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Evaluation of cold environments — Determination of required clothing insulation (IREQ)

Évaluation des ambiances froides — Détermination de l'isolement requis des vêtements

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 11079, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Sub-Committee SC 5, *Ergonomics of the physical environments*.

A series of International Standards related to the assessment of thermal environments are being produced within the framework of ISO/TC 159/SC5. For cold environments there are few methods available, insufficient experimental support and limited practical experience. More experimental work is needed to validate and further elaborate the methods contained in this Technical Report before there is a basis for the development of an International Standard.

This document is being issued in the type 2 Technical Report series of publications (according to subclause G.4.2.2 of part 1 of the ISO/IEC Directives, 1992) as a "prospective standard for provisional application" in the field of assessment of thermal environments because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this type 2 Technical Report will be carried out not later than two years after its publication with the options of: extension for another two years; conversion into an International Standard; or withdrawal.

Annexes A and B form an integral part of this Technical Report. Annexes C, D, E, F and G are for information only.

Introduction

Wind-chill is commonly encountered in cold climates, but low temperatures first of all endanger body heat balance. By proper adjustment of clothing, man can often control and regulate body heat loss to balance a change in the ambient climate. The method presented here is therefore based on the evaluation of the clothing insulation required to maintain in equilibrium the thermal balance of the body. The heat balance equation used takes into account the most recent scientific findings concerning heat exchanges at the surface of the skin as well as the clothing.

Evaluation of cold environments — Determination of required clothing insulation (IREQ)

1 Scope

This Technical Report proposes methods and strategies to assess the thermal stress associated with exposure to cold environments. They apply to continuous, intermittent and occasional exposure and in both indoor and outdoor work. Specific effects associated with certain meteorological phenomena (e.g. precipitation) are not covered and should be assessed by other methods.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Technical Report. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Technical Report are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7726:1985, *Thermal environments — Instruments and methods for measuring physical quantities.*

ISO 7730:1984, *Moderate thermal environments — Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.*

ISO 8996:1990, *Ergonomics — Determination of metabolic heat production.*

ISO 9920:—[1)], *Ergonomics of the thermal environment — Estimation of the thermal insulation and evaporative resistance of a clothing ensemble.*

1) To be published.

3 Symbols and abbreviations

A_{du} body surface area, in square metres (m^2)

A_r body surface area partaking in radiation heat exchange, in square metres (m^2)

C convective heat exchange, in watts per square metre (W/m^2)

c_e latent heat of evaporation, in joules per kilogram

c_p specific heat of dry air at constant pressure, in joules per kilogram of dry air

C_{res} respiratory convective heat exchange, in watts per square metre (W/m^2)

DLE duration limited exposure, in hours (h)

E evaporative heat exchange by sweating, in watts per square metre (W/m^2)

E_{res} respiratory evaporative heat exchange, in watts per square metre (W/m^2)

f_{cl} ratio of surface area of the clothed body to the surface area of the nude body, dimensionless

h_c convective heat transfer coefficient, in watts per square metre degree Celsius ($W/m^2 \cdot °C$)

h_r radiation heat transfer coefficient, in watts per square metre degree Celsius ($W/m^2 \cdot °C$)

I_a	boundary air layer insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
I_{cl}	basic clothing insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
I_{clr}	resultant clothing insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
I_T	total insulation of clothing and boundary air layer, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
I_{Tr}	resultant total insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
i_m	Woodcock permeability index, dimensionless
IREQ	required clothing insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
$IREQ_{min}$	minimal required clothing insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
$IREQ_{neutral}$	neutral required clothing insulation, in square metre degrees Celsius per watt ($m^2 \cdot °C/W$)
K	conductive heat exchange, in watts per square metre (W/m^2)
M	metabolic power, in watts per square metre (W/m^2)
p_a	ambient water vapour pressure, in kilopascals (kPa)
p_{ex}	saturated water vapour pressure at expired air temperature, in degrees Celsius (°C)
p_{sk}	water vapour pressure at skin temperature, in kilopascals (kPa)
p_{sks}	saturated water vapour pressure at skin temperature, in kilopascals (kPa)
Q	body heat gain or loss, in watt hours per square metre ($W \cdot h/m^2$)
Q_{lim}	limit value for Q, in watt hours per square metre ($W \cdot h/m^2$)
R	radiation heat exchange, in watts per square metre (W/m^2)
R_T	resultant evaporative resistance of clothing and boundary air layer, in square metre kilopascals per watt ($m^2 \cdot kPa/W$)
RT	recovery time, in hours (h)
S	rate of change in body heat content, in watts per square metre (W/m^2)
t_a	ambient air temperature, in degrees Celsius (°C)
t_{ch}	chilling temperature, in degrees Celsius (°C)
$\bar{t}_{cl}$	clothing surface temperature, in degrees Celsius (°C)
t_{ex}	expired air temperature, in degrees Celsius (°C)
t_o	operative temperature, in degrees Celsius (°C)
$\bar{t}_r$	mean radiant temperature of the environment, in degrees Celsius (°C)
t_{sk}	local skin temperature, in degrees Celsius (°C)
$\bar{t}_{sk}$	mean skin temperature, in degrees Celsius (°C)
V	ventilation rate, in kilograms per second (kg/s)
v_a	air velocity, in metres per second (m/s)
v_{ar}	relative air velocity, in metres per second (m/s)
W	effective mechanical power, in watts per square metre (W/m^2)
w	skin wettedness, the equivalent fraction of the skin surface which can be considered as fully wet, dimensionless
W_a	humidity ratio of inhaled air, in kilograms of water per kilogram of dry air
W_{ex}	humidity ratio of exhaled air, in kilograms of water per kilogram of dry air
WCI	wind chill index, watts per square metre (W/m^2)

4 Principles of methods for evaluation

Cold stress is suggested to be evaluated in terms of both general cooling of the body and local cooling of particular parts of the body (e.g. extremities and face).

For general cooling, an analytical method is presented in clause 5 for the evaluation and interpretation of the thermal stress. It is based on a calculation of the body heat exchange and of the required clothing insulation (IREQ) for the maintenance of thermal equilibrium.

For local cooling, several methods are proposed in clause 6 for the evaluation of local thermal effects, e.g. cold injury or cold hands.

The scientific basis of each of the proposed methods in this Technical Report can be found in the relevant publications cited in annex G.

5 General cooling

A general equation for body heat balance is defined. In this equation, clothing thermal properties, body heat production and physical characteristics of the environment are the determinant factors. The equation is solved for the required clothing insulation (IREQ) for maintained heat balance under specified criteria of physiological strain. As there is an upper limit for the amount of insulation clothing can provide, a duration limited exposure (DLE) is calculated for the existing clothing insulation on the basis of acceptable levels of body cooling. Detailed equations, coefficients and criteria are proposed in annexes A and B.

The method involves the following steps, outlined schematically in figure 1:

— measurements of the thermal parameters of the environment;

— determination of activity level (metabolic rate);

— calculation of required clothing insulation (IREQ);

— comparison with insulation provided by existing clothing;

— evaluation of the conditions for thermal balance and calculation of recommended maximal exposure time (DLE).

5.1 Definition of required insulations, IREQ

IREQ is defined as the resultant clothing insulation required during the actual environmental conditions to maintain the body in a state of thermal equilibrium at acceptable levels of body and skin temperatures.

IREQ can be applied as

— a measure of cold stress integrating the effects of air temperature, mean radiant temperature, humidity, air velocity and metabolic heat production;

— a method for the analysis of effects of specific parameters and evaluation of measures of improvement;

— a method for specification of clothing insulation requirements and the subsequent selection of clothing to be used under the prevailing environmental conditions.

5.2 Calculating of factors affecting IREQ

Calculation of IREQ is based on a rational analysis of man's heat exchange with the environment. The following subclauses review the general principles for calculation of the various factors affecting IREQ.

5.2.1 General heat balance equation

The general heat balance equation is as follows:

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

where the left hand side of the equation represents the internal heat production, which is balanced by the right hand side which represents the sum of heat exchanges in the respiratory tract, heat exchanges on the skin and the heat storage accumulating in the body.

5.2.2 Metabolic power

M is the metabolic power and is evaluated using methods specified in ISO 8996.

5.2.3 Effective mechanical power

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

5.2.4 Respiratory heat exchange

Heat is lost from the respiratory tract by warming and saturating inspired air and is the sum of convective heat loss (C_{res}) and evaporative heat loss (E_{res}), determined, respectively, by

$$C_{res} = c_p\, V(t_{ex} - t_a)/A_{du} \qquad \ldots (2)$$

and

$$E_{res} = c_e\, V(W_{ex} - W_a)/A_{du} \qquad \ldots (3)$$

5.2.5 Evaporative heat exchange

The evaporative heat exchange, E, is defined by

$$E = w(p_{sks} - p_a)/R_T \qquad \ldots (4)$$

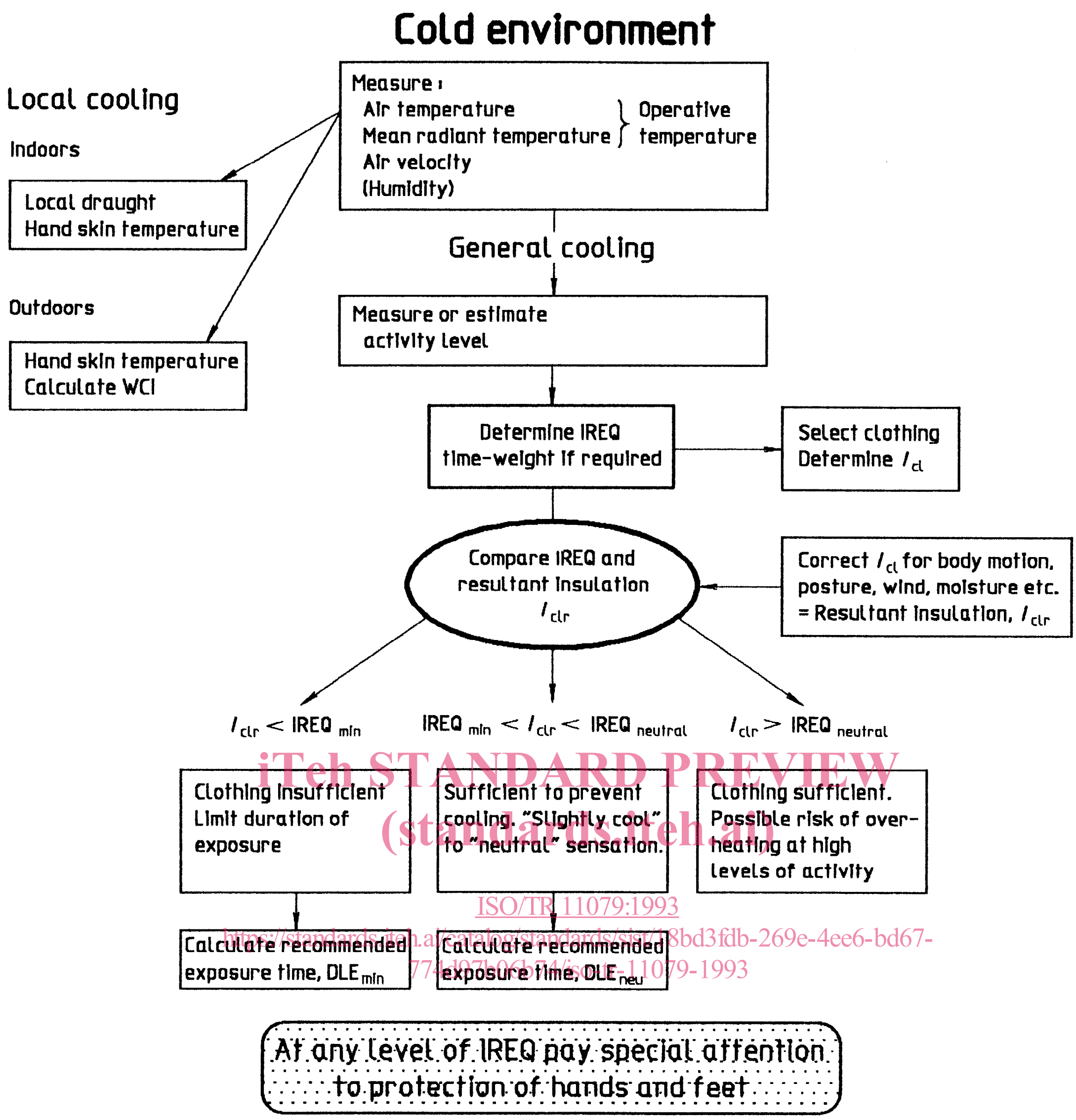

Figure 1 — Procedure for the evaluation of cold environments

5.2.6 Conductive heat exchange

Conductive heat exchange is related to the area of body parts in direct contact with external surfaces. Although it can be of significant importance for local heat balance, conductive heat exchange is mostly small and can be accounted for by the expressions for convective and radiation heat exchange.

5.2.7 Convective exchange

The heat exchange by convection between the clothing surface including uncovered skin and the environment, C, is defined by

$$C = f_{cl}\, h_c (t_{cl} - t_a) \qquad \ldots (5)$$

5.2.8 Radiation heat exchange

The radiation heat exchange between the clothing surface including uncovered skin and the environment, R, is defined by

$$R = f_{cl}\, h_r (t_{cl} - \bar{t}_r) \qquad \ldots (6)$$

5.2.9 Heat exchange through clothing

Heat exchange through clothing takes place by conduction, convection and radiation (dry heat exchange) and by the transfer of evaporated sweat (latent heat). The effect of clothing on latent heat exchange is accounted for in equation (4). The effect of clothing on dry heat exchange is determined by the thermal insulation of the clothing ensemble and the skin to clothing surface temperature gradient. Dry heat flow to the clothing surface is equivalent to the heat transfer between the clothing surface and the environment. Heat exchange through clothing, therefore, can be expressed in terms of the factual, resultant, thermal insulation of the clothing, I_{clr}, as follows:

$$\frac{\bar{t}_{sk} - t_{cl}}{I_{clr}} = R + C = M - W - E_{res} - C_{res} - E \qquad \ldots (7)$$

5.3 Calculation of IREQ

On the basis of equations (1) to (7) and using the hypothesis made concerning heat flow by conduction, the required clothing insulation, IREQ, can now be calculated on the basis of the following two equations:

$$\text{IREQ} = \frac{\bar{t}_{sk} - t_{cl}}{M - W - E_{res} - C_{res} - E} \qquad \ldots (8)$$

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

Equation (8) expresses the dry heat exchange at the clothing surface and is rewritten from equation (7). Equation (9) states that the dry heat exchange must balance the internal heat production minus evaporative and respiratory heat losses and is rewritten from equation (7).

Equation (8) contains two unknown variables (IREQ and t_{cl}). Therefore, equation (8) is solved for t_{cl} as follows:

$$t_{cl} = \bar{t}_{sk} - \text{IREQ}\,(M - W - E_{res} - C_{res} - E) \ldots (10)$$

This expression replaces t_{cl} in the computation formulas for the variables in equation (9), where the formulas for R and C contain t_{cl} [see equations (5) and (6)]. The value of IREQ that satisfies equation (9) is then calculated by iteration. A computer program is provided in annex F for this purpose. IREQ is expressed in square metre degrees Celsius per watt $(m^2 \cdot °C/W)$. It may also be expressed in clo-units $(1 \text{ clo} = 0{,}155\ m^2 \cdot °C/W)$.

5.4 Interpretation of IREQ

5.4.1 IREQ as a cold index

IREQ is a measure of the thermal stress presented by the combined effects of internal heat production and heat exchange with the environment. The greater the cooling power of the environment, the higher is the value of IREQ at any given activity level. At any given set of climatic conditions, cold stress, and thereby IREQ, is reduced with increasing activity due to the extra demand for dissipation of metabolic heat.

5.4.2 IREQ and physiological strain

Thermal equilibrium can be achieved at different levels of thermoregulatory strain, defined in terms of values for mean skin temperature, sweating (skin wettedness) and change in body heat content. It is suggested that IREQ be defined at two levels of physiological strain.

a) IREQ_{min} defines a minimal thermal insulation required to maintain body thermal equilibrium at a subnormal level of mean body temperature. The minimal IREQ represents the highest admissible body cooling in occupational work.

b) $\text{IREQ}_{neutral}$ is defined as the thermal insulation required to provide conditions of thermal neutrality, i.e. thermal equilibrium maintained at a normal level of mean body temperature. This level represents no or minimal cooling of the human body.

Relevant physiological criteria are presented and discussed in annex B.

5.4.3 IREQ and existing clothing insulation

IREQ is the resultant clothing insulation value that is required for the actual conditions. It may, therefore, serve as a guideline for the selection of appropriate clothing by a comparison with measured insulation values of ensembles. Almost all thermal insulation values reported for existing clothing ensembles are measured with a static, thermal manikin and defined as basic insulation values, I_{cl}. Their protective value during wear and to what extent they compare with IREQ, can only be judged by determining their resultant insulation (I_{clr}). This subject is dealt with in annex C.

The interval between IREQ_{min} and $\text{IREQ}_{neutral}$ can be regarded as a clothing regulatory zone, in which each individual chooses the appropriate protection level. With insulation values lower than IREQ_{min} there is a risk of progressive body cooling. With values higher than $\text{IREQ}_{neutral}$, conditions will be considered warm and overheating can occur.

5.5 Definition and calculation of duration limited exposure, DLE

When the resultant insulation value of the selected clothing ensemble (I_{clr}) is less than the calculated required insulation (IREQ), exposure has to be time-limited to prevent progressive body cooling. A certain reduction in body heat content (Q) is acceptable during an exposure of a few hours and can be used to calculate the duration of exposure when the rate of heat storage is known.

Duration limited exposure (DLE) to cold, is defined as the recommended maximum time of exposure with available or selected clothing. DLE is calculated by the following formula

$$\mathrm{DLE} = Q_{\mathrm{lim}}/S \qquad \ldots (11)$$

where Q_{lim} is the limit value of Q and S is calculated from equation (12), in which t_{cl} is substituted for the expression in equation (13). Available insulation (I_{clr}) replaces IREQ and is used to calculate t_{cl} and S. The equation is then solved by mathematical iteration.

$$S = M - W - C_{res} - E_{res} - E - R - C \qquad \ldots (12)$$

$$t_{\mathrm{cl}} = \bar{t}_{\mathrm{sk}} - I_{\mathrm{clr}}(M - W - C_{res} - E_{res} - E - S) \ldots (13)$$

DLE may be calculated for both levels of strain (see 5.4.2). The same amount of reduction in body heat content is applied. However, the deficit in thermal insulation between selected clothing and $\mathrm{IREQ}_{\mathrm{min}}$ is always smaller than between selected clothing and $\mathrm{IREQ}_{\mathrm{neutral}}$. Accordingly, the exposure (DLE) becomes longer at a higher level of strain for $\mathrm{IREQ}_{\mathrm{min}}$. If, at the onset of exposure, the worker has adopted a certain heat debt, the exposure time should be reduced accordingly.

After exposure, a recovery period should be allowed to restore normal body heat balance. Recovery time (RT) is calculated in the same way as DLE, substituting the “cold conditions” with the exposure conditions during the recovery period. In other words, $\mathrm{RT} = Q_{\mathrm{lim}}/S'$, where S' is the rate of heat storage (positive) calculated from equations (12) and (13) for the exposure conditions during the recovery period. Since recovery is supposed to start when the body has achieved a certain heat debt, the value of Q_{lim} should be the same when calculating RT.

The physiological criteria to be used are presented in annex B and examples of the application of DLE and RT in annex D.

6 Local cooling

Local cooling of any part of the body with emphasis on hands, feet and head, can produce discomfort, deterioration of manual and physical performance and cold injury. The amount of knowledge on responses to local cooling is insufficient for the development of a single evaluation method. Several approaches are proposed and more research work is encouraged on the subject.

Effects of local cooling should be evaluated separately for indoor and outdoor conditions. The indoor thermal environment is relatively easily modified by engineering techniques, whereas the outdoor environment is determined by weather and climate, and protective measures mostly comprise adjustment of clothing or control of exposure. At very low temperatures, respiratory and eye protection can be required.

6.1 Indoor conditions

Light, stationary work makes a person more prone to unpleasant effects of local cooling, caused by draught or radiation heat loss to cold surfaces, for example. Evaluation of discomfort due to these factors should be based on the same criteria as for moderate thermal environments (ISO 7730). In addition, a physiological criteria related to hand skin temperature is applied.

6.2 Outdoor conditions

For outdoor conditions, cold stress is determined by calculating the local cooling effect of wind, i.e. the wind-chill. As a complement, measurements of hand skin temperature are used.

6.2.1 Definition and calculation of wind-chill

The wind-chill index (WCI) is defined as the rate of heat loss from an unprotected skin surface area. It is given by the general equation:

$$\mathrm{WCI} = (h_{\mathrm{c}} + h_{\mathrm{r}})(t_{\mathrm{sk}} - t_{\mathrm{a}}) \qquad \ldots (14)$$

where the values of the coefficients h_{c} and h_{r} are those for a local skin segment. The value of h_{r} is almost constant and independent of the wind and becomes small in relation to h_{c} at high air velocities. The expression to be used for the heat transfer coefficients and examples of the evaluation of WCI and t_{ch} are presented in annex D.

7 Practical assessment of cold environments

7.1 Procedure for the determination of IREQ

The procedure for the assessment of cold environments is shown schematically in figure 1 and is as follows:

a) Measure the following climate parameters according to ISO 7726:

1) air temperature;

2) mean radiant temperature;

3) air velocity; and

4) humidity.

The operative temperature may replace air and mean radiant temperatures. The water content of air at low temperatures is very small, so a standard value of 50 % relative humidity may be used below − 5 °C.

b) Determine the metabolic heat production in accordance with ISO 8996.

c) Determine the required clothing insulation (IREQ) from 5.3 or by reading directly from the graphs in figures 2 to 6. With intermittent exposure or activity (e.g. fixed work-rest regimens), IREQ is calculated for each different work and rest period and the time-weighted average for continuous periods is calculated. The continuous period shall not be less than 1 h and shall not exceed 2 h, depending on organization and nature of work.

d) Determine the basic clothing insulation (I_{cl}) of the selected or available clothing ensemble by measurements or from tables (see ISO 9920 and annex C). Calculate the resultant insulation (I_{clr}) on the basis of I_{cl} to account for the effect of body motion, posture and wind (see annex C). A representative value of I_{clr} may also be obtained from measurements according to prEN-342.

e) Evaluate the conditions for heat balance on the basis of a comparison of IREQ and I_{clr}. There are three possible situations:

1) $I_{clr} < \text{IREQ}_{min}$

Selected clothing ensemble does not provide adequate insulation to prevent body cooling. There is an increasing risk of hypothermia with progressive exposure.

2) $\text{IREQ}_{min} \leqslant I_{clr} \leqslant \text{IREQ}_{neutral}$

Selected clothing ensemble provides sufficient insulation. The level of physiological strain is acceptable and the thermal conditions are perceived as "slightly cold" or "neutral".

3) $I_{clr} > \text{IREQ}_{neutral}$

Selected clothing ensemble provides more than sufficient insulation. Too much insulation may increase the risk of overheating, excessive sweating and moisture absorption by clothing and a prospective risk of progressive hypothermia.

f) If IREQ cannot be met, a recommended maximal exposure time (DLE) and a required recovery time (RT) with available insulation shall be calculated. DLE and RT may be calculated for conditions imposing high as well as low physiological strain (see 5.5 and figures 7 to 11).

g) At any level of IREQ, special attention should be paid to risks of local cooling of the face, hands and feet, for example. This problem is dealt with in clause 6.