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.

The PMV_WBGT_PHS program available via my repertory DROPBOX makes possible to compute the PHS

1. Scope

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

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

The main objectives of this International Standard are the following:

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

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

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

2. Normative references

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

- ISO 7726, Ergonomics of the thermal environment — Instruments for measuring physical quantities
- ISO 8996, Ergonomics of the thermal environment — Determination of metabolic rate
- ISO 9886, Ergonomics — Evaluation of thermal strain by physiological

measurements

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

3. Symbols

For the purposes of this document, the symbols and abbreviated terms, designated below as “symbols” with their units, are in accordance with ISO 7726.
However, additional symbols are used to for the presentation of the Predicted Heat Strain index. A complete list of symbols is presented in Table 1.

Table 1 — Symbols and units

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

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

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

4. Principles of the method of evaluation

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

a) the parameters of the thermal environment:

- air temperature, ta;
- mean radiant temperature, tr;
- partial vapour pressure, pa;
- air velocity, va;

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

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

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

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

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

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

5. Main steps of the calculation

5.1. General heat balance equation

5.1.1. General

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

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

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

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

5.1.2. Metabolic rate, M

The estimation or measurement of the metabolic rate is described in ISO 8996. Indications for the evaluation of the metabolic rate are given in Annex C.

5.1.3. Effective mechanical power, W

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

5.1.4. Heat flow by respiratory convection, Cres

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

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

5.1.5. Heat flow by respiratory evaporation, Eres

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

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

5.1.6. Heat flow by conduction: K

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

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

5.1.7. Heat flow by convection at the skin surface, C

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

$$C = h_{\mathrm{cdyn}} \times f_{\mathrm{cl}} \times (t_{\mathrm{sk}} - t_{\mathrm{a}}) \qquad (4)$$

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

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

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

The heat flow by radiation may be expressed by the equation

$$R = h_{\mathrm{r}} \times f_{\mathrm{cl}} \times (t_{\mathrm{sk}} - t_{\mathrm{r}}) \qquad (5)$$

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

5.1.9. Heat flow by evaporation at the skin surface, E

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

$$E_{\mathrm{max}} = \frac{p_{\mathrm{sk,s}} - p_{\mathrm{a}}}{R_{\mathrm{tdyn}}} \qquad (6)$$

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

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

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

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

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

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

5.1.11. Heat storage, S

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

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

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

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

The required evaporative heat flow, E_{req}, is the evaporation heat flow required for the maintenance of the

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

thermal equilibrium of the body and, therefore, for the heat storage to be equal to zero. It is given by

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

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

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

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

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

- the maximum skin wettedness, wmax
- the maximum sweat rate: Swmax

and on two strain criteria

- the maximum rectal temperature: tre, max
- the maximum water loss: Dmax.

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.

In the case of non-equilibrium of the thermal balance, the rectal temperature increase must be limited at a maximum value, $t_{re,max}$ 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.

Annex B includes reference values for the stress criteria (w_{max} and Sw_{max}) and the strain criteria ($t_{re,max}$ and D_{max}). Different values are presented for acclimatized and non-acclimatized subjects, and according to the degree of protection that is desired [mean level or 95 % (alarm) level].

6.2. Analysis of the work situation

Heat exchanges are computed at time, t_i, from the body conditions existing at the previous computation time and as a function of the climatic and metabolic conditions prevailing during the time increment.

- The required evaporative heat flow (Ereq), skin wettedness (wreq) and sweat rate (Swreq) are first computed.
- Then the predicted evaporative heat flow (Ep), skin wettedness (wp) and sweat rate (Swp) are computed, considering the limitations of the body (wmax and Swmax) 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 evaporation heat flow. This heat contributes to increase or decrease the skin and body temperatures. These two parameters are then estimated, as well as the rectal temperature.
- From these values, the heat exchanges during the next time increment are computed. The evolutions of Swp and tre are in this way iteratively computed.

This procedure makes possible to take into account not only constant working conditions, but also any conditions with climatic parameters or work load characteristics varying in time.

6.3. Determination of maximum allowable exposure time (Dlim)

The maximum allowable exposure time, D_{lim}, is reached when either the rectal 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, Emax, is negative, leading to condensation of water vapour on the skin,
- or the estimated allowable exposure time is less than 30 min, so that the phenomenon of sweating onset plays a major role in the estimation of the evaporation loss of the subject,

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.

6.4. Organization of work in the heat

This International Standard makes it possible to compare different ways of organizing work and scheduling rest periods if it is necessary.

A computer programme in Quick Basic is given in Annex E. It allows for the calculation and the interpretation of any combination of sequences where the metabolic rate, the clothing thermal characteristics and 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 present state of knowledge. Some of them are likely to be amended in the light of increased knowledge.

The algorithms described in this annex were validated on a database including 747 lab experiments and 366 field experiments, from 8 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, it is recommended to use the present model with care and to bring special attention to the people exposed.

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

Parameters		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	100	450
I_{cl}	clo	0,1	1,0

A.2 Determination of the heat flow by respiratory convection, Cres

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

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

A.3 Determination of the heat flow by respiratory evaporation, Eres

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

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

A.4 Determination of the steady state mean skin temperature

In climatic conditions for which this 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} <= 0,2)		For clothed subjects (I_{cl} >= 0,6)	
$t_{sk,eq\ nu} = 7{,}19$	$+ 0{,}064\ t_a$	$t_{sk,eq\ cl} = 12{,}17$	$+ 0{,}020\ t_a$
	$+ 0{,}061\ t_r$		$+ 0{,}044\ t_r$
	$- 0{,}348\ v_a$		$- 0{,}253\ v_a$

	+ 0,198 p_a		+ 0,194 p_a
	+ 0,000 M		+ 0,005 346 M
	+ 0,616 t_{re}		+ 0,512 74 t_{re}

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

$$t_{sk,eq} = t_{sk,eq\,nu} + 2{,}5 \times (t_{sk,eq\,cl} - t_{sk,eq\,nu}) \times (I_{cl} - 0{,}2) \quad \text{(A.3)}$$

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 tsk,i-1 at time ti–1 one time increment earlier, and
- from the steady state skin temperature tsk,eq predicted from the conditions prevailing during the last time increment by the equations described in (A.4).

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

$$t_{sk,i} = 0{,}716\,5\ t_{sk,i-1} + 0{,}283\,5\ t_{sk,eq} \quad \text{(A.4)}$$

A.6 Determination of the heat accumulation associated with the metabolic rate, Seq

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:

$$t_{cr,eq} = 0{,}003\,6\ (M - 55) + 36{,}8 \quad \text{(A.5)}$$

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

$$t_{cr} = 36{,}8 + (t_{cr,eq} - 36{,}8) \times \left(1 - \exp\frac{-t}{10}\right) \quad \text{(A.6)}$$

This expression can be translated in the following

$$t_{cr,eq\,i} = t_{cr,eq\,i-1} \times k + t_{cr,eq} \times (1 - k) \quad \text{(A.7)}$$

where $k = \exp\left(\frac{-incr}{10}\right)$

The heat storage associated with this increase is

$$dS_{eq} = c_{sp} \times (t_{cr,eq\,i} - t_{cr,eq\,i-1}) \times (1 - \alpha) \quad \text{(A.8)}$$

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

$$C + R = \frac{t_{sk} - t_a}{I_{tot\ st}} \tag{A.9}$$

where the static heat resistance for nude subjects can be estimated equal to 0,111 $m^2 \cdot K \cdot W{-1}$.
For a clothed subject, this static heat resistance, $I_{tot\ st,}$ can be estimated using

$$I_{tot\ st} = I_{cl\ st} + \frac{I_{a\ st}}{f_{cl}} \tag{A.10}$$

where the ratio of the subject's clothed to unclothed surface areas, fcl, is given by

$$f_{cl} = 1 + 1{,}97\ I_{cl\ st} \tag{A.11}$$

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, it therefore needs to be corrected. The correction factor for the static clothing insulation and the external air layer insulation can be estimated with the following equations

$$I_{tot\ dyn} = C_{orr,tot} \times I_{tot\ st} \tag{A.12}$$

$$I_{a\ dyn} = C_{orr,Ia} \times I_{a\ st} \tag{A.13}$$

$$C_{orr,tot} = C_{orr,cl} = e^{(0{,}043\ -\ 0{,}398\, v_{ar}\ +\ 0{,}066\, v_{ar}^2\ -\ 0{,}378\, v_w\ +\ 0{,}094\, v_w^2)} \tag{A.14}$$

$I_{cl} \geqslant 0{,}6$ clo for nude persons or the adjacent air layer, by

$$C_{orr,tot} = C_{orr,I_a} = e^{(-0{,}472\, v_{ar}\ +\ 0{,}047\, v_{ar}^2\ -\ 0{,}342\, v_w\ +\ 0{,}117\, v_w^2)} \tag{A.15}$$

and for 0 clo <= $I_{cl <=}$ 0,6 clo, by

$$C_{orr,tot} = (0{,}6 - I_{cl})\ C_{orr,Ia} + I_{cl} \times C_{orr,cl} \tag{A.16}$$

with v_{ar} limited to 3 $m \cdot sec^{-1}$ and v_w limited to 1,5 $m \cdot sec^{-1}$.
When the walking speed is undefined or the person is stationary, the value for v_w can be calculated as

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

Finally, $I_{cl\ dyn}$ can be derived as

$$I_{cl\ dyn} = I_{tot\ dyn} - \frac{I_{a\ dyn}}{f_{cl}} \tag{A.18}$$

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

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

$$C + R = f_{cl} \times [h_{cdyn} \times (t_{cl} - t_a) + h_r \times (t_{cl} - t_r)] \tag{A.19}$$

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

$$C + R = \left(\frac{t_{sk} - t_{cl}}{I_{cl\ dyn}} \right) \tag{A.20}$$

which describes the heat exchanges between the skin and the clothing surface.
The dynamic convective heat exchange, h_{cdyn}, can be estimated as the greatest value of

$$2,38 \; |t_{sk} - t_a|^{0,25} \tag{A.21}$$

$$3,5 + 5,2 \; v_{ar} \tag{A.22}$$

$$8,7 \; v_{ar}^{0,6} \tag{A.23}$$

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

$$h_r = 5,67 10^{-8} \varepsilon \times \frac{A_r}{A_{Du}} \times \frac{(t_{cl} + 273)^4 - (t_r + 273)^4}{t_{cl} - t_r} \tag{A.24}$$

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 reflective clothing is being worn, h_r must be corrected by a factor $F_{cl,R}$ given by

$$F_{cl,R} = (1 - A_p)\, 0,97 + A_p \times F_r \tag{A.25}$$

Both expressions computing C R must be solved iteratively in order to derive t_{cl}.

A.10 Estimation of the maximum evaporative heat flow at the skin surface, Emax

The maximum evaporative heat flow at the skin surface is given by

$$E_{max} = \frac{p_{sk,s} - p_a}{R_{tdyn}} \tag{A.26}$$

The evaporative resistance, R_{tdyn}, is estimated from the following equation:

$$R_{tdyn} = \frac{I_{tot\,dyn}}{\frac{i_{mdyn}}{16,7}} \tag{A.27}$$

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

$$i_{mdyn} = i_{mst} \times C_{orr,\,E} \tag{A.28}$$

with

$$C_{orr,\,E} = 2,6\, C_{orr,tot}^2 - 6,5\, C_{orr,tot} + 4,9 \tag{A.29}$$

In this expression, imdyn is limited to 0,9.

A.11 Determination of the predicted sweat rate (Swp) and predicted evaporative heat flow (Ep)

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

R1: when the required evaporative heat flow Ereq is greater than the maximum evaporation rate, the skin is expected to be fully wetted: wreq greater than 1. wreq implies then the thickness of the water layer on the skin, rather than the equivalent fraction of the skin, which is covered with sweat. As the theoretical wreq is greater than 1, the evaporation efficiency is expected to become lower.

For $w_{req <=}$ 1, the efficiency is given by: $$r_{req} = \frac{1 - w_{req}{}^2}{2}$$

For w_{req} W 1, it is given by $$r_{req} = \frac{2 - w_{req}{}^2}{2}$$

This value, however, is at the minimum 5 %. This is reached for a theoretical wettedness of 1,684.

R2: 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, ($Sw_{p,i}$) is equal to a fraction k_{Sw} of the predicted sweat rate at time (t_{i-1}) ($Sw_{p,i-1}$) one time increment earlier plus the fraction (1– k_{Sw}) of the sweat rate required by the conditions prevailing during the last time increment (Sw_{req}), and k_{Sw} is given by.

$$k_{Sw} = \exp(-incr / 10)$$

R3: as explained above, the required skin wettedness is allowed to be theoretically greater than 1 for the computation of the predicted sweat rate. 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 cannot be greater than one. This occurs as soon as the predicted sweat rate is more than twice the maximum evaporation heat flow.

A.12 Evaluation of the rectal temperature

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

$$S = E_{req} - E_p + S_{eq} \qquad \text{(A.30)}$$

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

$$(1 - \alpha) = 0{,}7 + 0{,}09\,(t_{cr} - 36{,}8) \qquad \text{(A.31)}$$

This fraction is limited to

0,7 for t_{cr} < 36,8 °C

0,9 for t_{cr} > 39,0 °C

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

$$t_{cr,i} = \frac{1}{1 - \frac{\alpha}{2}} \left[\frac{dS_i}{C_p\ W_b} + t_{cr,i-1} - \frac{t_{cr,i-1} - t_{sk,i-1}}{2}\ \alpha_{i-1} - t_{sk,i} \frac{\alpha_i}{2} \right] \qquad \text{(A.32)}$$

The rectal temperature is estimated according to the following expression:

$$t_{re,i} = t_{re,i-1} + \frac{2\ t_{cr,i} - 1{,}962\ t_{re,i-1} - 1{,}31}{9} \qquad \text{(A.33)}$$

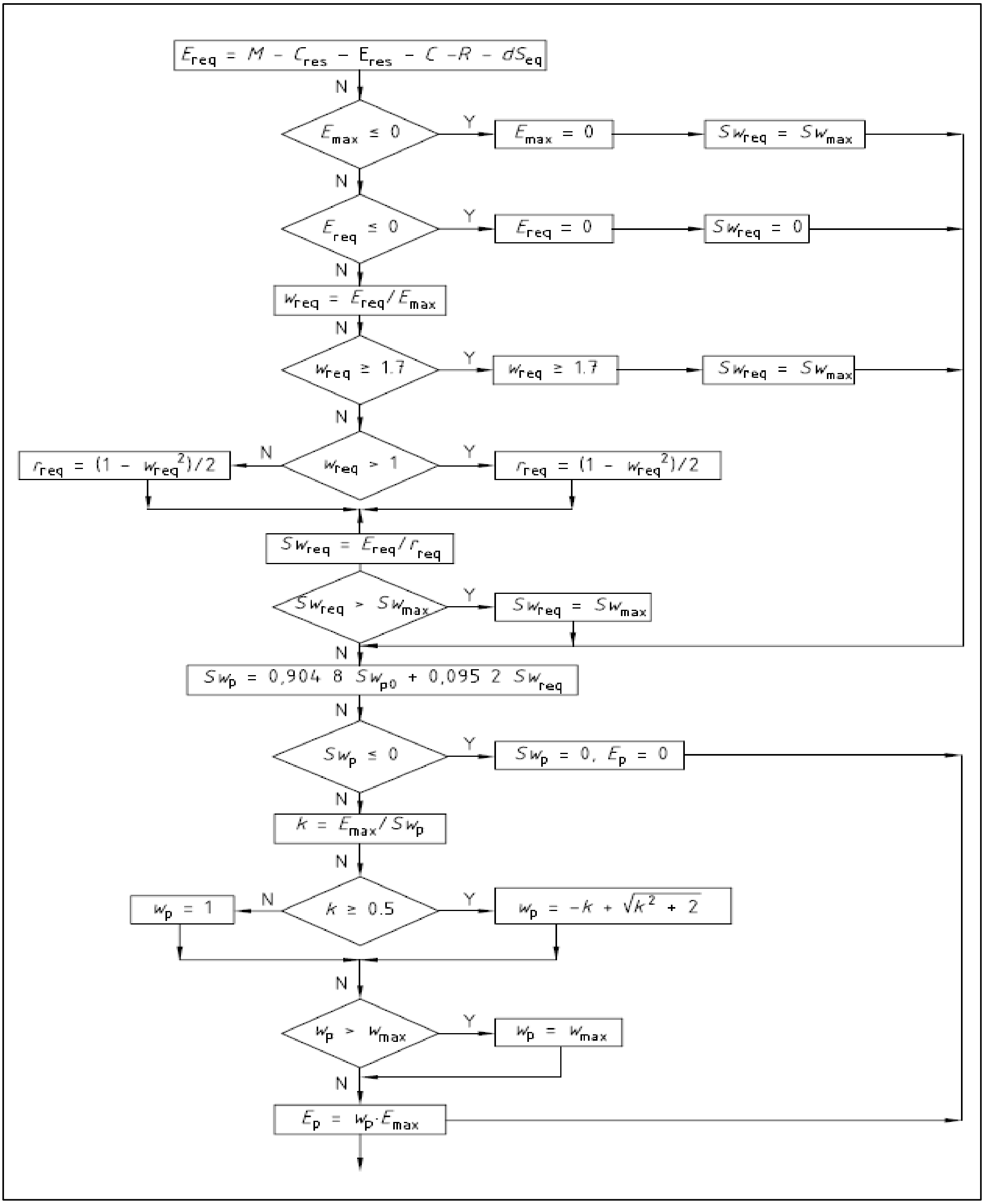

Figure A.1 — Flow chart for the determination of the predicted sweat rate (Sw_p) and the predicted evaporative heat flow (E_p)

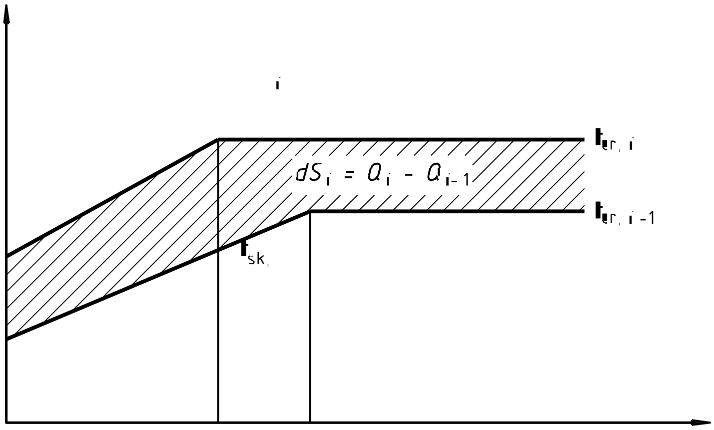

Figure A.2 — Distribution of heat storage in the body at times t_{i-1} and t_i

Annex B: 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-acclimatised subjects;
- a maximum wettedness wmax;
- a maximum sweat rate Swmax;
- consideration of the 50 % ("average" or "median" subject) and the 95 % percentile of the working population (representative of the most susceptible subjects);
- a maximum water loss Dmax;
- a maximum rectal temperature.

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 a 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}, Sw_{max}.

B.3 Maximum skin wettedness, wmax

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, Swmax

The maximum sweat rate can be estimated using the equations:

$Sw_{max} = 2{,}6\ (M - 32)\ X\ A_{Du}$ $\quad g\ h^{-1}$ $\quad$ in the range from 650 $g\ h^{-1}$ to 1 000 $g\ h^{-1}$.

or

$Sw_{max} = (M - 32)\ X\ A_{Du}$ $\quad W\ m^{-2}$ $\quad$ in the range from 250 $W \cdot m^{-2}$ to 400 $W \cdot m^{-2}$

For acclimatized subjects, the maximum sweat rate is, on average, 25 % greater than for un-acclimatized subjects.

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, a rehydration rate of 60 % is observed on average, regardless of the total amount of sweat produced, and is greater than 40 % in 95 % of the cases.

Based on these figures, the maximum water loss is set at

- 7,5 % of the body mass for an average subject (Dmax50), or
- 5 % of the body mass for 95 % of the working population (Dmax95).

Therefore, when the subjects can drink freely (DRINK = 1), the maximum allowable exposure time can be computed for an average subject on the basis of a maximum water loss of 7,5 % of the body mass and on the basis of 5 % of the body mass in order to protect 95 % of the working population.

If no water is provided (DRINK = 0), the total water loss should be limited to 3 %.

B.6 Maximum value of rectal temperature

Following the recommendations of the WHO technical report No 412 (1969) : “It is generally from the rectal temperature that is estimated the time at which it is necessary to interrupt a short duration exposure to intense heat in laboratory”, and “It is inadvisable for deep body temperature to exceed 38 °C in prolonged daily exposure to heavy work”.

When, for a group of workers in a given working conditions, the average rectal temperature is equal to 38 °C, 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 40 years among 1 000 workers) (250 days per year);
- for 39,2 °C less than 10–4 (less than one person at risk among 10 000 shifts).

Annex C: Metabolic rate

Methods for determination of metabolic rate are given in ISO 8996. Tables C.1, C.2 and C.3 depict three different ways (from simple to more accurate) to estimate the metabolic rate for different activities.

Table C.1 — Classification of metabolic rate (in W·m^{-2}) for kinds of activities (modified from ISO 7243[8]). Indicated metabolic rate refers to the average of 60 min of continuous work

C.	W·m^{-2}	Examples
Resting	70	Sitting, standing at rest.
Very light activity	90	Light manual work (writing, typing, drawing); hand work (small bench tools, inspection, assembly or sorting of light materials).
Light activity	115	Arm work (driving vehicle in normal conditions, operating foot switch or pedal); machining with low power tools; light strolling.
Moderate activity	145	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment.
Moderate to high activity	175	Arm and trunk work; work with pneumatic hammer, tractor assembly, intermittent handling of moderately heavy material, pushing or pulling light- weight carts or wheelbarrows, walking at a speed of 4 km/h to 5 km/h; snowmobile driving.
High activity	200	Intense arm and trunk work, carrying heavy material, shovelling; sledgehammer work; cutting trees by chainsaw, hand mowing; digging; walking at a speed of 5 km/h to 6 km/h Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying; snowmobile in heavy terrain.
Very high activity	> 230	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 6 km/h, walking in deep loose snow.

Table C.2 — Metabolic rate (in W·m^{-2}) as a function of area of the body involved and the intensity of the work with that part of the body

Areas of body involved	Work		
	light	medium	heavy
both hands	65	85	95
one arm	100	120	140
both arms	135	150	165
whole body	190	255	345

Table C.3 — Metabolic rate (in W·m^{-2}) for specific activities

Activities			W·m^{-2}
Sleeping			40
At rest, sitting			55
At rest; standing			70
Walking on the level, even path, solid			
1. without load	at 2 km/h at		110
	3 km/h at		140
	4 km/h at		165
	5 km/h		200
2. with load	10 kg, 4 km/h		185
	30 kg, 4 km/h		250
Walking uphill, even path, solid			
1. without load	5° inclination, 4 km/h		180
	15° inclination, 3 km/h		210
	25° inclination, 3 km/h		300
2. with load of 20 kg	15° inclination, 4 km/h		270
	25° inclination, 4 km/h		410
Walking downhill at 5 km/h, without load		5° inclination	135
		15° inclination	140
		25° inclination	180
Ladder at 70° going up at a rate of 11,2 m/min			
	without load		290
	with a 20 kg load		360
Pushing or pulling a tip-wagon, 3,6 km/h, even path, solid			
	pushing force: 12 kg		290
	pulling force: 16 kg		375
Pushing a wheelbarrow, even path, 4,5 km/h, rubber tires, 100 kg load			230
Filing iron	42 file strokes/min		100
	60 file strokes/min		190
Work with a hammer, 2 hands, weight of the hammer 4,4 kg, 15 strokes/min			290
Carpentry work	hand sawing		220
	machine sawing		100
	hand planning		300
Brick-laying, 5 bricks/min			170
Screw driving			100
Digging a trench			290
Work on a machine tool			
	light (adjusting, assembling)		100
	medium (loading)		140
	heavy		210
Work with a hand tool			
	light (light polishing)		100
	medium (polishing)		160
	heavy (heavy drilling)		230

Annex D Clothing thermal characteristics

D.1 General

The thermal characteristics of the clothing that must be considered are

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

D.2 Thermal insulation

The thermal insulation is defined in clo. Table D.1 gives the basic insulation values 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

D.3 Reflection of thermal radiation

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

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

Material	Treatment	F_r
Cotton	with aluminium paint	0,42
Viscose	with glossy aluminium foil	0,19
Aramid (Kevlar)	with glossy aluminium foil	0,14
Wool	with glossy aluminium foil	0,12
Cotton	with glossy aluminium foil	0,04
Viscose	vacuum metallized with aluminium	0,06
Aramid	vacuum metallized with aluminium	0,04
Wool	vacuum metallized with aluminium	0,05
Cotton	vacuum metallized with aluminium	0,05
Glass fiber	vacuum metallized with aluminium	0,07

This reduction 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 vapour pressure of the material, which can be defined by the static moisture permeability index (i_{mst}). As the present International Standard is not applicable to special clothing, a mean value of i_{mst} equal to 0,38 can be adopted.

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 following computer programme are detailed in Table E.1.

An electronic copy of this programme for the predicted heat-strain model calculations can be downloaded from the Web at the following address: http://www.deparisnet.be/chaleur/Chaleur.htm#normes

Table E.1 — Correspondence between the symbols given in Table 1 and those used in the computer programme

Symbol	Symbol in the program
—	defspeed
—	defdir
α	—
α_i	TskTcrwg
α_{i-1}	TskTcrwg0
ε	—
θ	Theta
A_{Du}	Adu
A_p	Ap
A_r	Ardu
C	Conv
c_e	—
$C_{orr,cl}$	CORcl
$C_{orr,Ia}$	CORia
$C_{orr,tot}$	CORtot
$C_{orr,E}$	CORe
c_p	—
C_{res}	Cres
c_{sp}	spHeat
D_{lim}	Dlim
$D_{lim\ tre}$	Dlimtre
$D_{limloss50}$	Dlimloss50
$D_{limloss95}$	Dlimloss95
D_{max}	Dmax
D_{max50}	Dmax50
D_{max95}	Dmax95
DRINK	DRINK
dS_i	dStorage
dS_{eq}	dStoreq
E	—
E_{max}	Emax
E_p	Ep
E_{req}	Ereq
E_{res}	Eres
f_{cl}	fcl
Fcl,R	FclR
Fr	Fr
Hb	height
hcdyn	Hcdyn
hr	Hr
Ia st	Iast
Icl st	Iclst
Icl	Icl
Itot st	Itotst
Ia dyn	Iadyn
Icl dyn	Icldyn
Itot dyn	Itotdyn
imst	imst
imdyn	imdyn
incr	Incr
K	—
M	Met
pa	Pa
psk,s	Psk
R	Rad
rreq	Eveff
Rtdyn	Rtdyn
S	—
Seq	
Swmax	SWmax
Swp	—
Swp,i	SWp
Swp,i–1	SWp0
Swreq	SWreq
t	t
ta	Ta
tcl	Tcl
tcr	Tcr
tcr,eqm	Tcreqm
tcr,eq i	Tcreq
$t_{cr,eq\ i-1}$	Tcreq0
$t_{cr,i}$	Tcr
$t_{cr,i-1}$	Tcr0
t_{ex}	Texp
t_r	Tr
t_{re}	—
$t_{re,\ max}$	—
$t_{re,i}$	Tre
$t_{re,i-1}$	Tre0
$t_{sk,eq}$	Tskeq
$t_{sk,eq\ nu}$	Tskeqnu
$t_{sk,eq\ cl}$	Tskeqcl
$t_{sk,i}$	Tsk
$t_{sk,i-1}$	Tsk0
V	—
v_a	Va
v_w	Walksp
v_{ar}	Var
w	w
W	Work
W_a	—
W_b	weight
W_{ex}	—
w_{max}	wmax
w_p	wp
w_{req}	wreq

E.2 Programme

```
'                     Predicted Heat Strain (PHS) model:
'               computation programme written in Quick Basic

'       This programme was developed by Prof. J. Malchaire,
'       Director of the Occupational Hygiene and Work Physiology Unit
'       University of Louvain in Belgium.
'       Clos Chapelle-aux-Champs 30-38, 1200  Bruxelles
'       E-mail: jacques.malchaireclouvain.be
'       Site www.deparisnet.be

' INITIALISATION
       CLS
'       The user must make sure that, at this point in the programme,
'       the following parameters are available.
'       Standard values must be replaced by actual values if necessary.
'     The water replacement is supposed to be sufficient so that the
'       workers can drink freely (DRINK=1), otherwise the value DRINK=0
'       must be used

       Drink = 1
     weight = 75: '  body mass       kilogrammes
       height = 1.8: '  body height     meters
       Adu = .202 * weight ^ .425 * height ^ .725
       spHeat = 57.83 * weight / Adu

       SWp = 0
       SWtot = 0: Tre = 36.8: Tcr = 36.8: Tsk = 34.1: Tcreq = 36.8: TskTcrwg = .3
       Dlimtre = 0: Dlimloss50 = 0: Dlimloss95 = 0
       Dmax50 = .075 * weight * 1000
       Dmax95 = .05 * weight * 1000

' EXPONENTIAL AVERAGING CONSTANTS
' Core temperature as a function of the metabolic rate: time constant: 10 minutes
       ConstTeq = EXP(-1 / 10)
' Skin Temperature: time constant: 3 minutes
       ConstTsk = EXP(-1 / 3)
' Sweat rate: time constant: 10 minutes
       ConstSW = EXP(-1 / 10)

Duration = 480: 'the duration of the work sequence in minutes

FOR time = 1 TO Duration
' INITIALISATION MIN PER MIN
Tsk0 = Tsk: Tre0 = Tre: Tcr0 = Tcr: Tcreq0 = Tcreq: TskTcrwg0 = TskTcrwg

' INPUT OF THE PRIMARY PARAMETERS
' The user must 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 the ISO 7933 standard are introduced.

Ta = 40: 'air temperature degrees celsius
Tr = 40: 'mean radiant temperature        degrees celsius
Pa = 2.5: 'partial water vapour pressure   kilopascals
Va = .3:   'air velocity    metres per second
Met = 150: 'metabolic rate  Watts per square meter
Work = 0: 'effective mechanical power      Watts per square metre
'Posture posture = 1 sitting, =2 standing, =3 crouching
posture = 2
Icl = .5:  'static  thermal insulation             clo
imst = .38: 'static moisture permeability index    dimensionless
Ap = .54: 'fraction of the body surface covered
        'by the reflective clothing             dimensionless
Fr = .97: 'emissivity of the reflective clothing   dimensionless
        '(by default: Fr=0.97)
'Ardu dimensionless
defspeed = 0: 'code =1 if walking speed entered, 0 otherwise
Walksp = 0: 'walking speed   metres per second
defdir = 0: 'code =1 if walking direction entered, 0 otherwise
THETA = 0: 'angle between walking direction and wind direction       degrees
accl = 100: 'code =100  if acclimatised subject, 0 otherwise

' Effective radiating area of the body
      IF posture = 1 THEN Ardu = .7
      IF posture = 2 THEN Ardu = .77
      IF posture = 3 THEN Ardu = .67

' EVALUATION OF THE MAXIMUM SWEAT RATE AS A FUNCTION OF THE METABOLIC
    RATE
      SWmax = (Met - 32) * Adu
      IF SWmax > 400 THEN SWmax = 400
      IF SWmax < 250 THEN SWmax = 250
' For acclimatised subjects (accl=100), the maximum Sweat Rate is greater by 25%
      IF accl >= 50 THEN SWmax = SWmax * 1.25
      IF accl < 50 THEN Wmax = .85 ELSE Wmax = 1

' EQUILIBRIUM CORE TEMPERATURE ASSOCIATED TO THE METABOLIC RATE
      Tcreqm = .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 = spHeat * (Tcreq - Tcreq0) * (1 - TskTcrwg0)

' SKIN TEMPERATURE PREDICTION
' Skin Temperature in equilibrium
' Clothed model
```

```
        Tskeqcl = 12.165 + .02017 * Ta + .04361 * Tr + .19354 * Pa - .25315 * Va
        Tskeqcl = Tskeqcl + .005346 * Met + .51274 * Tre
' Nude model
        Tskeqnu = 7.191 + .064 * Ta + .061 * Tr + .198 * Pa - .348 * Va
        Tskeqnu = Tskeqnu + .616 * Tre
' Value at this minute, as a function of the clothing insulation
        IF Icl >= .6 THEN Tskeq = Tskeqcl: GOTO Tsk
        IF Icl <= .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 - .2)
' Skin Temperature at this minute, by exponential averaging
Tsk:
        Tsk = Tsk0 * ConstTsk + Tskeq * (1 - ConstTsk)
' Saturated water vapour pressure at the surface of the skin
        Psk = .6105 * EXP(17.27 * Tsk / (Tsk + 237.3))

' CLOTHING INFLUENCE ON EXCHANGE COEFFICIENTS
' Static clothing insulation
        Iclst = Icl * .155
' Clothing area factor
        fcl = 1 + .3 * Icl
' Static boundary layer thermal insulation in quiet air
        Iast = .111
' Total static insulation
        Itotst = Iclst + Iast / fcl

' Relative velocities due to air velocity and movements
        IF defspeed > 0 THEN
                IF defdir = 1 THEN
                ' Unidirectional walking
                        Var = ABS(Va - Walksp * COS(3.14159 * THETA / 180))
                ELSE
                ' Omni-directional walking
                        IF Va < Walksp THEN Var = Walksp ELSE Var = Va
                END IF
        ELSE
                ' Stationary or undefined speed
                Walksp = .0052 * (Met - 58): IF Walksp > .7 THEN Walksp = .7
                Var = Va
        END IF

' Dynamic clothing insulation
' Clothing insulation correction for wind (Var) and walking (Walksp)
        Vaux = Var: IF Var > 3 THEN Vaux = 3
        Waux = Walksp: IF Walksp > 1.5 THEN Waux = 1.5
        CORcl = 1.044 * EXP((.066 * Vaux - .398) * Vaux + (.094 * Waux - .378) * Waux)
        IF CORcl > 1 THEN CORcl = 1
        CORia = EXP((.047 * Var - .472) * Var + (.117 * Waux - .342) * Waux)
        IF CORia > 1 THEN CORia = 1
```

```
        CORtot = CORcl
        IF Icl <= .6 THEN CORtot = ((.6 - Icl) * CORia + Icl * CORcl) / .6

        Itotdyn = Itotst * CORtot
        IAdyn = CORia * Iast
        Icldyn = Itotdyn - IAdyn / fcl

' Permeability index
' Correction for wind and walking
        CORe = (2.6 * CORtot - 6.5) * CORtot + 4.9
        imdyn = imst * CORe: IF imdyn > .9 THEN imdyn = .9
' Dynamic evaporative resistance
        Rtdyn = Itotdyn / imdyn / 16.7

' HEAT EXCHANGES
' Heat exchanges through respiratory convection and evaporation
        ' temperature of the expired air
        Texp = 28.56 + .115 * Ta + .641 * Pa
        Cres = .001516 * Met * (Texp - Ta)
        Eres = .00127 * Met * (59.34 + .53 * Ta - 11.63 * Pa)

'  Mean temperature of the clothing: Tcl
' Dynamic convection coefficient
        Z = 3.5 + 5.2 * Var
        IF Var > 1 THEN Z = 8.7 * Var ^ .6
        Hcdyn = 2.38 * ABS(Tsk - Ta) ^ .25
        IF Z > Hcdyn THEN Hcdyn = Z

        auxR = 5.67E-08 * Ardu
        FclR = (1 - Ap) * .97 + Ap * Fr
        Tcl = Tr + .1
Tcl:
' 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) > .001 THEN
                Tcl = (Tcl + Tcl1) / 2
                GOTO Tcl
        END IF

' Convection and Radiation heat exchanges
        Conv = fcl * Hcdyn * (Tcl - Ta)
        Rad = fcl * Hr * (Tcl - Tr)
' Maximum Evaporation Rate
        Emax = (Psk - Pa) / Rtdyn
' Required Evaporation Rate
        Ereq = Met - dStoreq - Work - Cres - Eres - Conv - Rad
```

```
' INTERPRETATION
' Required wettedness
        wreq = Ereq / Emax

' Required Sweat Rate
'     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
'     Required evaporation efficiency
        Eveff = (1 - wreq ^ 2 / 2)
        IF wreq > 1 THEN Eveff = (2 - wreq) ^ 2 / 2
        SWreq = Ereq / Eveff
        IF SWreq > SWmax THEN SWreq = SWmax

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 >= .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 = .3 - .09 * (Tcr1 - 36.8)
        IF TskTcrwg > .3 THEN TskTcrwg = .3
        IF TskTcrwg < .1 THEN TskTcrwg = .1

        Tcr = dStorage / spHeat + Tsk0 * TskTcrwg0 / 2 - Tsk * TskTcrwg / 2
        Tcr = (Tcr + Tcr0 * (1 - TskTcrwg0 / 2)) / (1 - TskTcrwg / 2)
        IF ABS(Tcr - Tcr1) > .001 THEN
        Tcr1 = (Tcr1 + Tcr) / 2: GOTO TskTcr
END IF

' PREDICTION OF THE RECTAL TEMPERATURE
        Tre = Tre0 + (2 * Tcr - 1.962 * Tre0 - 1.31) / 9
```

```
        IF Dlimtre = 0 AND Tre >= 38 THEN Dlimtre = time

' Total water loss rate during the minute (in W m-²)
        SWtot = SWtot + SWp + Eres
        SWtotg = SWtot * 2.67 * Adu / 1.8 / 60
        IF Dlimloss50 = 0 AND SWtotg >= Dmax50 THEN Dlimloss50 = time
        IF Dlimloss95 = 0 AND SWtotg >= Dmax95 THEN Dlimloss95 = time
      IF DRINK =0 then Dlimloss95 = Dlimloss95 * 0.6: Dlimloss50 = Dlimloss95

' End of loop on duration

NEXT time

'Dlim computation
        IF Dlimloss50 = 0 THEN Dlimloss50 = Duration
        IF Dlimloss95 = 0 THEN Dlimloss95 = Duration
        IF Dlimtre = 0 THEN Dlimtre = Duration


PRINT "tre="; Tre
PRINT "SWtotg="; SWtotg
PRINT "Dlimtre="; Dlimtre
PRINT "Dlimloss50="; Dlimloss50
PRINT "Dlimloss95="; Dlimloss95

END
```

Annex F:
Examples of the Predicted Heat Strain Model computations

This annex provides the primary data and the main output data for 10 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 rectal temperature and 1 % for water loss.
These 10 conditions were selected in order to tests all the different components of the programme.

Parameters (units)	Examples of working conditions									
	1	2	3	4	5	6	7	8	9	10
Acclimatized	Yes	Yes	Yes	No	No	Yes	No	No	Yes	Yes
Posture	Standing	Standing	Standing	Standing	Sitting	Sitting	Standing	Standing	Standing	Standing
t_a (°C)	40	35	30	28	35	43	35	34	40	40
p_a (kPa)	2,5	4,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
t_r (°C)	40	35	50	58	35	43	35	34	40	40
v_a ($m{\cdot}s^{-1}$)	0,3	0,3	0,3	0,3	1,0	0,3	0,3	0,3	0,3	0,3
M ($W{\cdot}m^{-2}$)	150	150	150	150	150	103	206	150	150	150
I_{cl} (clo)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1,0	0,4	0,4
θ (degrees)	0	0	0	0	0	0	0	0	0	90
Walk speed($m{\cdot}s^{-1}$)	0	0	0	0	0	0	0	0	0	1
Final t_{re} (°C)	37,5	39,8	37,7	41,2	37,6	37,3	39,2	41,0	37,5	37,6
Water loss (g)	6168	6935	7166	5807	3892	6763	7236	5548	6684	5379
$D_{lim\ tre}$ (min)	480	74	480	57	480	480	70	67	480	480
$D_{limloss50}$ (min)	439	385	380	466	480	401	372	480	407	480
$D_{limloss95}$ (min)	298	256	258	314	463	271	247	318	276	339

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