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International Standards for the Assessment of the Risk of Thermal Strain on Clothed Workers in Hot Environments

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The International Standards Organisation (ISO) has produced an integrated series of international standards for the assessment of human responses to thermal environments. They include standards for the assessment of thermal comfort, heat stress and cold stress and many have been adopted as European and British standards. This paper describes the series of standards and in particular those concerned with the assessment of risk in hot environments. A three tier approach is taken which involves a simple thermal index that can be used for monitoring and control of hot environments (ISO 7243), a rational approach which involves an analysis of the heat exchange between a worker and his or her environment (ISO 7933) and a standard that describes the principles of physiological measurement which can be used in the establishment of personal monitoring systems of workers exposed to hot environments (ISO 9886). The standards are self-contained and can be used independently. In any comprehensive assessment however they would be used in conjunction. The simple index provides a first stage analysis and can confirm whether or not there is likely to be unacceptable thermal strain. Where a more detailed analysis is required then ISO 7933 provides an analytical method that can provide a more extensive assessment and interpretation leading to recommendations for improvement to the working environment. Where a method needs to be confirmed, or conditions are beyond the scope of ISO 7243 and ISO 7933, then ISO 9886 provides guidance on physiological measurement and interpretation. This would be used in extreme environments where individual responses are required to ensure health and safety or, in the case where personal protective equipment (PPE) is worn, which is beyond the scope of ISO 7243 and ISO 7933. The ISO system therefore covers almost all exposures to hot environments. It would be useful however to extend the scope of the standards that provide a simple index or analytical approach. This paper describes the current standards and their scope and forms the basis and background for descriptions of proposed extensions to the scope of the standards described in other papers in this special issue. **© 1999 British Occupational Hygiene Society. Published by Elsevier Science Ltd. All rights reserved.**

Keywords: clothing; heat stress; international standards

INTRODUCTION

Appropriate indoor air temperatures have often been the subject of debate and suggested limit or guidance values for environments have been proposed over many years by a number of professional institutions and in legislation. It has become recognised that a comprehensive approach is required and ISO standards have been produced to do this. Standards for the assessment of hot environments are described below. Of particular interest is the extension of the scope of the standards to include the influence of protective clothing and personal protective equipment (PPE) on heat strain. This paper is one of a series in this special issue. It provides the background knowledge for subsequent papers that consider how the standards can be improved to account for protective clothing and PPE as well as other factors.

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THE ISO STANDARDS

The collection of ISO (International Organization for Standardization) standards and documents, concerned with the ergonomics of the thermal environment, can be used in a complementary way to provide a comprehensive assessment methodology. The subject is divided into three principal areas; hot, moderate and cold environments and the remaining standards are divided into human reaction to contact with solid surfaces and a series of supporting standards (Fig. 1).

For the assessment of hot environments a simple method based on the WBGT (wet bulb globe temperature) index is provided in ISO 7243. If the WBGT reference value is exceeded a more detailed analysis can be made (ISO 7933) involving calculation, from the heat balance equation, of sweating required in a hot environment. If the responses of individuals or of specific groups are required (for example in extremely hot environments) then physiological strain should be measured (ISO 9886).

ISO 7730 provides an analytical method for assessing moderate environments and is based on the predicted mean vote and predicted percentage of dissatisfied (PMV/PPD) thermal index and on criteria for local discomfort. If the responses of individuals or specific groups are required, then subjective measures should be used (ISO 10551).

ISO TR 11079 provides an analytical method for assessing cold environments involving calculation of the clothing insulation required (IREQ) from a heat balance equation. This can be used as a thermal index or as a guide to selecting clothing.

ISO work on contact with solid surfaces is divided into hot, moderate, and cold surfaces. Supporting standards include an introductory standard (ISO 11399) and standards for estimating the thermal properties of clothing (ISO 9920) and metabolic heat production (ISO 8996). Other standards consider instruments and measurement methods (ISO 7726), and standards still under development include those concerned with symbols and units, medical screening of persons to be exposed to heat or cold and the responses of disabled persons. The ISO working system showing how the collection of standards can be used in practice, is presented in Fig. 2. The standards related to the assessment of hot environments are presented below.

ISO 7243: HOT ENVIRONMENTS — ESTIMATION OF THE HEAT STRESS ON WORKING MAN, BASED ON THE WBGT-INDEX (WET BULB GLOBE TEMPERATURE)

This standard provides a simple convenient method and uses the wet bulb globe temperature (WBGT) heat stress index to assess hot environments.

Inside buildings and outside buildings without solar load,

$$\mathrm{WBGT} = 0.7t_{\mathrm{nw}} + 0.3t_{\mathrm{g}}, \quad (1)$$

while outside buildings with solar load,

$$\mathrm{WBGT} = 0.7t_{\mathrm{nw}} + 0.2t_{\mathrm{g}} + 0.1t_{\mathrm{a}}, \quad (2)$$

where t_{nw} is the natural wet bulb temperature, t_{g} the temperature of a 150 mm diameter black globe and t_{a} the air temperature.

Equipment used must be within specification. For example, if the globe size is incorrect or the air temperature is not shielded from radiation, this may have significant consequences for the outcome of the assessment. The following summarises the specification for the sensors.

Natural wet bulb sensor

The natural wet bulb sensor is cylindrical in shape (6 ± 1 mm diameter and 30 ± 5 mm long), with a measuring range from 5 to 40°C and accuracy of ± 0.5°C. The support of the sensor is 6 mm in diameter and a clean white wick of highly water absorbent material (for example, cotton), covers (as a sleeve fitted with precision) the whole of the sensor and 20 mm of the support.

ISO STANDARDS

Hot	Moderate	Cold
7243 (WBGT)	7730 (PMV)	TR11079 (IREQ)
7933 (Sreq)	10551 (Subj)	
9886 (Phys)	9886 (Phys)	9886 (Phys)
Hot Surfaces	Moderate Surfaces	Cold Surfaces

SUPPORTING

11399 (Umbrella), 8996 (Met), 9920 (Clo), 7726 (Inst's), (Units), 12894 (Screening)

Fig. 1. ISO standards for assessing thermal environments.

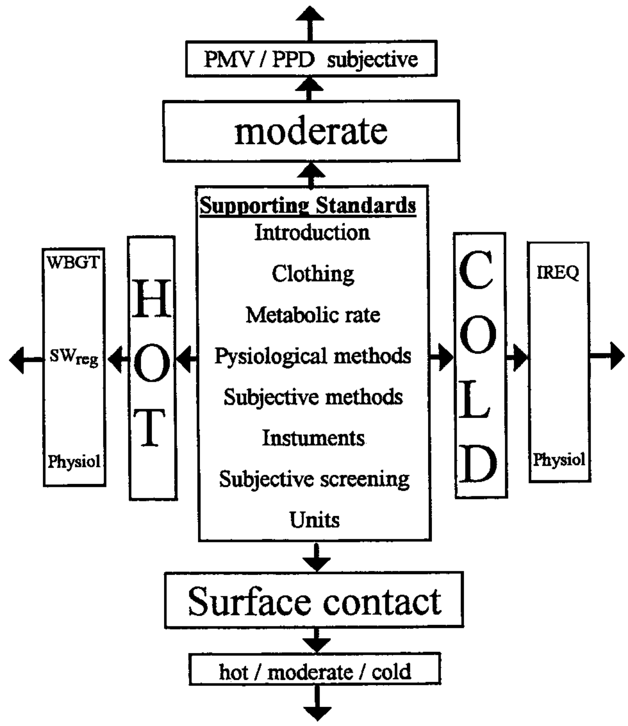

Fig. 2. Organization and use of ISO standards concerned with human thermal environments.

Globe temperature sensor

Globe temperature is the temperature at the centre of a thin, matt black globe (mean emission coefficient of 0.95) with a measuring range from 20 to 120°C with an accuracy from ±0.5 to 50°C and ±1 to 120°C. It is important that the globe is of 0.15 m in diameter.

Air temperature sensor

The air temperature sensor should be shielded from the effects of radiation by a device that does not restrict air circulation. It should measure over the range from 10 to 60°C with an accuracy of ±1°C.

The WBGT value used in the standard is a weighted average, over time and space, and is measured over a period of maximum heat stress. The weighting for spatial variation is given by

$$\mathrm{WBGT} = (\,\mathrm{WBGT}_{\mathrm{head}} + 2 \times \mathrm{WBGT}_{\mathrm{abdomen}} + \mathrm{WBGT}_{\mathrm{ankles}})/4. \quad (3)$$

For time variations (for example: in metabolic rate, WBGT, globe temperature) a time weighted average is taken over a period of work/resting of one hour. This is calculated from the beginning of a period of work.

The WBGT value of the hot environment is compared with a WBGT reference value, allowing for a maximum rectal temperature of 38°C (see Table 1).

The standard is at present limited in scope to workers wearing only light clothing. While the method may apply to protective clothing and PPE use, further work is needed to provide guidance. The WBGT index provides most weight to the natural wet bulb value (70%). It is therefore a representation of the response of a sweating worker in saturated clothing with free evaporation to the environment. Where impermeable clothing is worn it is debatable whether the WBGT index is appropriate. This is discussed in detail by Hanson (1999) and Bernard (1999) in this special issue.

ISO 7933: HOT ENVIRONMENTS — ANALYTICAL DETERMINATION AND INTERPRETATION OF THERMAL STRESS USING CALCULATION OF REQUIRED SWEAT RATE

This standard specifies a rational method for assessing hot environments by calculating and interpreting required sweat rate (S_{req}). The S_{req} index is a development of the heat stress index (HSI — Belding and Hatch, 1955) and of the index of thermal strain (ITS — Givoni, 1976). It is derived from the work of Vogt *et al.* (1981) in the CNRS laboratories in Strasbourg, France. During the development of the standard a number of investigations were carried out into its validity and practical use (for example: Wadsworth and Parsons, 1986; Parsons, 1987). In particular an extensive programme of work was undertaken by the European

Table 1. WBGT reference values from ISO 7243 (1989)[a]

Metabolic rate ($W\ m^{-2}$)	WBGT reference value (°C)			
	person acclimatised to heat		person not acclimatised to heat	
(0) Resting, $M < 65$	33		32	
(1) $65 < M < 130$	30		29	
(2) $130 < M < 200$	28		26	
	no sensible air movement	sensible air movement	no sensible air movement	sensible air movement
(3) $200 < M < 260$	25	26	22	23
(4) $M > 260$	23	25	18	20

a The values given have been established allowing for a maximum rectal temperature of 38°C for the persons concerned.

Iron and Steel community, involving researchers from many European countries (CEC, 1988). The results of these studies, involving both laboratory and industrial investigations, led to significant modifications to the proposed standard and it was eventually published in 1989.

Measurement of the hot environment in terms of air temperature, mean radiant temperature, humidity and air velocity, and estimates of factors relating to clothing, metabolic rate and posture, are used to calculate the heat exchange between a standard person and the environment. This allows the calculation of the required sweat rate (for the maintenance of the thermal equilibrium of the body) from the following equations:

$$E_{req} = M - W - C_{res} - E_{res} - C - R \quad (4)$$

and

$$S_{req} = E_{req}/r_{req}, \quad (5)$$

where M is the metabolic power, W the mechanical power, C_{res} the respiratory heat loss by convection, E_{res} the respiratory heat loss by evaporation, K the heat exchange on the skin by conduction, C the heat exchange on the skin by convection, R the heat exchange on the skin by radiation, E_{req} the required evaporation for thermal equilibrium, S_{req} the required sweat rate for thermal equilibrium and r_{req} the evaporative efficiency at required sweat rate.

Metabolic and mechanical power are estimated, although W is often taken as zero if detailed information about the task is not known. They can be determined using methods provided in ISO 8996. K is regarded as having negligible effect and the following equations are used to calculate the remaining terms. Table 2 gives a description of terms used.

$$C_{res} = 0.0014\ M\ (35 - t_a), \quad (6)$$

$$E_{res} = 0.0173\ M\ (5.624 - P_a), \quad (7)$$

$$C = h_c\ F_{cl}\ (t_{sk} - t_a), \quad (8)$$

$$R = h_r\ F_{cl}\ (t_{sk} - t_r), \quad (9)$$

where

$$w = E/E_{max},$$

$$r = 1 - w^2/2,$$

$$h_c = 2.38\ |\ t_{sk} - t_a|^{0.25} \quad \text{for natural convection},$$

$$h_c = 3.5 + 5.2\ v_{ar} \quad \text{for} \quad v_{ar} < 1 \quad ms^{-1},$$

$$h_c = 8.7\ v_{ar}^{0.6} \quad \text{for} \quad v_{ar} \geq 1 \quad ms^{-1},$$

$$v_{ar} = v_a + 0.0052\ (M - 58),$$

$$h_r = \sigma E_{sk} \frac{A_r}{A_{Du}} \frac{[(t_{sk} + 273)^4 - (t_r + 273)^4]}{t_{sk} - t_r},$$

$$F_{cl} = 1/[(h_c + h_r)\ I_{cl} + 1/f_{cl}],$$

$$f_{cl} = 1 + 1.97\ I_{cl},$$

$$E_{max} = (P_{sk,s} - P_a)/R_t, \quad (10)$$

$$R_t = 1\ /\ h_e F_{pcl},$$

$$h_e = 16.7\ h_c,$$

$$F_{pcl} = 1/\ \{1 + 2.22\ h_c\ [I_{cl} - (1 - 1/f_{cl})/(h_c + h_r)]\},$$

$$t_{sk} = 30.0 + 0.093\ t_a + 0.045\ t_r - 0.571\ v_a + 0.254\ p_a + 0.00128\ M - 3.57\ I_{cl}.$$

This regression equation for t_{sk} can be used for the following ranges for each individual parameter:

$t_a = 22.9 - 50.6\,^{\circ}C$,

$tr = 24.1 - 49.5\,^{\circ}C$,

$p_a = 0.8 - 4.8$ kPa,

Table 2. Description of terms used in ISO 79339 (1989)

Symbol	Term	Units
M	metabolic power	W m^{-2}
W	mechanical power	W m^{-2}
C_{res}	respiratory heat loss by convection	W m^{-2}
E_{res}	respiratory heat loss by evaporation	W m^{-2}
K	heat exchange on the skin by conduction	W m^{-2}
C	heat exchange on the skin by convection	W m^{-2}
R	heat exchange on the skin by radiation	W m^{-2}
E	heat flow by evaporation at skin surface	W m^{-2}
E_{req}	required evaporation for thermal equilibrium	W m^{-2}
S_{Wreq}	required sweat rate for thermal equilibrium	W m^{-2}
w	skin wettedness	ND
w_{req}	skin wettedness required	ND
r_{req}	evaporative efficiency at required sweat rate	ND
t_a	air temperature	°C
P_a	partial vapour pressure	kPa
h_c	convective heat transfer coefficient	W m^{-2} K^{-1}
F_{cl}	reduction factor for sensible heat exchange due to the wearing	ND
t_{sk}	mean skin temperature	°C
h_r	adiative heat transfer coefficient	W m^{-2} K^{-1}
t_r	mean radiant temperature	°C
$p_{sk,s}$	saturated vapour pressure at skin temperature	kPa
R_t	total evaporative resistance of limiting layer of air and clothing	m^2 kPa W^{-1}
E_{max}	maximum evaporative rate which can be achieved with the skin completely wet	W m^{-2}
v_{ar}	relative air velocity	ms^{-1}
v_a	air velocity for a stationary subject	ms^{-1}
σ	Stefan-Boltzman constant, 5.67×10^8	W m^{-2} K^{-4}
E_{sk}	skin emissivity (0.97)	ND
A_r/A_{du}	fraction of skin surface involved in heat exchange by radiation	ND
f_{cl}	ratio of the subject's clothed to unclothed surface area	ND
F_{pcl}	reduction factor for latent heat exchange	ND
h_e	evaporative heat transfer coefficient	W m^{-2} kPa^{-1}
I_{cl}	basic dry thermal insulation of clothing	Clo or m^2 °C W^{-1}

$$v_a = 0.2 - 0.9 \quad \mathrm{ms}^{-1},$$

$$M = 46.4 - 272 \quad \mathrm{W/m}^{-2},$$

$$I_{cl} = 0.1 - 0.6 \quad \mathrm{Clo},$$

$$t_{sk} = 32.7 - 38.4 \ {}^{\circ}\mathrm{C},$$

see Mairiaux *et al.* (1987).

An approximation of 36°C for t_{sk} can be made and this may be a more sensible value to use in many applications.

Predicted values for evaporation from the subject (E_p), sweat rate (S_{Wp}) and skin wettedness (w_p) are determined for the standard subject by a method shown in Fig. 3. Predictions are made taking into account required values (w_{req}, E_{req} and S_{req}) and limit values (w_{max}, S_{Wmax}). The required sweat rate is compared with the maximum limit values for skin wettedness (w_{max}) and sweat rate (S_{Wmax}) which can be achieved by persons. These are presented for acclimatised and non-acclimatised persons at work and rest (see Table 3).

In the case where thermal equilibrium cannot be achieved, there will be heat storage and hence the body core temperature will rise. Limiting values are presented for warning and danger, in terms of heat storage. They are also presented in terms of the maximum allowable water loss compatible with the maintenance of the hydromineral equilibrium of the body.

The predicted sweat rate can be determined from the required sweat rate and the limit values. If the required sweat rate can be achieved by persons and it will not cause unacceptable water loss, then there is no time limit due to heat exposure over an eight hour shift. If this is not the case, then allowable exposure times (duration limited exposures, DLEs) are calculated from the following equations:

When

$$E_p = E_{req}/8 \quad \text{and} \quad S_{Wp} < D_{max},$$

then DLE = 480 min and S_{Wp} can be used as a heat stress index. If the above conditions are not satisfied then

$$\mathrm{DLE}_1 = 60\ Q_{max}/S_{Wp}, \tag{11}$$

$$\mathrm{DLE}_2 = 60\ D_{max}/S_{Wp}. \tag{12}$$

DLE is the lower value of DLE_1 and DLE_2. If DLE is determined by DLE_1 (i.e. heat storage) then the worker must rest until there is no longer a risk of heat stress. If DLE is determined by DLE_2 (that is, dehydration), then no further exposure is allowed during the day.

If workers carry out a number of types of work during the day and under different thermal conditions ISO 7933 provides a method for assessing sequences of 'tasks' (including work and rest) based on a time weighting of E_{req} and E_{max} values. An example of the use of ISO 7933 in practical application is provided below.

If E_{max} is negative (that is, condensation will occur) or if exposure time is short (that is, < 30 min) or if the conditions are beyond the scope of the standard (for example where specialist clothing or equipment are worn or there is a high level of directional radiation) then the method used in ISO 7933 is inappropriate without modification. Physiological measurements on individuals should be taken according to ISO 9886.

A computer program is provided to allow ease of calculation and efficient use of the standard. (Annex D of ISO 7933 (1989)). Computer program listings are also available in Parsons (1993) and Mairiaux and Malchaire (1990). This rational method of assessing hot environments allows identification of the relative importance of different components of the thermal environment and hence can be used in environmental design.

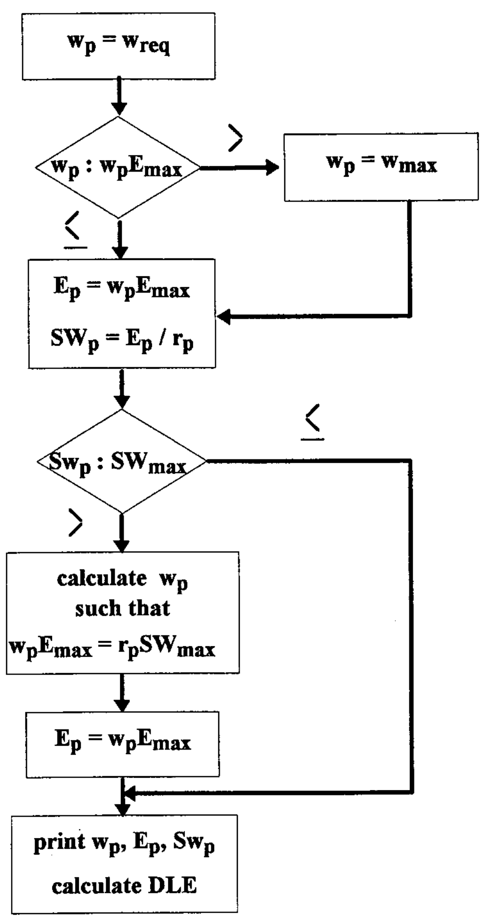

Fig. 3. Flow chart for the calculation and interpretation of values used ISO 7933 (1989).

The method presented in ISO 7933 is powerful and pragmatic. In its present form however it has recognised limitations in terms of its validity for specialist environments, many of which occur in practice. It also has limitations in terms of its usability. It is presented as a rather academic standard and apparently complex. These are issues that are addressed by a number of papers in this special issue. Of particular note has been the programme of research undertaken by laboratories under a BIOMED European programme. Improvements have been proposed in terms of the representation of the thermal properties of clothing, prediction of mean skin temperature, method of interpretation and other factors including usability. Some of this work is presented in this special issue and will contribute towards a revision of ISO 7933. It is of interest that when ISO 7933 was proposed as a European standard it was not accepted in its exact form but only with minor but important modifications. The European (and British) standard (EN 12515, BS EN 12515) emphasised the limitations in the scope of the ISO standard as these limitations had been shown to be of practical importance particularly by research in the German mining industry.

ISO 9886: EVALUATION OF THERMAL STRAIN BY PHYSIOLOGICAL MEASUREMENTS

In extreme environments, or for other reasons such as research, it may be necessary to measure the physiological strain on humans exposed to thermal environments. This standard describes methods for measuring and interpreting body core temperature, skin temperatures, heart rate and body mass loss (Table 4). Body core temperature refers to the internal temperature of the body and is the temperature of the body's vital organs including the brain. If the core temperature becomes too high or too low then there will be major affects on the performance and health of the person, eventually leading to collapse and death. The body attempts to maintain this temperature in hot environments by sweating in an attempt to lose heat by evaporation. If this mechanism does not allow sufficient heat to be lost, for example due to the wearing of impermeable clothing, then heat will be stored in the body. ISO 9886 provides the principles and practical guidance for the measurement and interpretation of body core temperature. Additional physiological measures that are described include heart rate which is a general indicator of stress on the body, mean skin temperature that can be interpreted in terms of the state of thermal strain and comfort, and body mass loss (mainly due to sweating). Body mass loss is related

Table 3. Reference values for criteria stress and strain used in ISO 7933 (1989) for the assessment of hot environments

Criteria	Nonacclimitized		Acclimatized	
	warning	danger	warning	danger
Maximum skin wettedness				
W_{max}	0.85	0.85	1	1
Maximum sweat rate				
rest ($M < 65$ W m^{-2})				
SW_{max} W m^{-2}	100	150	200	300
g h^{-1}	260	390	520	780
work ($M > 65$ W m^{-2})				
SW_{max}: W m^{-2}	200	250	300	300
g h^{-1}	520	650	780	1040
Maximum heat storage				
Q_{max}: W h m^{-2}	50	60	50	60
Maximum water loss				
D_{max}: W h m^{-2}	1000	1250	1500	2000
g	2600	3250	3900	5200

to heat strain and can be interpreted in terms of likely dehydration, water and electrolyte requirements and can be used as an indication of the thermal efficiency of clothing.

Annex I of the standard presents a comparison of the different methods concerning their field of application, their technical complexity, their discomfort and the risks that might involve. Measurement methods are described in Annex II and limit values are proposed in Annex III of the standard.

The principle of the standard is therefore to present information to allow the informed selection and correct application and interpretation of physiological measures. The standard does not recommend methods nor does it propose how to develop and use a personal monitoring system. A recently identified need for a standard is to provide the specification for the instrumentation to make physiological measurements. There has also been some debate about the rapid technological advances without guidance on how appropriate equipment will be for monitoring a state of health as well as the expertise required to use such equipment and interpret results. An example is the use of the widely available infra-red ear thermometer for measuring core temperature. If used in the wrong conditions or without great care in measurement then existing devices have been shown to give misleading results. If used in a personal monitoring system to protect health the consequences could be significant. When physiological measurements were first proposed in standardisation, it was envisaged that they would be rarely used in industry and mainly by experts for research. The restricted scope of existing standards, the need for effective assessment of hot environments, particularly when protective clothing and equipment is worn and the readily available instrumentation have all led to personal monitoring systems being seriously considered as standard working practise. ISO 9886 provides important information and more practical guidance is needed to allow appropriate development and use of personal monitoring systems.

Table 4. Physiological measures considered by ISO 9886(1992)

Physiological response	Measure considered
Body core temperature	oesophageal temperature
	rectal temperature
	gastrointestinal tract
	oral (mouth) temperature
	tympanic temperature
	auditory canal temperature
	urine temperature
Skin temperature	local skin temperature
	mean skin temperature:
	ISO 4 point method
	ISO 8 point method
	ISO 14 point method
Heart rate	the partial method is used to identify the component due to thermal stress
Body mass loss	due to respiration and sweating; take account of body inputs (food and drink) and body outputs (urine and stools)

Table 5. Characteristics of measuring instruments. From ISO 7726 (1985)

Air temperature (t_a)	
Measuring range	10–30°C for comfort, –40–120°C for stress
Accuracy	required for comfort = 0.5°C; desired = 0.2°C
	required for stress
	–40—0°C: $0.5+0.01t_a$°C
	> 0–50°C: 0.5°C
	> 50–120°C: $0.5+0.04t_a$–50°C
	desired: (required accuracy)/2
	these levels are to be guaranteed at least for a deviation of $t_a – t_r = 10$°C for comfort and 20°C for stress
Response time (90%)	the shortest possible; value to be specified as characteristic of the measuring appliance
Comment	The air temperature sensor shall be effectively protected from any effects of the thermal radiation coming from hot or cold walls. An indication of the mean value over a period of 1 min is also desirable
Mean radiant temperature (t_r)	
Measuring range	10–40°C for comfort, –40–150°C for stress
Accuracy	required = 2°C, desired = 0.2 for comfort
	these values may not be achievable in some circumstances, in which case the actual accuracy shall be reported
	required for stress
	–40–0°C: $(5+0.02t_r)$°C
	> 0–50°C: 5°C
	> 50–150°C: $5+0.08(t_r–50)$°C
	desired
	–40–0°C: $(0.5+0.01t_r)$°C
	> 0–50°C: 0.5°C
	> 50–150°C: $0.5+0.04(t_r–50)$°C
Response time	the shortest possible; value to be specified as characteristic of the measuring appliance
Comment	When the measurement is carried out with a black sphere, the inaccuracy relating to the mean radiant temperature can be as high as ±5°C for comfort and ±20°C for stress, according to the environment and the inaccuracies in measurement of air temperature, air velocity and globe temperature
Air velocity (v_a)	
Measuring range	0.05–1.0 m/s for comfort, 0.2–10 m/s for stress
Accuracy	required for comfort: $0.05+v_a$ m/s
	desired: $0.02+0.07v_a$ m/s
	required for stress: $0.1+0.05v_a$ m/s
	desired: $0.05+0.05v_a$ m/s
	these levels shall be guaranteed whatever the direction of flow within a solid angle $w=3\pi$ sr
Response time (90%)	required: 0.5 s; desired: 0.2 s for comfort; for stress, the shortest possible; value to be specified as characteristic of the measuring appliance
Comment	Except in the case of a unidirectional air current the air velocity sensor shall measure the effective velocity whatever the direction of the air. An indication of the mean value for a period of three minutes is also desirable. The degree of turbulence is an important parameter in the study of comfort problems, it is recommended that it be expressed as standard deviation of the velocity. In a cold environment it is recommended that comfort instrumentation be used for both comfort and stress analysis.
Absolute humidity (p_a as partial pressure of water vapour)	
Measuring range	0.5–2.5 kPa for comfort, 0.5–6 kPa for stress
Accuracy	0.15 kPa; this level shall be guaranteed even for air and wall temperatures equal to or greater than 30°C and for a difference $t_r – t_a$ of at least 10°C
Response time (90%)	the shortest possible; value to be specified as characteristic of the measuring appliance

ISO 7726. THERMAL ENVIRONMENTS — INSTRUMENTS AND METHODS FOR MEASURING PHYSICAL QUANTITIES

This standard provides definitions of the basic parameters (air temperature, mean radiant temperature, humidity, air velocity) and derived parameters (natural wet bulb temperature, globe temperature). It also provides methods of measurement and specifications of measuring appliances (see Table 5).

No specific instrument is standardised, only specifications. The standard can therefore serve as a guide for manufacturers of the instruments as well as for specifying measuring requirements, in a contract between an investigator and a client.

Table 6. Six methods for estimating metabolic heat production (ISO 8996)

Level	Method	Accuracy	Inspection of the work place
I	(A) classification according to kind of activity	rough information where the risk of error is very great	not necessary
	(B) classification according to occupation		information on technical equipment, work organisation
II	(A) use of tables of group assessment	high error risk; accuracy±15%	time study necessary
	(B) use of estimation tables for specific activities		
	(C) use of heart rate under defined conditions		not necessary
III	measurement	risk of errors within the limits of the accuracy of the measurement and of the time study; accuracy ±5%	time study necessary

ISO 8996: ERGONOMICS: DETERMINATION OF METABOLIC HEAT PRODUCTION

This standard provides methods and data for estimating the metabolic heat production of humans. It provides fundamental support to other ISO standards in the series, for assessing hot, moderate, and cold environments. The standard can also be used for the assessment of working practices, the metabolic cost of specific jobs or sports activities, the total metabolic cost of activity and for other applications.

The methods are derived from a number of studies concerned with determining metabolic rate, and some are well established. The data are mainly from the work of Spitzer and Hettinger (1986) in the laboratories of the University of Wupertaal, Germany. Six methods of estimation are presented in three types (Table 6).

The first is by use of tables, where estimates are provided based on a description of activity. These range from general description (for example, low, high, etc.) to specific descriptions of occupations (for example, bricklayer) and methods of summating components of tasks (for example, basal metabolic rate plus posture component plus movement component, etc.) Examples of the methods involving the use of tables are provided in Tables 7–9.

The second type of method is by the use of heart rate. The total heart rate is regarded as a sum of several components and, in general, is linearly related to the metabolic heat production for heart rates above 120 beats per minute. This method is shown in Table 10.

The third type of method is to calculate the metabolic heat production from measures of oxygen consumption, and carbon dioxide production during activity and recovery. This method is complex and would not normally be used in work. For a full description the reader is referred to the standard.

The methods and data provided in the standard are comprehensive, so implementation of the standard into a computer system is beneficial (for example; Parker and Parsons, 1990). Although one of the most extensive databases available on this topic, the inherent errors in use of the methods and derivation of the data should be taken into account; see Parsons and Hamley, 1989. The standard provides guidance on the level of accuracy one could expect with each method (Table 6).

All metabolic rate values are provided in units of W/m^2 of the body surface area. The values are based on the standard man (see Table 11). They should be corrected for 'non-standard' individuals or populations; for example, this will be particularly relevant when the activity involves tasks such as walking upstairs (overcoming gravity) where human body weight will be important. For conditions where the physical level of work varies, a time weighted average procedure is recommended; an example is shown in Table 12.

ISO 9920: ESTIMATION OF THE THERMAL CHARACTERISTICS OF A CLOTHING ENSEMBLE

This international standard presents methods for estimating the thermal characteristics (resistance to dry heat loss and evaporative heat loss) of a clothing

Table 7. Classification of metabolic rates by activity (ISO 8996 (1989))

Class	Mean metabolic rate ($W\ m^{-2}$)	Example
Resting	65	resting
Low	100	sitting at ease/standing
Moderate	165	sustained handlarm work
High	230	intense work
Very high	290	very intense to maximum activity

Table 8. Classification by occupation (examples from ISO 8996 (1989))

Occupation	Metabolic rate (W m^{-2})
Craftsmen	
bricklayer	110–160
carpenter	110–175
glazier	90–125
painter	100–130
Agriculture	
gardener	115–190
tractor driver	85–110
etc.	

ensemble based on values for known garments, ensembles and textiles. It does not take into account the influence of rain and snow on the thermal characteristics and special protective clothing (water cooled suits, ventilated suits, heated clothing) are not considered.

The main part of the standard is a large database of clothing insulation values which have been measured on copper manikins. The data are mainly from the work of McCullough *et al.* (1985) and Olesen and Dukes-Dubos (1988).

This standard provides methods for the determination of the thermal insulation of clothing. It is necessary to know this when evaluating the heat or cold stress, or degree of comfort provided by the physical environment, according to the standards for assessing hot, moderate and cold environments.

Values are provided for dry thermal insulation and resistance to water diffusion. Dry insulation is given in terms of basic thermal insulation (I_{cl}). Resistance of clothing to water diffusion is provided in terms of the (non-dimensional) permeability index, i_m. The i_m value ranges from around 0.5, for a nude person to around 0.2 for impermeable like clothing. A typical value would be around 0.4.

The tables of thermal insulation values of clothing are comprehensive. An example is provided in Table 13. Values for total ensembles are supplied as well as for dry insulation values for individual garments (I_{clu}) which make up ensembles. If the thermal insulation value of a total ensemble is not provided in the tables, then a summation procedure is provided for estimating the insulation provided by the ensemble from the I_{clu} values.

Table 9. Metabolic rate by group assessment (ISO 8996 (1989))

Metabolic rate = basal + posture + work + motion
Example: raking leaves on a lawn Metabolic rate = basal + n/a + light, two arm work + walking = 44 + 0 + 65 + 60 = 169 W m^{-2}

Table 10. Estimation of metabolic heat production using heart rate. (ISO 8996 (1989))

For the range 120 to (HR_{max}–20): $HR = HR_0 + RM(M - BM)$ bpm, where HR is the heart rate, M the metabolic rate, BM the basal metabolic rate, RM the increase in heart rate per unit of metabolic rate (this can be determined experimentally for individual subjects or groups performing relevant tasks) and HR_0 the heart rate at rest (in prone position) under thermoneutral conditions

The summation procedure to obtain I_{cl} from the insulation values of individual garments (I_{clu}) is

$$I_{cl} = \sum I_{clu} \quad m^2\,{}^\circ C / W \quad \text{or Clo.}$$

The I_{clu} values are effective thermal insulation values for garments. That is, they do not account for the increase in surface area for heat exchange over the body due to clothing. If basic thermal insulation values for garments (I_{cli}) are known then

$$I_{cl} = 0.82 \sum I_{cli}.$$

For example in ISO 7730, thermal insulation values are provided for garments in terms of I_{cli}. As well as information about garment style (for example, long sleeves, short sleeves, etc.), fabric type and thickness are also supplied.

The thermal insulation of an individual garment may also be estimated from the area of the body covered using

$$I_{clu} = 0.61 \times 10^{-2} A_{cov} \quad \text{(Clo).}$$

When the thickness of the fabric (H_{fab}) is also known, then

$$I_{clu} = 0.43 \times 10^{-2} A_{cov} + 1.4 H_{fab} \times A_{cov} \quad \text{(Clo),}$$

where A_{cov} is the body surface area covered (%) and H_{fab} the thickness of fabric (m) measured according to standard ASTM D 1777 using a 75 mm diameter preser foot and 69.1 N/m^2 pressure.

The estimate of f_{cl} (ratio of clothed to nude surface area) is

$$f_{cl} = 1 + 0.31 I_{cl} \quad \text{Clo.}$$

It is noted that the pumping effect may reduce the thermal insulation by between 5 and 50%. A typical reduction in thermal insulation of 20% is recommended as an estimate of the effects of wind pen-

Table 11. Standard persons used when estimating values of metabolic rate presented in ISO 8996 (1986)

	Male	Female
Height (m)	1.7	1.6
Weight (kg)	70	60
Surface area (m^2)	1.8	1.6
Age (yr)	35	35
Basal metabolic rate (W/m^2)	44	41

Table 12. Example calculation of average metabolic rate over a period where a number of tasks and activities are carried out. ISO 8996 (1989)

	Duration (s)	Metabolic rate (W/m^2)
Walk in factory 4 km/h	35	165
Carry sack of 30 kg	50	250
Standing	25	70
Time weighted average = 200 W/m^2		

etration. This emphasises that the I_{cl} values provided in the standard are very much a starting point for determining the insulation provided by clothing in practical applications. A more detailed method for accounting for wind and human movement is proposed in this special issue (Parsons *et al.*, 1999).

The evaporative resistance of clothing (R_T) is the sum of the resistance of the external air layer (R_a) and the clothing layer (R_{cl}). and can be estimated from I_{cl} for 'normal permeable clothing' by

$$R_T = 0.06[1/h_c + 2.22(I_{cl} - I_a)(1 - 1/f_{cl})]$$

$$m^2 \quad kPa/W,$$

where R_T and I_{cl} are as defined above and

$$I_a = 1/\ (h_r\ +\ h_c)$$

or

$$R_T = I_T/i_m L = (0.06/i_m)\ (I_a/f_{cl}\ +\ I_{cl}),$$

where I_{cl} is in m^2 C/W. For most normal clothing i_m has a value of about 0.38.

So

$$R_T = 0.16\ (I_a/f_{cl}\ +\ I_{cl})$$

and a further approximation gives

$$R_{cl} = 0.18\ \times\ I_{cl}.$$

The data provided in this standard are the most comprehensive available and have developed in parallel with the development of the standard. An interesting point however is that the database became so large that it is difficult to use (e.g. see McCullough *et al.*, 1985). Parker and Parsons (1990) describe a computer based system which allows efficient use of the standards.

NEW WORK TOWARDS ISO STANDARDS

New work items and areas where standards may be developed include contact with hot, moderate, and cold solid surfaces, quantities symbols and units, requirements for users with special needs, thermal environments in vehicles, working practices for cold environments, and the thermal performance of buildings. Of particular importance to heat stress assessment will be the revision of ISO 7243 to allow the WBGT index to be applied to work situations that involve the wearing of protective clothing, of ISO 7933 for the same reason and an increase in scope to include a wider range of environmental conditions, and of ISO 9886 to include the specification of physiological measurement instrumentation and further guidance on interpretation of results.

EXAMPLE OF THE APPLICATION OF INTERNATIONAL STANDARDS FOR THE ASSESSMENT OF HOT ENVIRONMENTS

Consider the practical case of firemen attending a fire. A requirement is for advice on how to ensure that they do not suffer from unacceptable heat strain. Some of the firemen will work outside and others will wear protective clothing and PPE.

The standards will not provide a complete solution to this problem but can provide guidance. Each of the types of work would be assessed separately. The environmental conditions must be quantified and thermal properties of clothing estimated as well as metabolic rates caused by activity (ISO 7726, ISO 9920, ISO 8996). The air temperature, radiant temperature, air velocity and humidity as well as natural wet bulb temperature, would be measured and required in the assessment. ISO 7243 would be used to provide a simple method involving the WBGT index. The index value would then be compared with the reference values given in Table 1. This standard can give a general indication of likely thermal strain but will be limited in terms of its inappropriate application to work involving protective clothing and high levels of directional radiation.

ISO 7933 (analytical method) will give a systematic analysis and advice where it is within the scope of the standard. In the context of the above example

Table 13. Example of clothing insulation values for a clothing ensemble (ISO 9920 (1995))

Garment	No.	Type	Weight (g)	F_{cl}	I_{clu} (clo)	$m^2\ °C\ W^{-1}$ [a]
Underpants	80	briefs	80		0.04	0.006
Undershirt	31	T-shirt	180		0.10	0.016
Coverall	120	work	890		0.51	0.079
Overtrouser	191	heat protective felt	1300		0.33	0.051
Over jacket	193	heat protective felt	1620		0.42	0.065
Socks	254	ankle length	61		0.02	0.003
Shoes	255	suede, rubber soles	499		0.02	0.003
Total ensemble	489	heat protective clothing	4630	1.50	1.55 (I_{cl})	0.240

a Value calculated from Clo values and *not* value for material.

it will be useful for some situations except where specialist protective clothing and equipment and high levels of directional radiation are involved. The standard will use the environmental measurements listed above with the estimates of clothing insulation and activity level. A computer program will be required to make the analysis. Where appropriate, the standard can provide an indication of thermal strain and guidance on acceptable exposure times to the conditions.

ISO 9886 provides guidance on physiological measurements and, in the particular example given, it may be necessary to monitor physiological responses. The standards can also be used to confirm the above standards and fine tune working practices during training and in simulations. It is the only method appropriate for monitoring the health of individuals and should be used for those wearing specialist protective clothing and equipment, particularly face masks and for extreme environments. It is important to recognize in the use of the standards that they should be used as tools to provide an integrated assessment approach. If they are used in conjunction with contextual factors and with a knowledge of the rationale and the limitations of each, they can offer a major contribution to the design of work in hot environments.

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