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Ergonomics of the thermal environment — Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects

Ergonomie des ambiances thermiques — Détermination et interprétation de la contrainte liée au froid en utilisant l'isolement thermique requis du vêtement (IREQ) et les effets du refroidissement local

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 11079 was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 5, *Ergonomics of the physical environment*.

This first edition of ISO 11079 cancels and replaces the ISO/TR 11079:1993, of which it constitutes a technical revision.

Introduction

Wind chill is commonly encountered in cold climates, but it is low temperatures that first of all endanger body heat balance. By proper adjustment of clothing, human beings can often control and regulate body heat loss, to balance a change in the ambient climate. The method presented here is based therefore on the evaluation of the clothing insulation required to maintain the thermal balance of the body in equilibrium. 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.

Ergonomics of the thermal environment — Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects

1 Scope

This International Standard specifies methods and strategies for assessing the thermal stress associated with exposure to cold environments. These methods apply to continuous, intermittent as well as occasional exposure and type of work, indoors and outdoors. They are not applicable to specific effects associated with certain meteorological phenomena (e.g. precipitation), which are assessed by other methods.

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 9237, *Textiles — Determination of permeability of fabrics to air*

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 13732-3, *Ergonomics of the thermal environment — Methods for the assessment of human responses to contact with surfaces — Part 3: Cold surfaces*

ISO 15831, *Clothing — Physiological effects — Measurement of thermal insulation by means of a thermal manikin*

EN 511, *Protective gloves against cold*

3 Terms, definitions and symbols

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

3.1 Terms and definitions

3.1.1
cold stress
climatic conditions under which the body heat exchange is just equal to or too large for heat balance at the expense of significant and sometimes uncompensable physiological strain (heat debt)

3.1.2
heat stress
climatic conditions under which the body heat exchange is just equal to or too small for heat balance at the expense of significant and sometimes uncompensable physiological strain (heat storage)

3.1.3
IREQ
required clothing insulation for the preservation of body heat balance at defined levels of physiological strain

3.1.4
thermoneutral zone
temperature interval within which the body maintains heat balance exclusively by vasomotor reactions

3.1.5
wind chill temperature
temperature related to the cooling effect on a local skin segment

3.2 Symbols

A_{Du}	Dubois body surface area, m^2
ap	air permeability, l · m^{-2} · s^{-1}
C	convective heat flow (exchange), W · m^{-2}
c_{e}	water latent heat of vaporization, J · kg^{-1}
c_{p}	specific heat of dry air at constant pressure, J · kg^{-1} · K^{-1}
C_{res}	respiratory convective heat flow (loss), W · m^{-2}
D_{lim}	duration limited exposure, h
D_{rec}	recovery time, h
E	evaporative heat flow (exchange) at the skin, W · m^{-2}
E_{res}	respiratory evaporative heat flow (loss), W · m^{-2}
f_{cl}	clothing area factor, dimensionless
h_{c}	convective heat transfer coefficient, W · m^{-2} · K^{-1}
h_{r}	radiative heat transfer coefficient, W · m^{-2} · K^{-1}
I_{a}	boundary layer thermal insulation, m^2 · K · W^{-1}
$I_{\mathrm{a,r}}$	resultant boundary layer thermal insulation, m^2 · K · W^{-1}

I_{cl}	basic clothing insulation, $m^2 \cdot K \cdot W^{-1}$
$I_{cl,r}$	resultant clothing insulation, $m^2 \cdot K \cdot W^{-1}$
I_T	basic total insulation, $m^2 \cdot K \cdot W^{-1}$
$I_{T,r}$	resultant total insulation, $m^2 \cdot K \cdot W^{-1}$
i_m	moisture permeability index, dimensionless
IREQ	required clothing insulation, $m^2 \cdot K \cdot W^{-1}$
IREQ_{min}	minimal required clothing insulation, $m^2 \cdot K \cdot W^{-1}$
$\text{IREQ}_{neutral}$	neutral required clothing insulation, $m^2 \cdot K \cdot W^{-1}$
K	conductive heat flow (exchange), $W \cdot m^{-2}$
M	metabolic rate, $W \cdot m^{-2}$
p_a	water vapour partial pressure, kPa
p_{ex}	saturated water vapour pressure at expired air temperature, kPa
p_{sk}	water vapour pressure at skin temperature, kPa
$p_{sk,s}$	saturated water vapour pressure at the skin surface, kPa
Q	body heat gain or loss, $kJ \cdot m^{-2}$
Q_{lim}	limit value for Q, $kJ \cdot m^{-2}$
R	radiative heat flow (exchange), $W \cdot m^{-2}$
$R_{e,T}$	total evaporative resistance of clothing and boundary air layer, $m^2 \cdot kPa \cdot W^{-1}$
S	body heat storage rate, $W \cdot m^{-2}$
t_a	air temperature, °C
t_{cl}	clothing surface temperature, °C
t_{ex}	expired air temperature, °C
t_o	operative temperature, °C
t_r	radiant temperature
t_{sk}	local skin temperature, °C
$\bar{t}_{sk}$	mean skin temperature, °C
t_{WC}	wind chill temperature, °C
V	respiratory ventilation rate, kg air $\cdot s^{-1}$
v_{10}	wind speed measured 10 m above ground level, $m \cdot s^{-1}$
v_a	air velocity, $m \cdot s^{-1}$
v_w	walking speed, $m \cdot s^{-1}$
W	effective mechanical power, $W \cdot m^{-2}$
w	skin wettedness, dimensionless

W_a humidity ratio of inhaled air, kg water/kg dry air

W_{ex} humidity ratio of exhaled air, kg water/kg dry air

σ Stefan-Boltzmann constant

ε_{cl} emissivity of clothing surface, dimensionless

4 Principles of methods for evaluation

Cold stress is evaluated in terms of both general cooling of the body and local cooling of particular parts of the body (e.g. extremities and face). The following types of cold stress are identified.

a) General cooling

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, the required clothing insulation (IREQ) for the maintenance of thermal equilibrium and the insulation provided by clothing ensemble in use or anticipated to be used.

b) Local cooling

1) convective cooling (wind chill)

2) conductive cooling

3) extremity cooling

4) airway cooling

For local cooling, methods are proposed in Clause 6. Criteria and limit values are also given in Clause 6 and Annex B.

In the following sections, the main steps of evaluation are described.

5 General cooling

5.1 Overview

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. IREQ is subsequently compared with the protection (insulation) offered by the worker's clothing. If worn insulation is less than required, a duration limited exposure (D_{lim}) is calculated on the basis of acceptable levels of body cooling. Detailed formulas, 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 IREQ;

— comparison of IREQ with resultant insulation provided by clothing in use;

— evaluation of the conditions for thermal balance and calculation of the recommended maximal exposure time (D_{lim}).

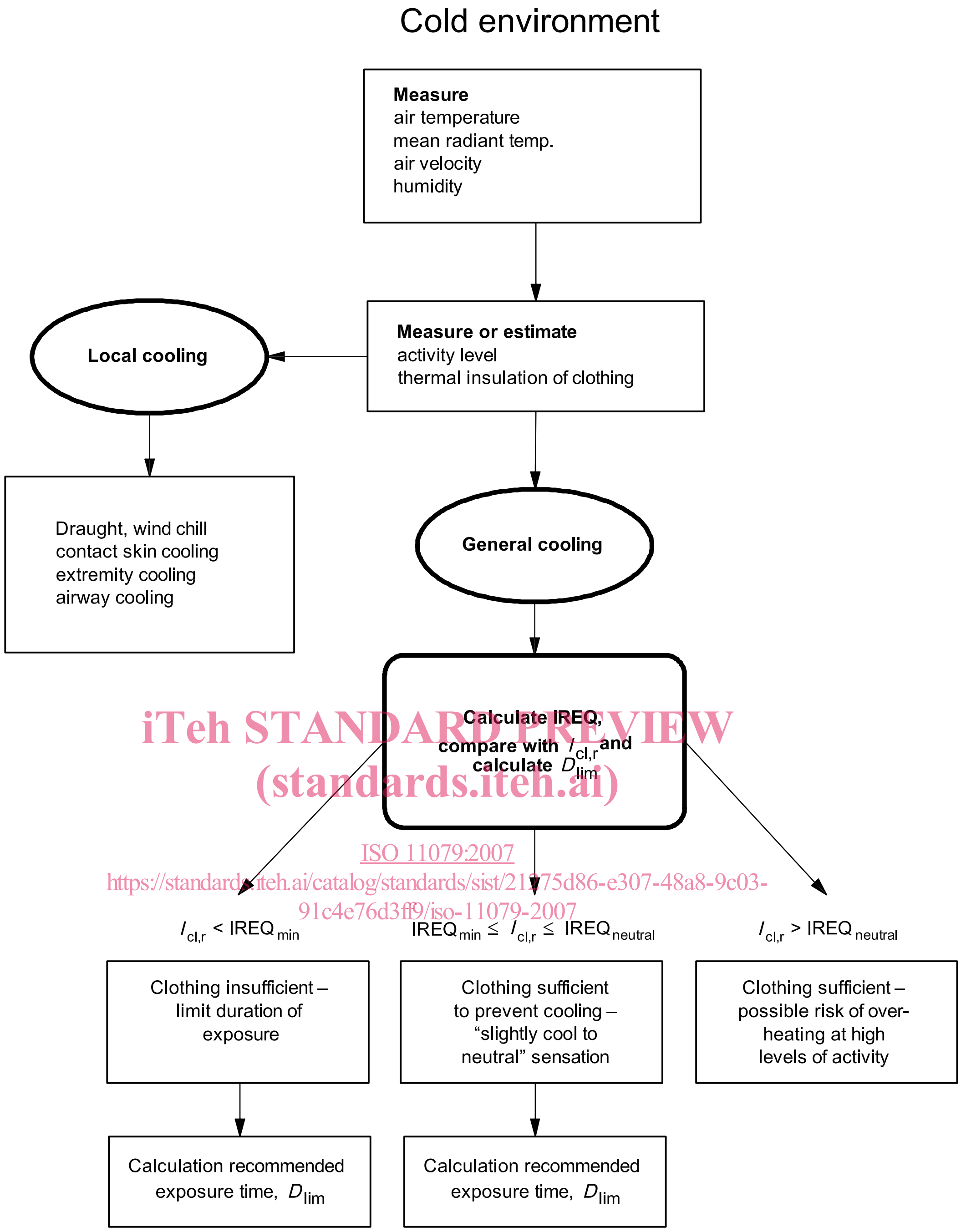

Figure 1 — Procedure for evaluation of cold environments

5.2 Definition of required clothing insulation, IREQ

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

IREQ is

a) a measure of cold stress integrating the effects of air temperature, mean radiant temperature, relative humidity and air velocity for defined levels of metabolic rate,

b) a method for the analysis of effects of the thermal environment and metabolic rate on the human body,

c) a method for specification of clothing insulation requirements and the subsequent selection of clothing to be used under the actual conditions, and

d) a method for evaluation of changes in heat balance parameters as measures for improvement of design and planning of work time and work regimes under cold conditions.

5.3 Derivation of IREQ

5.3.1 General heat balance equation

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

The general heat balance equation [Equation (1)] is as follows:

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

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. Variables of Equation (1) are defined in the following. For the meaning of symbols, see also 3.2.

5.3.2 Metabolic rate

M is the metabolic rate and is evaluated in accordance with ISO 8996.

5.3.3 Effective mechanical power

W is the effective mechanical power. In most industrial situations this is small and can be neglected. See also information in ISO 8996.

5.3.4 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

$$C_{\text{res}} = c_{\text{p}} \cdot V(t_{\text{ex}} - t_{\text{a}}) / A_{\text{Du}} \quad (2)$$

$$E_{\text{res}} = c_{\text{e}} \cdot V(W_{\text{ex}} - W_{\text{a}}) / A_{\text{Du}} \quad (3)$$

5.3.5 Evaporative heat exchange

The evaporative heat exchange, E, is defined by

$$E = (p_{sk} - p_a) / R_{e,T} \tag{4}$$

5.3.6 Conductive heat exchange

Conductive heat exchange, K, is related to the area of body parts in direct contact with external surfaces. Although it may 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.

5.3.7 Radiative heat exchange

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

$$R = f_{cl} \cdot h_r \cdot (t_{cl} - \bar{t}_r) \tag{5}$$

5.3.8 Convective heat exchange

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

$$C = f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \tag{6}$$

5.3.9 Heat exchange through clothing

Heat exchange through clothing takes place by conduction, convection and radiation and by the transfer of evaporated sweat. The effect of clothing on latent heat exchange is accounted for by 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, is expressed by the resultant, thermal insulation of clothing:

$$\frac{\bar{t}_{sk} - t_{cl}}{I_{cl,r}} = R + C = M - W - E_{res} - C_{res} - E - S \tag{7}$$

5.4 Calculation of IREQ

On the basis of Equations (1) to (7), in steady state and using the hypothesis made concerning heat flow by conduction, the required clothing insulation, IREQ, is calculated on the basis Equation (8):

$$\text{IREQ} = \frac{\bar{t}_{sk} - t_{cl}}{R + C} \tag{8}$$

Equations (7) and (8) express the dry heat exchange at the clothing surface when the body is in thermal equilibrium and state the relationship between $I_{cl,r}$ and IREQ. $I_{cl,r}$ is the value of clothing insulation corrected for the effects of wind penetration and activity, taking into account the air permeability of the outer garment layer. IREQ is the thermal insulation required for the maintenance of thermal equilibrium.

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

$$t_{cl} = \bar{t}_{sk} - \text{IREQ} \cdot (M - W - E_{res} - C_{res} - E) \tag{9}$$

