Emax = (Psk - Pa) / Rtdyn:         ' Maximum Evaporation Rate
    Ereq = Met - dStoreq - Work - Cres - Eres - Conv - Rad:  ' Required Evaporation Rate
' INTERPRETATION
    wreq = Ereq / Emax:                ' Required wettedness
' If no evaporation required: no sweat rate
        If Ereq < = 0 Then Ereq = 0: SWreq = 0: GoTo SWp
' If evaporation is not possible, sweat rate is maximum
        If Emax < = 0 Then Emax = 0: SWreq = SWmax: GoTo SWp
' If required wettedness greater than 1.7: sweat rate is maximum
        If wreq > = 1.7 Then wreq = 1.7: SWreq = SWmax: GoTo SWp
    Eveff = 1 - wreq ^ 2 / 2:       ' Required evaporation efficiency
        If wreq > 1 Then Eveff = (2 - wreq) ^ 2 / 2
```

```
     SWreq = Ereq / Eveff:           ' Required Sweat Rate
          If SWreq > SWmax Then SWreq = SWmax:  ' limited to the maximum evaporative
capacity
SWp:
' Predicted Sweat Rate, by exponential averaging
     SWp = SWp * ConstSW + SWreq * (1 - ConstSW)
          If SWp < = 0 Then Ep = 0: SWp = 0: GoTo Storage
' Predicted Evaporation Rate
     k = Emax / SWp
     wp = 1
          If k >  = 0.5 Then wp = -k + Sqr(k * k + 2)
          If wp > wmax Then wp = wmax
     Ep = wp * Emax
' Heat Storage
Storage:
     dStorage = Ereq - Ep + dStoreq
' PREDICTION OF THE CORE TEMPERATURE
     Tcr1 = Tcr0
TskTcr:
' Skin - Core weighting
     TskTcrwg = 0.3 - 0.09 * (Tcr1 - 36.8)
          If TskTcrwg > 0.3 Then TskTcrwg = 0.3
          If TskTcrwg < 0.1 Then TskTcrwg = 0.1
     Tcr = dStorage / (aux/60) + Tsk0 * TskTcrwg0 / 2 - Tsk * TskTcrwg / 2
     Tcr = (Tcr + Tcr0 * (1 - TskTcrwg0 / 2)) / (1 - TskTcrwg / 2)
     If Abs(Tcr - Tcr1) > 0.001 Then Tcr1 = (Tcr1 + Tcr) / 2:  GoTo TskTcr
' PREDICTION OF THE RECTAL TEMPERATURE
     Tre = Tre0 + (2 * Tcr - 1.962 * Tre0 - 1.31) / 9
' TOTAL WATER LOSS RATE AFTER THE MINUTE (in W m-2)
     SWtot = SWtot + SWp + Eres:   ' Total evaporation loss in watts per m2
     SWtotg = SWtot * 2.67 * Adu / 1.8 / 60:   ' Total water loss in grams
' COMPUTATION OF THE DURATION LIMIT OF EXPOSURE DLE IN MIN
' DLE for water loss, 95 % of the working population, in min
     If Dlimloss = 999 And SWtotg >  = Dmax Then Dlimloss = Time
' DLE for heat storage, in min
     If Dlimtcr = 999 And Tre >  = 38 Then Dlimtcr = Time
' End of loop on duration
Next Time
```


Annex F
(informative)

Examples of the predicted heat strain model computations

This annex provides the primary data and the main output data for five working conditions. It should be used to test that any particular version of the program prepared from Annex E provides correct results within computational accuracy of 0,1 °C for the predicted core temperature and 1 % for water loss.

These five conditions were selected in order to test all the different components of the program. The computations were conducted for a person 1,8 m tall and weighing 75 kg. In all cases, stationary or undefined walking conditions are assumed.

Parameters	**Examples of working conditions**				
(units)	**1**	**2**	**3**	**4**	**5**
Acclimatization	Yes	No	No	No	Yes
Posture	Standing	Standing	Standing	Standing	Sitting
Duration	480	480	480	480	480
T_a (°C)	40	35	30	30	35
T_g (°C)	40	35	45	30	50
V_a (ms^{-1})	0,30	0,10	0,10	1,00	1,00
RH (%)	35	60	35	45	30
M (W)	300	300	300	450	250
W (W)	0	0	0	0	0
I_{cl} (clo)	0,5	0,5	0,8	0,5	1,0
T_r (°C)	40,0	35,0	52,0	30,0	74,6
P_a (kPa)	2,58	3,37	1,48	1,91	1,69
A_p (fraction %)	–	–	30	–	20
F_r (–)	–	–	0,85	–	0,85
Final S_{Wp} (g/h)	813	633	764	547	718
Water loss (g)	6 538	6 345	6 419	4 593	5 813
Final T_{cr} (°C)	37,6	40,8	38,7	38,0	37,5
$D_{limloss}$ (min)	280	250	280	400	310
D_{limTcr} (min)	–	62	149	–	–

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