Ergonomics of the thermal environment
Analytical determination and interpretation of heat stress using calculation of the Predicted Heat Strain

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This document takes into account the modifications brought in 2018

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Content

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 mathematical model (the predicted heat strain model) for the analytical determination and interpretation of the thermal stress (in terms of water loss and core temperature) experienced by a subject in a hot environment and determines the "maximum allowable exposure times", with which the physiological strain is acceptable for 95 % of the exposed population (the maximum tolerable core 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 subject. 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 physiological strains.

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. It does not either account for transients in environmental conditions, metabolic rate and/or clothing and therefore makes it possible to predict the evolution of the core temperature and the water loss in conditions where these parameters remain steady.

This document 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. Recommendations about how and when to use this model are given in ISO 15265.

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 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 of the thermal environment — *Evaluation of thermal strain by physiological measurements*

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

ISO 13731, *Ergonomics of the thermal environment — Vocabulary and symbols*

ISO 13732-1, Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 1: Hot surfaces

ISO 15265, Ergonomics of the thermal environment — Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions

ISO 16595/WP, Ergonomics of the thermal environment: Working practices in hot environments

3 Symbols

For the purposes of this document, the symbols and abbreviated terms, designated in Table 1 as "symbols" with their units, are in accordance with ISO 13731.

However, additional symbols are used for the presentation of the predicted heat strain index. A complete list of symbols used in this International standard is presented in Table 2.

Table 1 — Symbols and units conforming to ISO 13731

Symbol	Term	Unit
α	fraction of the body mass at the skin temperature	–
α_i	skin-core weighting at time t_i	–
α_{i-1}	skin-core weighting at time t_{i-1}	–
ε	skin emissivity	–
ε_{cl}	emissivity of clothing	–
θ	angle between walking direction and wind direction	°
A_{Du}	DuBois body area surface	m^2
A_p	fraction of the body surface covered by the reflective clothing	–
A_r	effective radiating area of a body	m^2
C	convective heat flow	$W \cdot m^{-2}$
c_e	water latent heat of vaporization	$J \cdot kg^{-1}$
$C_{orr,im}$	correction factor for the static moisture permeability index	–
$C_{orr,Ia,st}$	correction factor for the static boundary layer thermal insulation	–
$C_{orr,Icl,st}$	correction factor for the static clothing thermal insulation	–
$C_{orr,Itot,st}$	correction factor for the static total clothing thermal insulation	–
c_p	specific heat of dry air at constant pressure	$J \cdot kg^{-1} \cdot K^{-1}$
$c_{p,b}$	specific heat of the body	$J \cdot kg^{-1} \cdot K^{-1}$
C_{res}	respiratory convective heat flow	$W \cdot m^{-2}$
D_{lim}	allowable exposure time	min
$D_{lim,tcr}$	allowable exposure time for heat storage	min
$D_{lim,loss}$	allowable exposure time for water loss, 95 % of the working population	min
D_{max}	maximum water loss	g
$D_{max,95}$	maximum water loss to protect 95 % of the working population	g
dS_i	body heat storage at the time i	$W \cdot m^{-2}$
dS_{eq}	body heat storage rate due to increase of core temperature associated with the metabolic rate	$W \cdot m^{-2}$
E	evaporative heat flow at the skin surface	$W \cdot m^{-2}$
E_{max}	maximum evaporative heat flow at the skin surface	$W \cdot m^{-2}$
E_p	predicted evaporative heat flow at the skin surface	$W \cdot m^{-2}$
E_{req}	required evaporative heat flow at the skin surface	$W \cdot m^{-2}$
E_{res}	respiratory evaporative heat flow	$W \cdot m^{-2}$
f_{cl}	clothing area factor	–
$F_{cl,R}$	reduction factor for radiation heat exchange due to wearing reflective clothes	–
F_r	Reflection coefficients for different special materials	–
H_b	body height	m
$h_{c,dyn}$	dynamic convective heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
h_r	radiative heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
$I_{a,dyn}$	dynamic boundary layer thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$I_{a,st}$	static boundary layer thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$I_{cl,dyn}$	dynamic clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$I_{cl,st}$	static clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$i_{m,dyn}$	dynamic moisture permeability index	–
$i_{m,st}$	static moisture permeability index	–
$incr$	time increment from time t_{i-1} to time t_i	min
$I_{T,dyn}$	dynamic total clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$I_{T,st}$	static total clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
K	conductive heat flow	$W \cdot m^{-2}$
k_{sw}	time constant of the increase of the sweat rate	min

k_{tcreq}	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	$W \cdot m^{-2}$
p_a	water vapour partial pressure at air temperature	kPa
$p_{sk,s}$	saturated water vapour pressure at skin temperature	kPa
R	radiative heat flow	$W \cdot m^{-2}$
$R_{e,T,dyn}$	dynamic 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	$W \cdot m^{-2}$
Sw_{max}	maximum sweat rate capacity	$W \cdot m^{-2}$
Sw_p	predicted sweat rate	$W \cdot m^{-2}$
$Sw_{p,i}$	predicted sweat rate at time t_i	$W \cdot m^{-2}$
$Sw_{p,i-1}$	predicted sweat rate at time t_{i-1}	$W \cdot m^{-2}$
Sw_{req}	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
$t_{cr,eq}$	steady state core temperature as a function of the metabolic rate	°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
$t_{cr,eq,m}$	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
$t_{cr,max}$	maximum acceptable core 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 subjects	°C
$t_{sk,eq,nu}$	steady state mean skin temperature for nude subjects	°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	skin wettedness	–
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}
w_{max}	maximum skin wettedness	–
w_p	predicted skin wettedness	–
w_{req}	required skin wettedness	–

4 Principles of the predicted heat strain (PHS) model

The PHS model is based on the thermal energy balance of the body which requires the values of the following parameters, which are estimated or measured according to ISO 7726:

a) the parameters of the thermal environment:

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

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

- the metabolic rate, M, estimated on the basis of ISO 8996; and
- 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 water 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 for interpreting the results from Clause 5, which leads to the determination of the predicted sweat rate, the predicted core temperature and the allowable exposure times. The determination of the allowable exposure times is based on two strain criteria: maximum core temperature increase and maximum body water loss, 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 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 Heat balance equation

The thermal energy balance of the human 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, 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 energy is stored in the body, S.

The different terms of Equation (1) are successively reviewed in 5.1.1 to 5.1.10 in terms of the principles of calculation (detailed expressions are shown in Annex A).

5.2 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.

5.3 Effective mechanical power, W

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

5.4 Heat flow by respiratory convection, C_{res}

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

$$C_{\text{res}} = 0,00002 c_{\text{p}} \times V_{\text{ex}} \times \left(\frac{t_{\text{ex}} - t_{\text{a}}}{A_{\text{Du}}} \right) \tag{2}$$

5.5 Heat flow by respiratory evaporation, E_{res}

The heat flow by respiratory evaporation can be expressed, in principle, by the following equation:

$$E_{\text{res}} = 0,00002 c_{e} \times V_{\text{ex}} \times \left(\frac{W_{\text{ex}} - W_{\text{a}}}{A_{\text{Du}}} \right) \tag{3}$$

5.6 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, not directly taken into account and quantitatively assimilated to the heat losses by convection and radiation which would occur on these surfaces if they were not in contact with any solid body.

ISO 13732-1 [6] deals specifically with the risks of pain and burns when parts of the body contact hot surfaces.

5.7 Heat flow by convection, C

The heat flow by convection on the bare skin may be expressed by the following equation:

$$C = h_{c,dyn} \times (t_{sk} - t_a) \tag{4}$$

For clothed person, the heat flow by convection occurs at the surface of the clothing and is expressed by the following equation:

$$C = h_{c,dyn} \times f_{cl} \times (t_{cl} - t_a) \tag{5}$$

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

5.8 Heat flow by radiation, R

The heat flow by radiation may be expressed by the following equation:

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

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

5.9 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:

$$E_{\text{max}} = \frac{p_{\text{sk,s}} - p_{\text{a}}}{R_{\text{e,T,dyn}}} \tag{7}$$

where the dynamic clothing total water vapour resistance, $R_{e,T,dyn}$, takes into account the clothing characteristics as well as the movements of the subject 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:

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

5.10 Heat storage for increase of core temperature associated with the metabolic rate, dSeq

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, dS_{eq}, does not contribute to the onset of sweating and should therefore be deducted from the heat balance equation.

5.11 Heat storage, S

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

5.12 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:

$$E + S = M - W - C_{res} - E_{res} - C - R \quad (9)$$

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:

$$E_{req} = M - W - C_{res} - E_{res} - C - R - dS_{eq} \quad (10)$$

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.

The calculation of the required sweat rate is made as follows on the basis of the required evaporative heat flow, but taking account of the evaporative efficiency of the sweating, r_{req}:

$$w_{req} = \frac{E_{req}}{E_{max}} \quad (11)$$

The required sweat rate is then given by:

$$S_{wreq} = \frac{E_{req}}{r_{req}} \quad (12)$$

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 subject (1,8 m² of body surface).

6 Interpretation of required sweat rate

6.1 Basis of the method of interpretation

The interpretation of the values calculated by the recommended analytical method is based on two stress criteria (see 6.1.1):

- the maximum skin wettedness, w_{max}; and
- the maximum sweat rate: Sw_{max},

and on two strain criteria (see 6.1.2):

- the maximum core temperature: $t_{cr,\,max}$; and
- the maximum water loss: D_{max}.

6.2 Stress criteria

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

6.3 Strain criteria

In the case of non-equilibrium of the thermal balance, the core temperature increase should be limited at a maximum value, $t_{cr,max}$, such that the probability of any pathological effect is extremely limited. Finally, whatever the thermal balance, the water loss should be restricted to a value, D_{max}, compatible with the maintenance of the hydromineral equilibrium of the body.

6.4 Reference values

Annex B includes reference values for the stress criteria (w_{max} and Sw_{max}) and the strain criteria ($t_{cr,\ max}$ and D_{max}). Different values are presented for acclimatized and non-acclimatized subjects.

6.5 Analysis of the work situation

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

The steps are:

- the required evaporative heat flow, E_{req}, skin wettedness, w_{req}, and sweat rate, Sw_{req}, are first computed;
- from these, the predicted evaporative heat flow, E_p, skin wettedness, w_p, and sweat rate, Sw_p, are then computed considering the stress criteria (E_{max}, w_{max} and Sw_{max}) 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 the skin and body temperatures;
- body and core temperature are estimated; and
- from these values, the heat exchanges during the next time increment are computed.

The evolutions of Sw_p and t_{cr} are in this way iteratively computed.

In the present state of the standard, this procedure makes it possible to take into account only constant working conditions.

6.6 Determination of allowable exposure time, Dlim

The allowable exposure time, D_{lim}, is reached when either the core temperature or the cumulated water loss reaches the corresponding maximum values.

In work situations for which either:

- 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,

special precautionary measures need to be taken and direct, and individual physiological supervision of the workers is particularly necessary. The conditions for carrying out this surveillance and the measuring techniques to be used are described in ISO 9886.

A computer programme in Quick 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) to be used for the validation of any computer programme 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 equations given in this annex conform to the present state of knowledge. 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 lab experiments and 366 field experiments from 8 European research institutions. Table A.1 gives the ranges of conditions for which the predicted heat strain (PHS) model can be considered to be validated. When one or more parameters are outside this range, the present 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	4.5
$t_r - t_a$	°C	0	60
v_a	ms^{-1}	0	3
M	$W{\cdot}m^{-2}$	56	250
$I_{cl,st}$	clo	0.1	1.0

The time increment used during this validation study was equal to 1 min.

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

The heat flow by respiratory convection can be estimated by the following empirical expression:

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

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

The heat flow by respiratory evaporation can be estimated by the following empirical expression:

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

A.4 Determination of the steady state mean skin temperature

In climatic conditions for which this International Standard is applicable, the steady state mean skin temperature can be estimated as a function of the parameters of the working situation, using the following empirical expressions.

— For nude subjects ($I_{cl,st} \leq 0{,}2$):

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

— For clothed subjects ($I_{cl.st} \geq 0{,}6$):

$$t_{sk,eq,cl} = 12{,}17 + 0{,}02t_a + 0{,}04t_r - 0{,}253v_a + 0{,}194p_a + 0{,}00535M + 0{,}513t_{re} \qquad (A.4)$$

For $I_{cl,st}$ values between 0,2 and 0,6, the steady state skin temperature is extrapolated between these two values using:

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

A.5 Determination of the instantaneous value of skin temperature

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

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

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

The time constant of the response of the skin temperature being equal to 3 min, the following equation is used:

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

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

A.6 Determination of the heat accumulation associated with the metabolic rate, dS_{eq}

In a neutral environment, the core temperature increases with time during exercise, as a function of the metabolism rate relative to the individual's maximum aerobic power.

For an average subject, it can be assumed that this equilibrium core temperature increases as a function of the metabolic rate, according to the following expression:

$$t_{cr,eq} = 0{,}0036 \cdot (M - 55) + 36{,}8 \quad \text{(A.8)}$$

The core temperature reaches this equilibrium core temperature following a first order system with a time constant equal to 10 min:

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

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

The heat storage associated with this increase is:

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

A.7 Determination of the static insulation characteristics of clothing

For a nude subject and in static conditions without movements either of the air or of the person, the sensible heat exchanges ($C + R$) can be estimated by the following:

$$C + R = \frac{t_{sk} - t_a}{I_{tot\,st}} \quad \text{(A.12)}$$

For a clothed subject, this static heat resistance, $I_{tot,st}$, can be estimated using:

$$I_{tot,st} = I_{cl,st} + \frac{I_{a,st}}{f_{cl}} \quad \text{(A.13)}$$

where

— , $I_{a,st}$, can be estimated equal to 0.111 $m^2\,K \cdot W^{-1}$;

— the clothing area factor, f_{cl}, is given by:

$$f_{cl} = 1 + 1.97 \cdot I_{cl,st} \quad \text{(A.14)}$$

A.8 Determination of the 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 $C_{orr,tot}$ can be estimated as follows:

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

$$C_{orr,Itot,st} = C_{orr,Ia,st} = e^{[(0{,}047 v_{ar} - 0{,}472) v_{ar} + (0{,}117 V_w - 0{,}342) V_w]} \quad \text{(A.15)}$$

— for a person wearing clothes with $I_{cl,st}$ > 0.6 clo:

$$C_{\text{orr,Itot,st}} = C_{\text{orr,Icl,st}} = e^{[0,043\ +\ (0,066V_{\text{ar}} -\ 0,398)V_{\text{ar}} + (0,094V_{\text{w}}\ -\ 0,378)V_{\text{w}}\ ]} \quad \text{(A.16)}$$

with the relative air velocity, v_{ar}, limited to 3 m s^{-1} and the walking speed, v_w, limited to 1.5 m s^{-1}.

When the walking speed is undefined or the person is stationary, the value for v_w can be calculated as:

$v_w = 0{,}0052v(M - 58)$ with $v_w \leq 0{,}7$ m.s^{-1} (A.17)

with M expressed in W m^{-2}

For conditions with I_{cl} between 0 and 0.6 clo, the correction factor is estimated by interpolation between these two values, by the following expressions:

$C_{orr,Itot,st} = [(0{,}6 - I_{cl,st}) \times C_{orr,Ia,st} + I_{cl,st} \times C_{orr,Icl,st}]/0.6$ (A.18)

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

Finally:

$I_{a,dyn} = C_{orr,Ia,st} \times I_{a,st}$ (A.19)

$I_{T,dyn} = C_{orr,Itot,st} \times I_{T,st}$ (A.20)

$$I_{\text{cl dyn}} = I_{\text{T,dyn}} - \frac{I_{\text{a,dyn}}}{f_{\text{cl}}} \quad \text{(A.21)}$$

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

The dry heat exchanges can be estimated using the following equations:

$C + R = f_{cl} \times [h_{c,dyn} \times (t_{cl} - t_a) + h_r \times (t_{cl} - t_r)]$ (A.22)

which describes the heat exchanges between the clothing and the environment, and:

$$C + R = \left(\frac{t_{\text{sk}} - t_{\text{cl}}}{I_{\text{cl,dyn}}} \right) \quad \text{(A.23)}$$

which describes the heat exchanges between the skin and the clothing surface.

The dynamic convective heat transfer coefficient, $h_{c,dyn}$, can be estimated as the greatest value of:

$2.38 \mid t_{cl} - t_a \mid^{0,25}$ (A.24)

$3.5 + 5{,}2v_{ar}$ (A.25)

$8.7v_{ar}^{0.6}$ (A.26)

The radiative heat exchange, h_r, can be estimated using the following equation:

$$h_{\text{r}} = \varepsilon \times \sigma \times \frac{A_{\text{r}}}{A_{\text{Du}}} \times \frac{(t_{\text{cl}} + 273)^4 - (t_{\text{r}} + 273)^4}{t_{\text{cl}} - t_{\text{r}}} \quad \text{(A.27)}$$

where

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

 is the emissivity of the skin equal to 0,97.

The fraction of skin surface involved in heat exchange by radiation, A_r/A_{Du}, is equal to 0,67 for a crouching subject, 0,70 for a seated subject and 0,77 for a standing subject.

When a clothing with a reflection coefficient F_r is worn on a fraction A_p of the body surface, h_r should be corrected by a factor, $F_{cl,R}$, given by:

$F_{cl,R} = (1 - A_p)\varepsilon_{cl} + A_p \times F_r$ (A.28)

Both expressions A.22 and A.23 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:

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{e,T,dyn}} \quad (A.29)$$

The dynamic clothing total water vapour resistance, $R_{e,T,dyn}$, is estimated from the following equation:

$$R_{e,T,dyn} = \frac{I_{T,dyn}}{16.7 i_{m,dyn}} \quad (A.30)$$

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

$$i_{m,dyn} = i_{m,st} \times C_{orr,im} \quad (A.31)$$

with:

$$C_{orr,im} = 2{,}6\ C_{orr,Itot,st}^2 - 6{,}5\ C_{orr,Itot,st} + 4{,}9 \quad (A.32)$$

In this expression, $i_{m,dyn}$ is limited to 0,9.

A.11 Determination of the predicted sweat rate, S_{wp}, and predicted evaporative heat flow, E_p

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

1) A greater skin wettedness is associated with (in fact, 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}, estimated from expression (11) is greater than 1, and the evaporation efficiency, r_{req}, is expected to become lower than 0,5. r_{req} is computed from w_{req} using the following expressions:

— for $w_{req} \leq 1$, $r_{req} = 1 - w_{req}^2 / 2$ (A.33)

— for $w_{req} > 1$, $r_{req} = \frac{(2 - w_{req})^2}{2}$ (A.34)

r_{req}, however, is at the minimum 5 %, reached for a theoretical required wettedness value of 1.684.

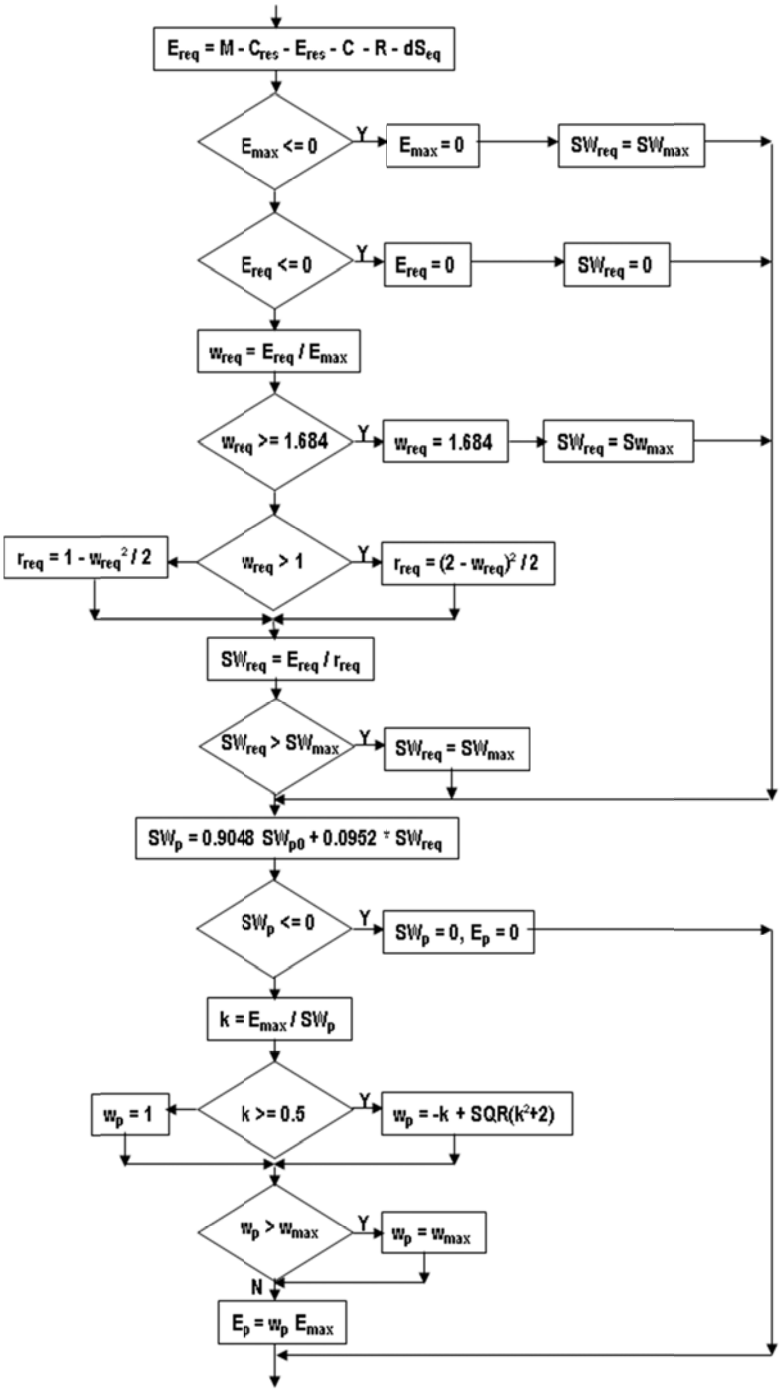
2) The sweat rate response can be described by a first order system with a time constant of 10 min. Therefore, the predicted sweat rate at time t_i is given by the following expression:

$$Sw_{p,i} = k_{Sw} \times Sw_{p,i-1} + (1 - k_{Sw}) \times Sw_{req} \quad (A.35)$$

where $k_{Sw} = \exp(-1/10)$ (A.36)

3) As explained in item 1), the *required* skin wettedness, w_{req}, is allowed to be theoretically greater than 1 for the computation of the required sweat rate, Sw_{req}.
As the evaporative heat loss is restricted to the surface of the water layer, that is, the surface of the body, the *predicted* skin wettedness, w_p, cannot be greater than one. The evaporative efficiency is then equal to 0,5 and the *predicted* sweat rate, Sw_p, is equal to twice the maximum evaporation heat flow, E_{max}.

Figure A.1 – Flow chart for the determination of the predicted sweat rate, Sw_p, and the predicted evaporative heat flow rate E_p



A.12 Evaluation of the rectal temperature

The heat storage during the last time increment at time, t_i, is given by:

$$dS_i = E_{req} – E_p + dS_{eqi} \quad \text{(A.37)}$$

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:

$$(1 - \alpha) = 0.7 + 0.,09(t_{cr} - 36,8) \quad \text{(A.38)}$$

This fraction is limited to:

— 0.7 for $t_{cr} \leq 36.8$ °C;

— 0.9 for $t_{cr} \geq 39.0$ °C.

Figure A.2 illustrates the distribution of the temperature in the body at time, $t_{i\text{-}1}$, and time t_i. From this it can be computed that:

$$t_{\mathrm{cr},i} = \frac{1}{1-\frac{\alpha_i}{2}}\left[\frac{dS_i \times A_{\mathrm{du}} \times 60}{c_{\mathrm{sp}} \times W_{\mathrm{b}}} + t_{\mathrm{cr},i-1} - \frac{t_{\mathrm{cr},i\text{-}1} - t_{\mathrm{sk},i\text{-}1}}{2}\alpha_{i\text{-}1} - t_{\mathrm{sk},i}\frac{\alpha_i}{2}\right] \quad \text{(A.39)}$$

The rectal temperature is estimated according to the following expression:

$$t_{\mathrm{re},i} = t_{\mathrm{re},i\text{-}1} + \frac{2t_{\mathrm{cr,I}} - 1.926t_{\mathrm{re},i\text{-}1} - 1,31}{9} \quad \text{(A.40)}$$

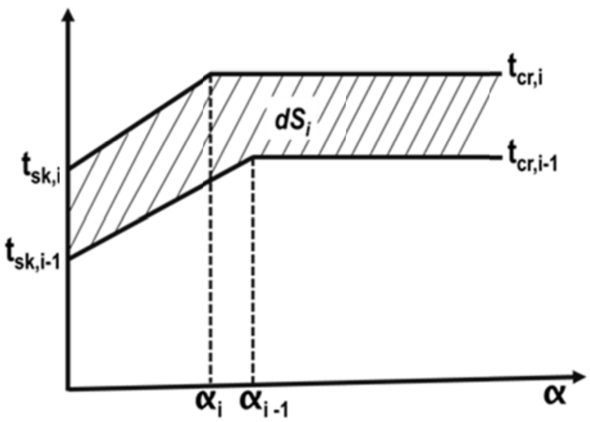


Figure A.2 — Distribution of heat storage in the body at times $t_{i\text{-}1}$ and t_i

Annex B
(Informative)
Criteria for estimating acceptable exposure time in a hot work environment

B.1 Introduction

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

- acclimatized and non-acclimatized subjects;
- a maximum skin wettedness, w_{max};
- a maximum sweat rate capacity, Sw_{max};
- consideration of the 95 % percentile of the working population (representative of the most susceptible subjects);
- a maximum water loss, D_{max};
- a maximum acceptable core temperature, $t_{cr,max}$.

B.2 Acclimatized and non-acclimatized subjects

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

This distinction between acclimatized and non-acclimatized is therefore essential. It concerns w_{max}, and Sw_{max}.

When the state of climatization is uncertain, the subjects are assumed to be non-acclimatized.

B.3 Maximum skin wettedness, w_{max}

The maximum skin wettedness is set to 0.85 for non-acclimatized subjects and to 1.0 for acclimatized workers.

B.4 Maximum sweat rate, Sw_{max}

The maximum sweat rate capacity is estimated equal to 400 W·m-2 for unacclimatized subjects and 500 for acclimatized subjects. This corresponds to possible productions of 1 and 1.25 litres maximum of sweat per hour.

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 in industry (not in the army or for sportsmen).

For exposure lasting 4 h to 8 h, the rehydration rate is greater than 40 % in 95 % of the cases.

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

B.6 Maximum value of core temperature

Following the recommendations of the WHO technical report No 412 (1969) [7]: “It is inadvisable for deep body temperature to exceed 38 °C in prolonged daily exposure to heavy work”.

Annex C
(Informative)
Metabolic rate

ISO 8996 describes methods for estimating the metabolic rate. These methods are classified in 4 levels of increasing accuracy.

Level 1, *Screening*: a method simple and easy 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; and

direct calorimetry method.

While the screening method described in ISO 7243 [3] (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 predicted heat strain model described in this International Standard.

The use of the Level 3, Analysis, method based on heart rate recordings is highly recommended.

ISO standards 16265 and 16595 provide guidance for estimating the average metabolic rate for a group of subjects in a given work situation.

The following formulae make it possible to predict the (HR – M) relationship as a function of the characteristics of the subject.

Maximum working capacity (MWC, *W*):

- Men: $(19.45 - 0.133 \cdot Age) \cdot W_{bl}$
- Women: $(17.51 - 0.150 \cdot Age) \cdot W_{bl}$

where:

Age is the age of the subject in years; and

W_{bl} is the lean body mass in kilograms (kg).

The lean body mass may be estimated using the following expression:

- Men: $W_{bl} = (1,08 – W_b / (80 \times H_b^2) \times W_b$;
- Women: $W_{bl} = (0,86 – W_b / (107,5 \times H_b^2) \times W_b$

where:

W_b is the body mass of the subject in kilograms (kg); and

H_b is the body height in metres (m).

Metabolic rate at rest, seated M_0, *W*:

- Men: $60 \times A_{Du}$;
- Women: $55 \times A_{Du}$

Maximum heart rate $HR_{max,}$ beats·min^{-1}:

Men and women: $208 - 0,7 \times Age$

Heart rate at rest HR_0, beats·min^{-1}:

the heart rate value exceeded during 99% of the time of the HR recording, provided that the subject was at rest in a neutral environment at least 5 min during the recording.

The mean metabolic rate (M_m) over the recorded period of time may then be derived from the mean heart rate HR_m using the following expression:

$$M_m = M_0 + (HR_m - HR_0)/RM$$

where:

$$RM = (HR_{max} - HR_0) / (MWC - M_0)$$

I must be noted that, while the method presented above and at the Level 3, Analysis of ISO 8996, makes it possible to evaluate the metabolic rate in watts, the PHS model is calculated the heats exchanges in watts per square meter of body surface and therefore uses as input value the metabolic rate in watts per square meter given by:

$$M \text{ in } Wm^{-2} = M \text{ in } W / A_{Du}$$

Annex D (Informative)
Clothing thermal characteristics

D.1 General

The thermal characteristics of the clothing to be considered are:

- its thermal insulation;
- its reflection of thermal radiation, and
- its permeability to water vapour.

D.2 Clothing thermal insulation

The clothing thermal insulation unit used in the standard 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 clothing thermal insulation values in clo, for selected garment ensembles.

Table D.1 — Basic insulation values for selected garment ensembles

Garment ensembles	$I_{cl,st}$ 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 dynamic clothing thermal insulation is used in the calculation. The equations for determination of the dynamic insulation characteristics of clothing are presented in A.8.

D.3 Reflection of thermal radiation

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

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

Material	Treatment	F_r
Cotton	with aluminum paint	0.42
Viscose	with glossy aluminum foil	0.19
Aramid (Kevlar)	with glossy aluminum foil	0.14
Wool	with glossy aluminum foil	0.12
Cotton	with glossy aluminum foil	0.04
Viscose	vacuum metallized with aluminum	0.06
Aramid	vacuum metallized with aluminum	0.04
Wool	vacuum metallized with aluminum	0.05
Cotton	vacuum metallized with aluminum	0.05
Glass fiber	vacuum metallized with aluminum	0.07

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, Ap, 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
Tights	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 vapour pressure of the material, which can be defined by the static moisture permeability index, $i_{m,st}$. As the present International Standard is not applicable to special impermeable clothing, a mean value of $i_{m,st}$ equal to 0,38 can be adopted.

Annex E (Informative)
Computer programme 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 following computer programme 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 programme

Symbol in the programme	Symbol
Ardu	A_r/AD_u
Conv	C
ConstSW	k_{Sw}
ConstTeq	k_{tcr}
ConstTsk	k_{tsk}
CORcl	$C_{orr,Icl,st}$
CORe	$C_{orr,im}$
CORia	$C_{orr,Ia,st}$
CORtot	$C_{orr,Itot,st}$
dStorage	dSi
dStoreq	dS_{eq}
Eveff	r_{req}
FclR	$F_{cl,R}$
Hcdyn	$h_{c,dyn}$
height	H_b
Iadyn	$I_{a,dyn}$
Iast	$I_{a,st}$
Icl	$I_{cl,st}$
Icldyn	$I_{cl,dyn}$
imdyn	$I_{m,dyn}$
imst	$I_{m,st}$
Itotdyn	$I_{tot,dyn}$
Itotst	$I_{tot,st}$
ConstTsk	k_{tsk}
ConstTeq	k_{tcreq}
ConstSw	k_{swq}
Met	M
Psk	$p_{sk,s}$
Rad	R
Rtdyn	$R_{e,T,dyn}$
SWp0	$Sw_{p,i-1}$
Tcr	$t_{cr,i}$
Tcr0	$t_{cr,i-1}$
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 Programme

```
' 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 SUBJECTS
' 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 subject, =0 otherwise
  Drink = 1:  ' Water replacement: =1 if the workers 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 E of ISO 7933 are introduced.
  Duration = 480:  ' Duration of the work sequence in minutes
  Ta = 40:  ' Air temperature in degrees Celsius
  Tg = 40:  ' Black globe temperature: °C
  Diam = 15:  ' Diameter of the black globe, in cm
  Va = 0.3:  ' Air velocity 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, watts
    Met = M / Adu:  ' Metabolic rate, Watts per square metre
  Work = 0:  ' Effective mechanical power watts per square metre
  Icl = 0.5:  ' Static thermal insulation 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
' Refective clothing
  Ap = 0.54:  ' Fraction of the body surface covered by the reflective clothing
  Fr = 0.97:  ' Emissivity of the reflective clothing (by default: Fr=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 + 0.3 * 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 * Var - 0.472) * Var + (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:  ' Duration limit of exposure due to increase in temperature, min
   Dlimloss = 999:  ' Duration limit of exposure 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 subjects, 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
   FclR = (1 - Ap) * 0.97 + Ap * Fr
   Tcl = Tr + 0.1
Tcl:
' Dynamic convection coefficient
   Hcdyn = 2.38 * Abs(Tcl - Ta) ^ 0.25
      If Z > Hcdyn Then Hcdyn = Z
' Radiation coefficient
   HR = FclR * auxR * ((Tcl + 273) ^ 4 - (Tr + 273) ^ 4) / (Tcl - Tr)
   Tcl1 = ((fcl * (Hcdyn * Ta + HR * Tr) + Tsk / Icldyn)) / (fcl * (Hcdyn + 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 * Hcdyn * (Tcl - Ta):  ' Heat exchanges 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
End Sub
```

Annex F
(Normative)
Examples of the predicted heat strain model computations

This annex provides the primary data and the main output data for five working conditions. This should be used to test that any particular version of the programme 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 programme. 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 (units)	Examples of working conditions				
	1	2	3	4	5
Acclimatation	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
Ap (fraction %)	–	–	30	–	20
F_r (-)	–	–	0.15	–	0.15
Final SW_p (g/h)	812	633	766	543	722
Water loss (g)	6 531	6 345	6 425	4 563	5 847
Final T_{cr} (°C)	37.5	40.8	38.6	38.0	37.5
$D_{limloss}$ (min)	280	250	280	400	310
D_{limTcr} (min)	–	63	158	–	–

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