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

I was the main writer (Prof J. Malchaire) of this document which became the international standard ISO 7933. I was never remunerated for this work and I never yielded the royalties to anybody. Therefore, I consider that I have the right to diffuse the document that was sent to ISO to edit the standard.
This document takes into account the modifications brought in 2020
The PMV_WBGT_PHS program available via my repertory DROPBOX makes possible to compute the PHS

Contenu

1 Scope

This document describes a mathematical 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”, with 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 physiological strains.
In its present form, this method of assessment is not applicable to cases where special protective clothing (such as fully reflective clothing, active cooling and ventilation, impermeable coveralls…) is worn.

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 permit 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.

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 ergonomists, industrial hygienists, etc. Recommendations about how and when to use this model are given in ISO 16595/WP.

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.

<std>ISO 7726, *Ergonomics of the thermal environment — Instruments for measuring physical quantities*
— ISO 8996, *Ergonomics of the thermal environment — Determination of metabolic rate*
— ISO 9886, *Ergonomics — Evaluation of thermal strain by physiological measurements*
— ISO 9920, *Ergonomics of the thermal environment — Estimation of 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*

3 Terms and definitions

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

4 Symbols

The symbols and abbreviated terms are listed in Table 1

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_{cl}	emissivity of outer clothing surface assuming this is non-reflective	—
$\varepsilon_{cl,r}$	emissivity of outer clothing surface	—
θ	angle between walking direction and wind direction	—
A	age	years
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	$J \cdot kg^{-1}$
$Corr,i_m$	correction factor for the static moisture permeability index	—
$Corr,I_a$	correction factor for the static boundary layer thermal insulation	—
$Corr,I_{cl}$	correction factor for the static clothing thermal insulation	—
$Corr,I_T$	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_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	$W \cdot m^{-2} \cdot K^{-1}$
$I_{a,r}$	resultant boundary layer thermal insulation	$m^2 \cdot K \cdot W^{-1}$
I_a	static (or basic) boundary layer thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$I_{cl,r}$	resultant clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
I_{cl}	static (or basic) clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
$i_{m,r}$	resultant moisture permeability index	—
i_m	static (or basic) moisture permeability index	—
$incr$	time increment from time t_{i-1} to time t_i	min
$I_{T,r}$	resultant total clothing thermal insulation	$m^2 \cdot K \cdot W^{-1}$
I_T	static (or basic) 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	$W \cdot m^{-2}$
$R_{e,T,r}$	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	$W \cdot m^{-2}$
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
$t_{re,max}$	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	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	—

5 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 ;
— water vapour partial pressure, p_a ; and
— 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 water 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 rectal temperature increase and maximum 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 values which are adopted. It is also a function of the accuracy of estimation and measurement of the physical parameters and of the accuracy with which the metabolic rate and the thermal insulation of the clothing are estimated.

6 Main steps of the calculation

6.1 Heat balance equation

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

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

This equation expresses that the internal heat production of the body, which corresponds to the metabolic rate, *M*, minus the effective mechanical power, *W*, are balanced by the heat exchanges in the respiratory tract by convection, C_{res}, and evaporation, E_{res}, as well as by the heat exchanges on the skin by conduction, *K*, convection, *C*, radiation, *R*, and evaporation, *E*.
If the balance is not satisfied, some energy is stored in the body, *S*.
The different terms of Equation (1) are successively reviewed in 6.1.1 to 6.1.10 in terms of the principles of calculation (normative expressions for the computations are provided in Annex A).

6.1.1 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.

6.1.2 Effective mechanical power, *W*

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

6.1.3 Heat flow by respiratory convection, C_{res}

The heat flow by respiratory convection may be expressed, in principle, by Equation (2) :

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

6.1.4 Heat flow by respiratory evaporation, E_{res}

The heat flow by respiratory evaporation can be expressed, in principle, by Equation (3) :

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

6.1.5 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[6] deals specifically with the risks of pain and burns when parts of the body contact hot surfaces.

6.1.6 Heat flow by convection, *C*

The heat flow by convection on the bare skin may be expressed by Equation (4) :

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

For clothed person, the heat flow by convection occurs at the surface of the clothing and is expressed by Equation (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.

6.1.7 Heat flow by radiation, *R*

The heat flow by radiation may be expressed by Equation (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).

6.1.8 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, Equation (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 Equation (8) :

$E = w \times E_{max}$ (8)

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

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 Equation (1).

6.1.10 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 a significant avenue of heat exchange, the general Equation (1) can be written as Equation (9) :

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

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 Equation (10) :

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

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 :

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

The calculation of the required sweat rate, SW_{req}, is made on the basis of the required evaporative heat flow, but taking account of the evaporative efficiency of the sweating, r_{req} as follows in Equation 12 :

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

NOTE : The sweat rate in $W \cdot m^{-2}$ represents the equivalent in heat of the sweat rate expressed in $g \cdot m^{-2}\ h^{-1}$. 1 $W \cdot m^{-2}$ corresponds to a flow of sweat of 1,47 $g \cdot m^{-2}\ h^{-1}$ or 2,67 $g \cdot h^{-1}$ for a standard person (1,8 m² of body surface).

7 Interpretation of required sweat rate

7.1 Basis of the method of interpretation

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

— two stress criteria (see 7.1.1) :

  — the maximum skin wettedness w_{max};
  — the maximum sweat rate SW_{max};

— two strain criteria (see 7.1.2) :

— the maximum rectal temperature $t_{re, max}$
— the maximum water loss D_{max}.

7.1.1 Stress criteria

The required sweat rate, SW_{req}, cannot exceed the maximum sweat rate, SW_{max}, 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.

7.1.2 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.

7.1.3 Reference values

Annex B includes reference values for the stress criteria (w_{max} and SW_{max}) and the strain criteria ($t_{re, max}$ and D_{max}). w_{max}, SW_{max} 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 current climatic, 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, Sw_{req}, are first computed;
— from these, the predicted sweat rate, SW_p, skin wettedness, w_p, and evaporative heat flow, E_p, are 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 is estimated ;
— body and core temperature are estimated; and
— from these values, the heat exchanges during the time increment are computed.

The evolutions of SW_p, 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.
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 persons 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 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
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 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 lab experiments and 366 field experiments from 8 European research institutions[12]. 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, 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	$W·m^{-2}$	56	250
$I_{cl,st}$	clo	0,1	1,0

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

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

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

$$C_{res} = 0{,}00152\, M\, (28{,}56 – 0{,}885\, t_a + 0{,}641\, p_a) \quad (A.1)$$

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

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

$$E_{res} = 0{,}00127\, M\, (59{,}34 + 0{,}53\, t_a – 11{,}63\, p_a) \quad (A.2)$$

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 Equations (A.3) and (A.4).

— For $I_{cl} \le 0{,}2$ clo :

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

— For $I_{cl} \ge 0{,}6$ clo :

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

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

$t_{sk,eq} = t_{sk,eq,nu} + 2{,}5 \times (t_{sk,eq,cl} - t_{sk,eq,nu}) \times (I_{cl,st} - 0{,}2)$ (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, Equations (A.6) and (A.7) are used :

$t_{sk,i} = k_{tsk} \times t_{sk,i-1} + (1 - k_{tsk}) \times t_{sk,eq}$ (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 as a function of metabolic rate. For an average person, equilibrium core temperature is related to metabolic rate according to Equation (A.8) :

$t_{cr,eq} = 0{,}0036 \cdot (M - 55) + 36{,}8$ (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 Equations (A.9) and (A.10) :

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

where

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

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

$dS_{eq} = c_{p,b} \times W_b / (A_{Du} \times 60) \times (t_{cr,eq,i} - t_{cr,eq,i-1}) \times (1 - \alpha_{i-1})$ (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 or of the person, the sensible heat exchanges ($C + R$) can be estimated by Equation (A.12) :

$$C + R = \frac{t_{sk} - t_a}{I_T} \qquad \text{(A.12)}$$

For a clothed person, this static heat resistance, $I_{tot,st}$, can be estimated using Equation (A.13) :

$$I_T = I_{cl} + \frac{I_a}{f_{cl}} \qquad \text{(A.13)}$$

where

— I_a can be estimated as 0.111 $m^2\,K \cdot W^{-1}$;

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

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

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 $Corr,I_T$ can be estimated with Equations (A.15) and (A.16) :

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

$$Corr,I_T = Corr,I_a = e^{[(0,047 v_{ar} - 0,472) v_{ar} + (0,117 V_w - 0,342) V_w]} \quad \text{(A.15)}$$

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

$$Corr,I_T = Corr,I_{cl} = e^{[0,043 + (0,066 V_{ar} - 0,398) V_{ar} + (0,094 V_w - 0,378) V_w]} \quad \text{(A.16)}$$

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 with Equation (A.17) :

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

For conditions with I_{cl} between 0 and 0.6 clo, the correction factor is estimated by interpolation between these two values, by Equations (A.18) to (A.21) :

$$Corr,I_T = [(0,6 - I_{cl}) \times Corr,I_a + I_{cl} \times Corr,I_{cl}]/0.6 \quad \text{(A.18)}$$

In any case, this correction factor is limited to 1.
Finally, resultant (or dynamic) thermal insulation values are calculated as :

$$I_{a,r} = \text{Corr,I}_a \times I_a \quad \text{(A.19)}$$
$$I_{T,r} = Corr,I_T \times I_T \quad \text{(A.20)}$$
$$I_{cl,r} = I_{T,r} - \frac{I_{a,r}}{f_{cl}} \quad \text{(A.21)}$$

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

The dry heat exchanges can be estimated using Equations (A.22) to (A.26) :

$$C + R = f_{cl} \times [h_c \times (t_{cl} - t_a) + h_r \times (t_{cl} - t_r)] \quad \text{(A.22)}$$

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

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

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

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

$2.38|t_{cl} - t_a|^{0,25}$ (A.24)
$3.5 + 5,2 v_{ar}$ (A.25)
$8.7 v_{ar}^{0.6}$ (A.26)

The radiative heat exchange coefficient, h_r, can be estimated using Equation (A.27) :

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

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

$\varepsilon_{cl,r} = \varepsilon_{cl}$ the emissivity of outer surface of ordinary clothing, when no reflective clothes are used. This emissivity is taken to be 0.97.
When a clothing with a reflection coefficient F_r is worn on a fraction A_p smaller than 50% of the body surface, the emissivity in Equation (A.27) should be calculated as :

$\varepsilon_{cl,r} = (1 - A_p)\, \varepsilon_{cl} + A_p\, (1 - F_r)$ (A.28)
As stated in Section 1. Scope, , this method of assessment is not applicable to cases where special protective clothing such as fully reflective clothing are worn.

Both Equations 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 Equation (A.29) :

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

The resultant (or dynamic) clothing total water vapour resistance, $R_{e,T,r}$, is estimated from Equations (A.30) to (A.32) :

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

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.

$i_{m,r} = i_m \times Corr,i_m$ (A.31)

with :

$Corr,i_m = 2,6\, Corr,I_T^2 - 6,5\, Corr,I_T + 4,9$ (A.32)

In this Equation, $i_{m,r}$ is limited to 0,9.

A.11 Determination of the predicted sweat rate, SW_p, 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.

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

— for $w_{req} \leq 1$, the efficiency is given by Equation (A.33) :

$$r_{req} = 1 - w_{req}^2 / 2 \qquad \text{(A.33)}$$

— for $w_{req} > 1$, the efficiency is given by Equation (A.34) :

$$r_{req} = \frac{\left(2 - w_{req}\right)^2}{2} \qquad \text{(A.34)}$$

— if $r_{req} < 0.05$, r_{req} is set to 0.05

In any case, the required sweat rate SW_{req} may not be greater than SW_{max}

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 Equations (A.35) and (A.36) :

$$SW_{p,i} = k_{Sw} \times SW_{p,i-1} + (1 - k_{SwW}) \times SW_{req} \qquad \text{(A.35)}$$

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}.

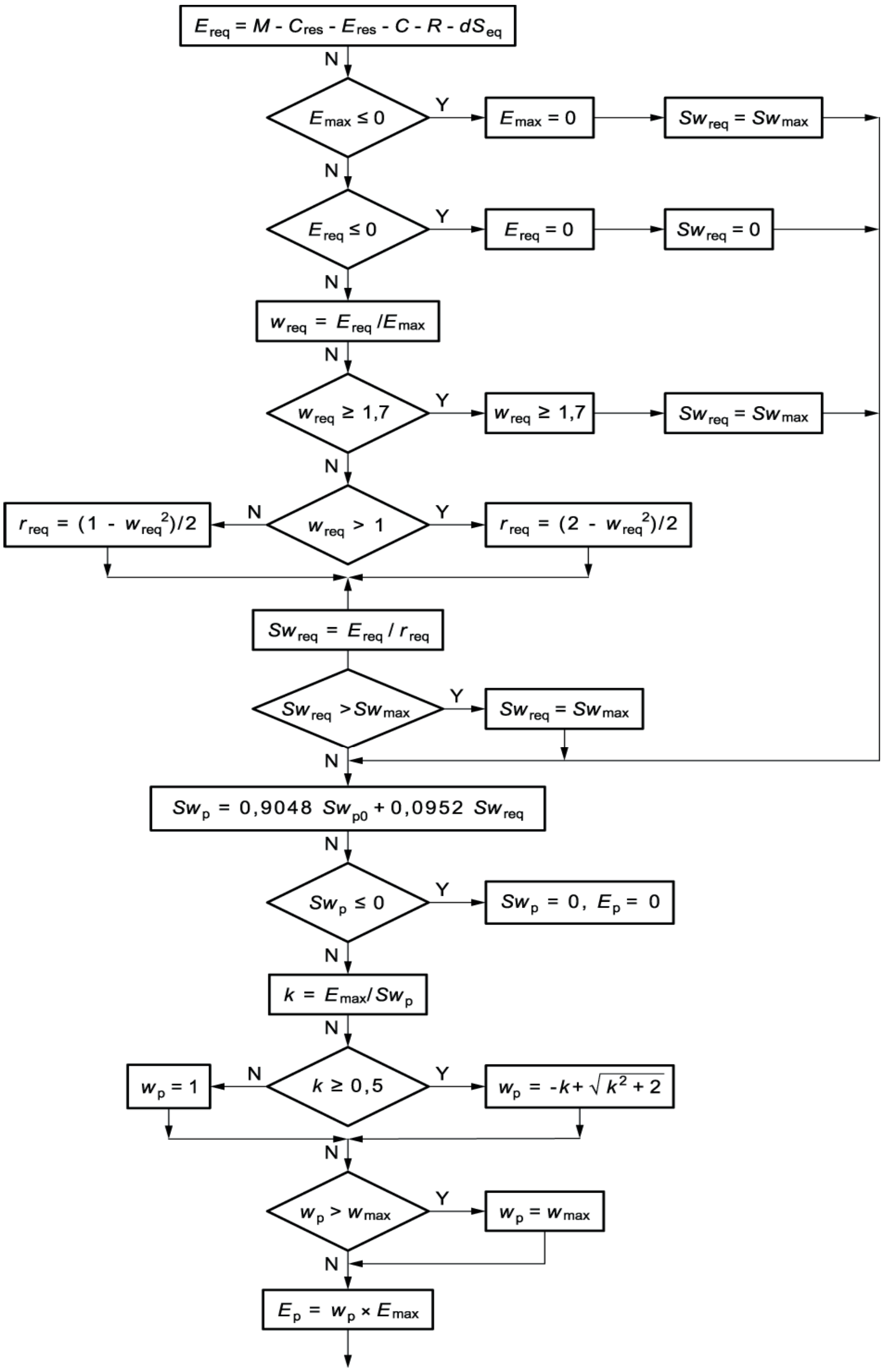

Figure A.1 – Flow chart for the determination of the predicted sweat rate, SW_p, and the predicted evaporative heat flow rate E_p

A.12 Evaluation of the rectal temperature

The heat storage during the last time increment at time, t_i, is given by Equation (A.37) :

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

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 Equation (A.38) :

$$(1 – \alpha) = 0,7 + 0,09 \, (t_{cr} – 36,8) \quad (A.38)$$

This fraction is limited to :

- 0,7 for $t_{cr} \leq 36,8$ °C;
- 0,9 for $t_{cr} \geq 39,0$ °C.

Then, the core temperature at time *i* may be computed using Equation (A.39) :

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

The rectal temperature is estimated according to Equation (40) :

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

Annex B
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 the following :

- — acclimatized and unacclimatized persons in good health and fit for assigned duties;
- — a maximum skin wettedness, w_{max};
- — a maximum sweat rate capacity, SW_{max};
- — 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 to be 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 SW_{max}.
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 to 1,0 for an acclimatized person.

B.4 Maximum sweat rate, SW_{max}

For this standard, 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 and 1,25 litres 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 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 (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)[7] underlined the importance of limiting deep body temperature. During the development of PHS, a 38ºC prediction criterion was confirmed as a population-based goal [11]. 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 1 000 persons) (250 days per year);

- for 39,2°C : less than 10^{-4} (less than one person at risk among 1 000 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 [12].

Annex C
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 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 at ISO 8996 make it possible to evaluate the metabolic rate in watts, the PHS model is calculating the heat exchanges in watts per square meter of body surface. The metabolic rate to be used in the formulas 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
Clothing thermal characteristics

D.1 General

The thermal characteristics of the clothing to be considered are :

- — thermal insulation;
- — reflection of thermal radiation, and
- — 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} 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 equations for determination of the resultant (or dynamic) insulation characteristics of clothing are provided in A.8.

D.3 Reflection of thermal radiation

Table C.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 (Kevlar)	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
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 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
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 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	$Corr,I_{cl}$
CORe	$Corr,i_m$
CORia	Corr,I_a
CORtot	Corr,I_T
dStorage	dSi
dStoreq	dS_{eq}
Eclr	$\varepsilon_{cl,r}$
Eveff	r_{req}
hc	h_c
height	H_b
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_{tcreq}
ConstSw	k_{swq}
Met	M
Psk	$p_{sk,s}$
Rad	R
Rtdyn	$R_{e,T,r}$
SWp0	$SW_{p,i\text{-}1}$
Tcr	$t_{cr,i}$
Tcr0	$t_{cr,i\text{-}1}$
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

Note : For a certain range of exposure conditions, the model predicts 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 could 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 the programmes not only provide the final values of accumulated water loss and rectal temperature, but make it possible to analyze, 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
  Fr = 0.42                  ' Reflection coefficient for different special materials

' 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
  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 + 0.3 * 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 * 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) * 0.97 + 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
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 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
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
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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