Industrial Health 2006, **44**, 368–379 **Review Article**

Heat Stress Standard ISO 7243 and its Global Application

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Received February 14, 2006 and accepted April 11, 2006

Abstract: This paper presents heat stress Standard ISO 7243, which is based upon the wet bulb globe temperature index (WBGT), and considers its suitability for use worldwide. The origins of the WBGT index are considered and how it is used in ISO 7243 and across the world as a simple index for monitoring and assessing hot environments. The standard (and index) has validity, reliability and usability. It is limited in application by consideration of estimating metabolic heat and the effects of clothing. Use of the standard also requires interpretation in terms of how it is used. Management systems, involving risk assessments, that take account of context and culture, are required to ensure successful use of the standard and global applicability. For use outdoors, a WBGT equation that includes solar absorptivity is recommended. A 'clothed WBGT' is proposed to account for the effects of clothing. It is concluded that as a simple assessment method, ISO 7243 has face validity and within limits is applicable worldwide.

Key words: ISO 7243, Standards, Heat stress, WBGT, Clothing, Hot environments

Introduction

In 1957, Yaglou and Minard[1] reported on their study into the control of heat casualties at military training centres in the USA. The purpose of the study 'was to define the conditions under which heat injury may occur in basic and advanced trainees and to develop safe limits for physical exertion in the heat that will control casualties'. The mechanism they chose to control heat casualties was through a simple heat stress index called the Wet Bulb Globe Temperature (WBGT). This index is now used across the globe to control heat stress in many contexts including military, industrial, domestic, sporting and commercial applications.

The WBGT is also used in national (e.g. UK, China, Japan, USA, Australia etc) regional (e.g. European) and international (ISO) Standards.

ISO 7243 'Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)', is the accepted international standard that provides a simple method for the assessment and control of hot environments. The purpose of this paper is to present that standard and to consider it in terms of its suitability for use in the wide range of hot environments in which people work throughout the world.

The WBGT Index

The WBGT index was proposed in order to avoid the elaborate procedure of determining the Effective Temperature Index (ET)[2] which was an empirical index derived from a series of laboratory studies around 1920 that became the established method used to evaluate heat stress. The index combined temperature, humidity, radiation and wind into a single value which could be used for assessment[3]. Yaglou and Minard[1] modified the index by correcting the temperature of a 150 mm diameter black globe thermometer for solar absorptivity of military clothing. Using the corrected value they derived the Effective Temperature corrected for the radiation component (ETR). This cumbersome method was replaced with the WBGT which 'is determined by two single readings, the wet bulb temperature and the globe temperature, weighted as follows for olive drab shades of military clothing'.

$$WBGT = 0.7 \text{ psychrometric wet bulb temp} + 0.3 \text{ black globe temp} \quad (1)$$

It is interesting that environmental measures made in the shade include 'shade dry and wet bulb temperature by sling psychrometers'[1] and that equation (1) refers to psychrometric wet bulb temperature. The accepted version of the equation today is for 'natural wet bulb temperature—t_{nw}[1], to be used, which is not aspirated and hence different from the aspirated wet bulb temperature—t_w that would be obtained when operating a sling psychrometer.

The original version of the WBGT equation takes account of clothing colour (or absorptivity) in calculating globe temperature. A communication from C P Yaglou in 1960[4] provides the following clarification, quoted in full as follows:

'*The Wet Bulb-Globe Temperature (WB-GT)*

This is a simplified version of the effective temperature scale, combining the dry and wet bulb temperatures, radiation and air movement into a single heat index that is best suited to practical use in the field by personnel unskilled in psychrometry. It is determined from readings of the natural wet bulb temperature (t_w), the black globe temperature (bgt), and shade air temperature (t_a), weighted as follows:

For indoor environments (infra red radiation only)

$$WB\text{-}GT = 0.7t_w + 0.3bgt \quad (2)$$

For outdoor environments (solar radiation)

$$WB\text{-}GT = 0.7\, t_w + 0.3\,(a \times 0.95\,(bgt - t_a) + t_a) \quad (3)$$

where

a = absorptivity of clothing for total solar radiation

0.95 = absorptivity of black globe

for khaki shades of clothing (a=0.63) in the sunlight,

$$WB\text{-}GT = 0.7t_w + 0.18bgt + 0.12t_a$$

The natural wet bulb temperature is that shown by a wet bulb thermometer exposed to the given radiation and wind.

The above formulae apply to atmospheres that are warm enough to induce sweating. In comfortable or in cold environments the coefficients will be different.'

McIntyre (1980)[5] summarises the early work[1] and presents the following equation.

$$WBGT = 0.7\, t_{nw} + 0.3\,(\propto(t_g - t_a) + t_a) \quad (4)$$

where

t_{nw} : national wet bulb temperature,

t_g : 150 mm diameter black globe temperature,

t_a : air temperature,

$\propto$: solar absorptivity.

For indoor conditions $\propto = 1$ and for 'normal' clothing in sunlight $\propto$ is around 0.67 giving an estimated 'clothed' globe temperature of $0.2\, t_g + 0.1\, t_a$. WBGT is now defined in detail in International Standard ISO 7243 which is described below after a brief review of associated ISO Standards.

ISO Standards for the Human Thermal Environment

ISO 7243 was first published in 1982 as part of a series of related standards for the assessment of the effects of thermal environments on people. It should be considered in terms of how it relates to those other standards and these are listed in Appendix 1.

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 an assessment methodology. The subject is divided into three principal areas (hot, moderate and cold environments) and remaining standards are divided into human reaction to contact with solid surfaces, supporting standards and standards concerned with specific populations and areas of application (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 and predicted heat strain. 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) index, and on criteria for local thermal 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 and standards are in final

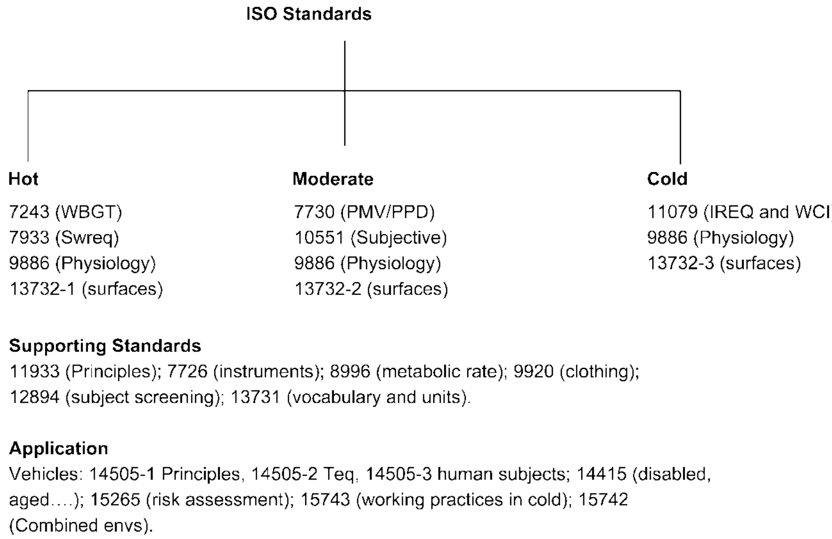

Fig. 1. ISO Standards for assessing thermal environments.

stages of development (ISO 13732 Parts 1, 2, and 3). 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 concerned with vocabulary, symbols and units (ISO 13731), medical screening of persons to be exposed to heat or cold (ISO 12894) and a standard that considers the responses of disabled persons (ISO TR 14415). Standards under development include ISO 14505 Parts 1, 2, and 3 for the assessment of vehicle environments; ISO 15265, concerned with the combined stress of environmental components (including thermal); a standard (ISO 15743) concerned with working practices in cold environments; and a standard providing an overall philosophy of application including risk assessment (ISO 15742).

The ISO working system showing how the collection of standards can be used in practice, is presented in Fig. 2.

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

$$WBGT = 0.7t_{nw} + 0.3t_g \quad (5)$$

While outside buildings with solar load

$$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a \quad (6)$$

where

t_{nw} : the natural wet bulb temperature,
t_g : the temperature of a 150 mm diameter black globe,
t_a : is 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 summarizes the specification for the sensors (see Fig. 3).

The *natural wet bulb sensor* is cylindrical in shape (6 ± 1 mm diameter and 30 ± 5 mm long), with a measuring range of 5–40°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 (e.g. cotton) covers (as a sleeve fitted with precision) the whole of the sensor and 20 mm of the support.

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

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 of 10 to 60°C with an accuracy of ± 1°C.

The WBGT value used in the standard is a weighted

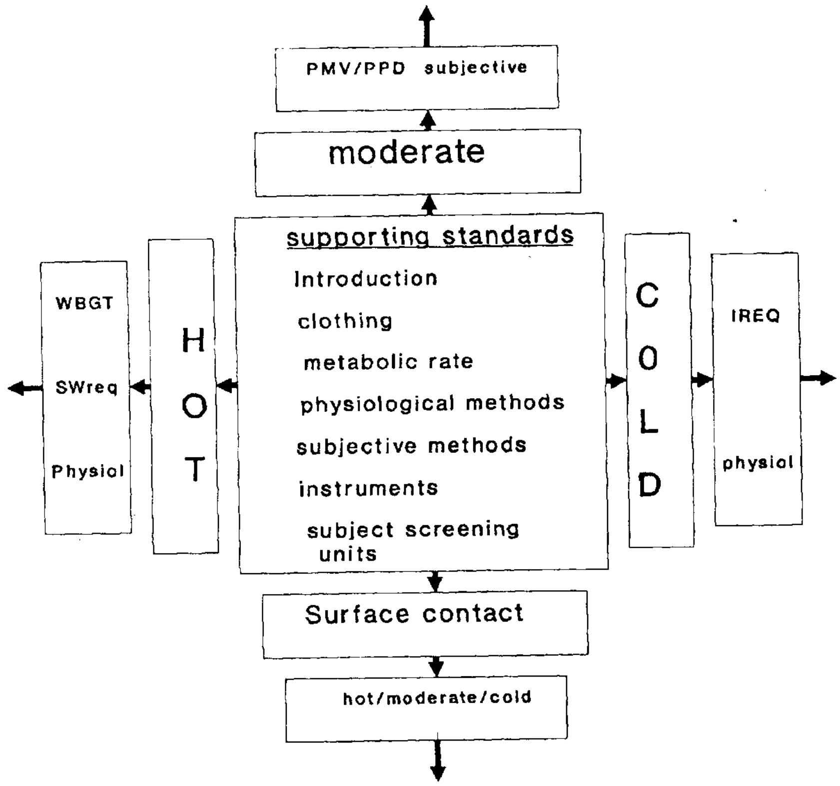

Fig. 2. Organisation and use of ISO Standards concerned with human thermal environments.

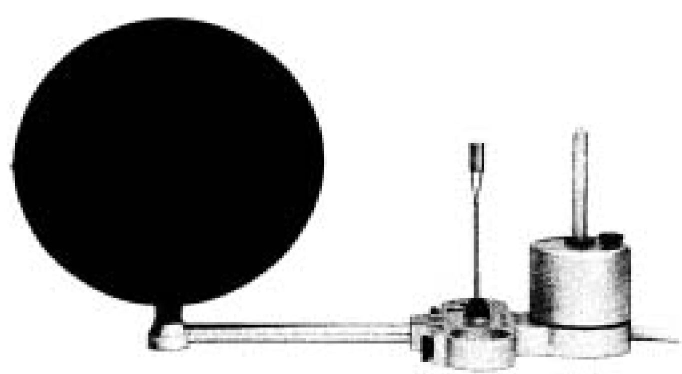

Fig. 3. WBGT Transducers.

average, over time and space, and is measured over a period of maximum heat stress. The weighting for spatial variation is given by:

$$\text{WBGT} = \frac{\text{WBGT head} + 2 \times \text{WBGT abdomen} + \text{WBGT ankles}}{4}$$

For time variations (e.g. 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 (Table 1).

An example of how ISO 7243 can be used in practice and how it relates to other ISO standards is presented below. It should be noted that if the WBGT reference values are exceeded then an option is to take a more analytical approach. The analytical approach taken in the present example is from

Table 1. ISO 7243: WBGT reference values

Metabolic rate (Wm^{-2})	WBGT reference value	
	Acclimatized (°C)	Not acclimatized (°C)
Resting $M < 65$	33	32
$65 < M < 130$	30	29
130 < M < 200	28	26
$200 < M < 260$	25 (26)*	22 (23)*
$M > 260$	23 (25)*	18 (20)*

The values given have been established allowing for a maximum rectal temperature of 38°C for the persons concerned.
*: Figures in brackets refer to sensible air movement.

Table 2. WBGT values (°C) for four work phases

Work phase (min)	WBGT*	WBGT reference
0–60	25	30
60–90	23	33
90–150	23	30
150–180	30	28

*: $WBGT = \frac{WBGTank + 2 \times WBGTabd + WBGThd}{4}$

Table 3. Basic data for the analytical assessment

Work phase (min)	t_a (°C)	t_r (°C)	P_a (kpa)	v (ms^{-1})	*Clo* (Clo)	*Act* (Wm^{-2})
0–60	30	50	3	0.15	0.6	100
60–90	30	30	3	0.05	0.6	58
90–150	30	30	3	0.20	0.6	100
150–180	30	60	3	0.30	1.0	150

From ISO 7933 (1989)

ISO 7933 (1989) and is illustrative. A more recent analytical method for ISO 7933 based upon the Predicted Heat Strain method is now available but the principle still applies.

Example of the Application of International ISO Standards to the Assessment of a Hot Environment

The following hypothetical example demonstrates how ISO Standards can be used in the assessment of hot environments. Workers in a steel mill perform work in four phases. They don clothing and perform light work in a hot radiant environment for one hour. They rest for 30 min and then perform the same light work shielded from the radiant heat, for one hour, then perform work involving moderate activity in a hot radiant environment for 30 min.

ISO 7243 provides a simple method for monitoring the environment using the WBGT index. If the calculated WBGT levels are less than the WBGT reference values given in the standard, then no further action is required. If the levels exceed the reference values then the strain on the workers must be reduced. This can be achieved by engineering controls and/or working practices. A complementary or alternative action is to conduct an analytical assessment as described in ISO 7933.

The WBGT values for the work are presented in Table 2. The environmental and personal factors relating to the four phases of the work are presented in Table 3. It can be seen that for part of the work the WBGT levels exceed those of the reference values. It is concluded that a more detailed analysis is required.

The analytical assessment method presented in ISO 7933 was performed using the data presented in Table 3 and the computer program provided in the standard. The results for acclimatized workers in terms of an alarm level are presented in Table 4.

An overall assessment therefore predicts that acclimatized workers suitable for the work could carry out an eight-hour shift without undergoing unacceptable (thermal) physiological strain. If greater accuracy is required, or individual workers are to be assessed, then ISO 8996 and ISO 9920 will provide more detailed information on metabolic heat production and clothing insulation. ISO 9886 provides methods for measuring physiological strain on workers and can be used to design and assess environments for specific workforces. For example, internal body temperature, mean skin temperature, heart rate and sweat loss may be of interest in this example.

Validity, Reliability and Usability of ISO 7243

The *validity* of the WBGT index is related to how well the WBGT value reflects the heat stress to which people are subjected and how that relates to thermal strain. There have been a number of, mostly laboratory based, studies. Bethea and Parsons[6] have provided a summary and a number of limitations are identified (e.g. when used for individuals or when wearing specialist protective clothing). There is a general finding that within these limits WBGT provides a valid index for the assessment of heat stress. The principle of the standard is that the WBGT is an index that is affected by all of the basic factors that are important to human response

Table 4. Analytical assessment

Work phase (min)	Predicted values			Duration limited exposure (min)	Reason for limit
	t_{sk} (°C)	w (ND)	s_w (gh^{-1})		
0–60	35.5	0.93	553	423	water loss
60–90	34.6	0.30	83	480	no limit
90–150	34.6	0.57	213	480	no limit
150–180	35.7	1.00	566	45	body temperature
Overall	-	0.82	382	480	no limit

From ISO 7933 (1989)

to heat. These are air temperature, radiant temperature, humidity and air velocity. Most weight is provided to natural wet bulb temperature so face validity is provided by the similarity between a sweating person in a hot environment and a saturated wick over a temperature sensor. The response of both is dependent upon evaporation for cooling. The globe temperature, given lower weight commensurate with the response of a sweating person in the heat, accounts for radiation, air temperature and air velocity and the adjustment to include air temperature, when solar radiation is present, accounts for absorptivity of clothing. In principle, therefore, the WBGT index has face validity. However, consideration of the effects of metabolic heat production and in particular clothing will limit this validity in terms of scope (area of application).

Reliability is related to whether ISO 7243, if used a number of times in identical conditions across the world to assess a hot environment, would give the same result. That is independently, of whether it is valid or not. The standardisation of the WBGT equation, as well as equipment to measure it, provides a major contribution to ensure reliability. The place, time and method of measurement are well presented in the standard but can be interpreted as guidelines. Estimates of metabolic rate may vary depending upon the tasks and context of the assessment. This will influence interpretation of the WBGT value. Tasks varying in time and place as well as interpretation for different clothing types will all require decisions from the use of the standard that may influence reliability. Reliability would therefore be greatly improved if standardised procedures for the use of ISO 7243, and hence WBGT, were produced to embed the standard in risk assessment and other systems for managing people in hot environments.

Usability is concerned with whether users of the standard can use it effectively. This raises the question of who are the intended users. The standard provides little guidance and therefore by default assumes decisions elsewhere. Annex C of the standard (informative) provides an example of an evaluation report and requests that the 'authority of person carrying out the evaluation' be recorded. It is usually assumed that the WBGT index, and hence the standard, will be recorded by a safety officer or someone responsible for the working environment. Also that it will be used in a monitoring role to ensure that the WBGT value is below the reference value and hence that the hot environment is safe and acceptable. If not, then the user of the standard would take action, probably by referring to an expert. The issue of management systems is partly covered in ISO 15265 which provides guidance. The issue of setting up systems, training of users and so on, particularly in small and medium sized enterprises throughout the world has not been addressed. For further discussion of the validity, reliability, usability and scope of ISO 7243 the reader is referred to Bethea and Parsons (2002)[6].

ISO 7243 and Estimation of Metabolic Heat Production

The type and level of activity performed by people exposed to hot environments will determine the energy used (metabolic rate) and hence the heat produced by the body. Table 1 of ISO 7243 provides a method for selecting metabolic rate in five classes (see Table 1). For a more detailed assessment, ISO 8996 can be used, however the reference values presented in Annex A of the standard, use the five classes for interpretation. Because activities vary, and estimation of metabolic rate is subject to error, those that are estimated to be around a border between the classes will be difficult to interpret (the 'cliff edge effect'). This will be particularly difficult in industrially developing countries where metabolic rates for typical tasks are not widely measured. Individual differences, including the effects of gender, disability, ethnic origin and cultural differences, including human behaviour, will all influence estimates of metabolic rate.

A particular issue is the effects of clothing type on metabolic rate. For example caused by resistance to movement or the weight of the clothing. This will become particularly important when wearing personal protective clothing and equipment (PPE). A British Standard, BS 7963: 2000[7] provides estimated increases in metabolic rate due to wearing PPE (Table 5).

ISO 7243 and Clothing

Apart from the correction made for olive drab material in the formulation of the WBGT equation, little account is taken of clothing insulation in ISO 7243. The reference values given in Annex A of the standard (Table 1 above) are for normally clothed workers (thermal insulation of 0.6 Clo) physically fit for the activity being considered and in good health. An insulation of 0.6 Clo approximately corresponds to light trousers and T-shirt which will be a reasonable estimate for most work in hot environments throughout the world. ISO 9920 will provide more accurate estimates of clothing insulation but ISO 7243 provides no guidance on adjusting WBGT reference values for clothing type. Also, ISO 9920 does not include detailed information about clothing other than that of western style. A loose garment which completely covers all or most of the body is often worn in hot climates. The properties of such garments are not only of thermal insulation but also of the dynamic air exchange, or pumping effect, which will cool (involving convection and evaporation of sweat) skin below clothing.

The influential ACGIH Threshold Limit Values[8] (TLVs) for heat stress are provided in terms of WBGT values (Table 6). It is no coincidence that WBGT is defined and measured in an identical way to that defined in ISO 7243 and that the WBGT TLV values are very similar to the reference values provided in ISO 7243 (Table 1) as the first drafts of the

Table 5. Estimated increases in metabolic rate due to wearing PPE (from BS 7963)[7]

PPE Item	Increase in metabolic rate due to wearing PPE Wm-2				
	Resting	Low metabolic rate	Moderate metabolic rate	High metabolic rate	Very high metabolic rate
Safety shoes/short boots	0	5	10	15	20
Safety boots (long)	0	10	20	30	40
Respirator (low/moderate performance, e.g. P1, P2, (see note 2)	5	10	20	30	40
Respirator (high performance, e.g. P3, see note 2)	5	20	40	60	80
Self-contained breathing apparatus	10	30	60	95	125
Light, water vapour permeable chemical coverall (e.g. disposable)	5	10	20	30	40
Chemical protective water vapour impermeable ensemble [e.g. polyvinyl chloride (PVC)] with hood, gloves and boots	10	25	50	80	100
Highly insulating, water vapour semi-permeable, ensemble (e.g. firefighters' gear consisting of helmet, tunic, over trousers, gloves and boots	15	35	75	115	155

Values have been rounded to the nearest 5 Wm-2.
Respirator classifications P1, P2 and P3 are defined in BS EN 143: 1991.
Very high metabolic rates probably cannot be maintained when wearing some forms of PPE.
It is not appropriate to add the increase in metabolic rate due to wearing footwear when tasks are stationary or sedentary.
The values in this table have been extrapolated from experimental data. The values are approximate and more accurate measurements might be obtained in practice using the method given in BS EN 8996. This more accurate method of measuring metabolic rate requires no correction for the PPE worn.

standard were based upon standards in the USA.

The values are based upon 'the assumption that nearly all acclimatised, fully clothed workers with adequate water and salt intake should be able to function effectively under the given working conditions without exceeding a deep body temperature of 38°C'. The values are for physically fit, acclimatized workers wearing light summer clothing (0.6 Clo). ACGIH (1996) provides WBGT correction factors for cotton coveralls (1.0 Clo)—take 2°C off the WBGT limit value; winter work uniform (1.4 Clo)—take off 4°C and for water barrier, permeable suits take off 6°C. For special clothing or other significant deviations, an expert is required to provide assessment. Guidance is also provided in terms of measurement of the environment, assessment of workload, work-rest regimen, water and salt supplementation, clothing and acclimatization and fitness.

Of particular importance to the validity of the WBGT method and hence ISO 7243 is the effect of the vapour permeability of clothing. The highly weighted (0.7) natural wet bulb simulates a completely soaked sweating person. If a person is wearing impermeable clothing then the 'simulation' will have limited validity. A method of taking account of both dry insulation and vapour permeability would be to place a shaped 'swatch' of clothing material over (or partially over, depending upon exposed skin) the natural wet bulb thermometer to simulate sweating under clothing and a swatch of clothing material around the globe to simulate the effects of clothing absorptivity particularly in sunlight (the swatch could be made up of layers and would simulate actual clothing worn). A validation study would be required but it may allow the WBGT reference values to be more stable, not requiring adjustment to 'limits' for clothing, the effect having been taken into account at the measurement stage. For example, for a WBGT reference value of 30°C, covering the natural wet bulb (wet wick and all) with a (loosely fitted) cylindrically shaped swatch of the clothing worn by the workers (as well as the globe) will restrict evaporation and hence the measured WBGT value will be higher and validly compared with the reference value. This would not of course take account of the 'pumping' effects of clothing which would have to be considered separately. A useful advantage of using a clothing 'swatch' over the globe is that it would eliminate the need for an air temperature sensor.

ISO 7243 and Indoor Environments

If people are exposed to solar radiation indoors, through a window, or simulated solar radiation from stage lighting for example, then the WBGT equation for outdoors in the sun will apply. Otherwise the WBGT equation for indoors will provide a simple index value involving only natural wet bulb temperature and globe temperature. Within the limitations described above, there seems to be no reason why the WBGT index will not be applicable worldwide. Indoor environments will vary in type throughout the world and in some countries, outside environments may far exceed WBGT reference values given in ISO 7243. In buildings with low thermal inertia and maybe heat providing industrial processes, hot conditions could be even more extreme indoors. While it is important to recognise that the reference values in the Standard (Table 1) are informative and therefore not part of the standard, they refer to physiological limits (internal body temperature of 38°C). People who work in such indoor environments may well be acclimatised to those conditions and may be used to working and living in the heat. Fit and thin workers may have an advantage and cultural and behavioural factors will be influential. Nutritional and hydration status will also be important.The WBGT index however will provide a method of assessment. Any adjustment to 'limit' (reference) values must be made with caution. It will be more useful to consider the working context and for example to make adjustments to metabolic rate and clothing where appropriate for people in non-western style environments. A particular point not always recognised is to use the metabolic rate (Wm^2) based upon estimated actual body surface area, instead of the 1.8 m^2 assumed for a 'western sized' average man. An adjustment can also be made for body mass, particularly important when walking up stairs or gradients. Heat casualties have often occurred because it has been considered that some people (often using their own judgement) are inherently more resistant to heat than others and that the laws of physics do not apply to them.

Table 6. WBGT Threshold limit values (°C)

Work-rest regimen	Work load		
	Light	Moderate	Heavy
Continuous work	30.0	26.7	25.0
75% work+25% rest; each hour	30.6	28.0	25.9
50% work+50% rest; each hour	31.4	29.4	27.9
25% work+75% rest; each hour	32.2	31.1	30.0

From ACGIH (1996)

ISO7243 and Outdoor Environments

Outdoor environments are characterised by weather conditions and in particular the sun but also wind and possible rain. Speculatively and in principle the ‘clothed WBGT’ described above, could be left in the rain when, in the absence of sun, the wet bulb and globe temperature would be similar and simulate the soaked worker. In direct sunlight and varied clothing across the world (from white to black often for religious purposes) the WBGT equation that takes account of the solar absorptivity of clothing would provide a more accurate assessment than the current estimate based upon ‘normal’ (green) clothing presented in ISO 7243 (equation (6) above).

An additional issue is the variation in weather conditions. In particular in a clouded sky where the sun varies from direct and full to absent behind a cloud then ‘out’ again. A judgement has to be made on what the mean WBGT will be. This will be difficult to measure, especially as the WBGT measuring instrument will have inertia and an unknown time constant. It is often quoted that the globe temperature, for example, takes 20 min to reach steady state with its environment.

In extreme conditions throughout the world the WBGT index must be used with careful interpretation. In desert conditions the sun may be very strong and clothing absorptivity will be particularly important. Reflected and re-radiated radiation from the sand (ground and surrounding surfaces) will also be important and will provide a longer wavelength input into the globe thermometer temperature. The air in the desert will however be dry and the wet bulb temperature will be a sensitive measure of heat stress.

In northern hemisphere countries in summer, where there is often direct uninterrupted (midnight sun) sunlight, WBGT values may be low due to low air temperatures and low humidity, but continuous due to constant solar radiation and constant temperatures of surrounding surfaces which do not cool at night. In desert conditions cool nights due to clear skies should avoid high WBGT values.

In tropical conditions when overcast, around the monsoon season, high humidity will be reflected in natural wet bulb temperatures being close to air and globe temperatures and hence the WBGT will reflect thermal stress in those conditions.

For sporting events (such as marathon running and others) WBGT will provide an index with face validity especially as light clothing is worn and sportsmen and women will sweat profusely. The very high levels of metabolic heat production and relative air velocity on the runner, for example, will mean that some interpretation of ISO 7243 will be required and management systems involving WBGT values, risk assessment, re-hydration and other measures to be put in place. If WBGT measures exceed limits then specific cooling measures will be required (e.g. cool showers, shade and first aid support).

ISO 7243 and Adaptive Opportunity

Whether a hot environment can be considered safe or not will depend upon the range and type of actions a person can take to reduce exposure to the heat stress. This is often called ‘adaptive opportunity’. Two environments with identical WBGT values may have very different associated risks and hence levels of safety. Examples of adaptive opportunities in the heat will include the reduction of work speed or stopping, ability to move out of the heat, reduction in clothing levels, ability to switch on fans or open windows, ability to move into the shade and so on. ISO 7243 considers changes in parameters, metabolic rate and clothing. However, it does not compare risk for the same WBGT values. A person who wears protective clothing and cannot remove it or has no opportunity to move into the shade when working in the sun, is at much greater risk than one who has that opportunity. The risk will vary for the same environmental conditions and hence the WBGT reference value may be required to vary accordingly.

Calculation of WBGT from ‘Basic Parameters’

It is generally accepted that to provide a detailed assessment of a human thermal environment, four basic environmental factors or parameters must be known[3]. These are air temperature, radiant temperature, humidity and air velocity. In principle it is not relevant or meaningful to calculate WBGT values from basic parameters as the point about the WBGT index is that it avoids detailed analysis and extensive expertise. However, as a large ‘database’ of assessments of hot environments exists, it has become of interest to be able to compare more detailed assessments, where the four basic parameters are measured, to the ‘derived’ parameters (natural wet bulb and globe temperature) of the WBGT. A complete analysis will not be provided here as it is beyond the scope of this paper. For more detail the reader is referred to Azer and Hsu[9]. The relationship between the basic parameters, mean radiant temperature (t_r based upon a globe) and globe temperature is given by

$$t_r = \left[(t_g+273)^4+\frac{0.25 \times 10^8}{\varepsilon}\left(\frac{t_g-t_a}{d}\right)^{1/4} \times (t_g-t_a)\right]^{0.25} -273 \quad \text{......(7)}$$

and for forced convection, e.g. v>0.15 ms^{-1}

$$t_r = \left((t_g+273)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon d^{0.4}} \times t_g - t_a) \right)^{0.25} - 273 \quad \text{(8)}$$

For the standard globe, values of ε =0.95 and d =0.15 m can be used.

McIntyre[5] provides the following approximation for a black globe of 0.15 m diameter and for t_r within a few degrees of t_a (which may not be the case in radiation environments)

$$t_r = t_g + 2.44\sqrt{v}\ (t_g - t_a) \quad \text{(9)}$$

so

$$t_g = \frac{t_r + 2.44\sqrt{v}\ t_a}{1+2.44\sqrt{v}} \quad \text{(10)}$$

Note that as v tends to zero, t_g tends to t_r

The natural wet bulb temperature provides a more complex relationship between the environment and a completely wetted cylinder of specified diameter. It will be affected by all four basic parameters (t_a, t_r, rh, v) and will involve a calculation of heat transfer between the sensor and the environment that would lead to a steady state value. For high air velocities > 3.5 ms^{-1} this will be equivalent to an aspirated wet bulb temperature.

For lower air velocities the natural wet bulb temperature will be related to the rate of evaporation from the sensor as well as any effects of convection and radiation. For a dry sensor the temperature will be an average of air and radiant temperatures weighted by the convective and radiative heat transfer coefficients, respectively[3]. Heat loss by evaporation will determine the thermal decrement (t_a–t_{nw}) and will be related (by the evaporative heat transfer coefficient) to the difference in the saturated vapour pressure at the natural wet bulb surface and the partial vapour pressure in the environment which is a basic parameter and measure of humidity.

Discussion

The discussion of how suitable ISO 7243 is for use worldwide depends upon interpretation of the scope of the standard. As a simple index with face validity, experience of use and 'normal' conditions, the standard can be regarded as 'fit for purpose'. The limitations described may be regarded as examples of where further expertise and more detailed analysis is required. Theoretical derivations of the WBGT therefore miss the point and are not necessary. Limitations regarding clothing (even if not specialised), metabolic rate estimation and guidance on use and interpretation of the standard should be enhanced to include a global context and be embedded in management systems, including those involved in risk assessment.

Consideration of the 'clothed WBGT' suggests in principle that it would provide a more stable and valid index than that used in the standard, however it would increase the 'complexity' of the measurement system and would increase cost. In any event clothing will play an important role in the assessment of heat stress and the importance is underestimated in the existing standard. A modification to the WBGT index to include clothing absorptivity would seem appropriate for assessments of conditions with significant solar radiation.

Conclusions

1. As a simple assessment method for determining heat stress ISO 7243 has face validity, and within limits, is applicable worldwide.
2. The standardisation of the equations for WBGT and measuring instruments in ISO 7243 greatly enhances reliability worldwide. Method of use and interpretation of results allow variations in use that need to be considered in terms of context and application.
3. Estimates of metabolic rate are important and are subject to error, particularly if the adjustments are not made for type of person and context of application.
4. Clothing is important in determining heat stress yet little guidance is provided in the standard. The use of absorptivity of clothing in the WBGT equation would enhance validity for work in the sun.
5. Use of the proposed 'clothed WBGT' would enhance validity and should be investigated.
6. Any system of controlling health and safety in hot environments should be embedded in management systems, including training of operators, that can be used effectively worldwide.

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Appendix 1: ISO Standards Concerned with the Ergonomics of the Thermal Environment

1. ISO 7243, 1982, Hot Environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). Geneva: International Standards Organization.
2. ISO 7243, 2003, Hot Environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). Geneva: International Standards Organization.
3. ISO 7726, 2003, Ergonomics of the thermal environment—Instruments for measuring physical quantities. Geneva: International Standards Organization.
4. ISO 7730, 2005, Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: International Standards Organisation.
5. ISO 7933, 1989, Ergonomics of the thermal environment—Analytical determination and interpretation of thermal stress using calculation of the required sweat rate. Geneva: International Standards Organization.
6. ISO 7933, 2005 Ergonomics of the thermal environment—Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. Geneva: International Standards Organization.
7. ISO 8996, 2004, Ergonomics—Determination of metabolic rate. Geneva: International Standards Organization.
8. ISO 9886, 2004, Ergonomics—Evaluation of thermal strain by physiological measurements, Geneva: International Standards Organization.
9. ISO 9920, 2005, Ergonomics of the thermal environment—Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. Geneva: International Standards Organization.
10. ISO 10551, 2005, Ergonomics of the thermal environment—Assessment of the influence of the thermal environment using subjective judgement scales. Geneva: International Standards Organization.
11. ISO TR 11079, 1993, Evaluation of cold environments—Determination of Required Clothing Insulation (IREQ). Geneva: International Standards Organization.
12. ISO 11399, 1995, Ergonomics of the thermal environment—Principles and application of relevant International Standards. Geneva: International Standards Organization.
13. ISO 12894, 2001, Ergonomics of the thermal environment—Medical supervision of individuals exposed to extreme hot or cold environments. Geneva: International Standards.
14. ISO 13731, 2002, Ergonomics of the thermal environment—Vocabulary and symbols. Geneva: International Standards Organization.
15. ISO 13732-1 2005, Ergonomics of the thermal environment—Methods for assessment of human responses to contact with surfaces. Part 1: Hot surfaces. Geneva: International Standards Organization.
16. ISO TS 13732-2, 2003, Thermal environment—Methods for assessment of human responses to contact with surfaces. Part 2: Human contact with surfaces at moderate temperature. Geneva: International Standards Organization.
17. ISO 13732-3, 2005, Ergonomics of the thermal environment—Methods for assessment of human responses to contact with surfaces. Part 3: Cold surfaces. Geneva: International Standards Organization.
18. ISO DIS 14505-1, 2003, Ergonomics of the thermal environment—Evaluation of the thermal environments in vehicles. Part 1: Principles and Methods for Assessment of Thermal Stress. Geneva: International Standards Organization.
19. ISO DIS 14505-2, 2003, Ergonomics of the thermal environment—Evaluation of the thermal environments in vehicles. Part 2: Determination of equivalent temperature. Geneva: International Standards Organization.
20. ISO 14505-3, 2006, Ergonomics of the thermal environment—Evaluation of the thermal environments

in vehicles. Part 3: Test method for the assessment of thermal comfort using human subjects. Geneva: International Standards Organization.
21. ISO TS 14515, 2003, Ergonomics of the thermal environments: The Application of International Standards for People with special requirements. Geneva: International Standards Organization.
22. ISO 15265, 2004, Ergonomics of the thermal environment—Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions. Geneva: International Standards Organization.
23. ISO NWI 15742, 2006, Determination of the combined effect of the thermal environment, air pollution, acoustics and illumination on humans. Geneva: International Standards Organization.
24. ISO FDIS 15743, 2006, Ergonomics of the thermal environment—Cold workplaces. Risk assessment and management. Geneva: International Standards Organization.