



# Development of a Draft British Standard: the Assessment of Heat Strain for Workers Wearing Personal Protective Equipment

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Existing methods for estimating heat stress, enshrined in British/International Standards (the Wet Bulb Globe Temperature (WBGT) index [BS EN 27243] and the Required Sweat Rate equation [BS EN 12515; ISO 7933 modified]), assume that the clothing worn by the individual is water vapour permeable; the WBGT index also assumes that the clothing is relatively light. Because most forms of personal protective equipment (PPE) either have a higher insulative value than that assumed or are water vapour impermeable, the Standards cannot be accurately applied to workers wearing PPE. There was, therefore, a need to develop a British Standard which would allow interpretation of these existing Standards for workers wearing PPE. Relevant information was obtained through reviewing the literature and consulting experts. Two questionnaire surveys of potential users of the Standards were conducted, and physiological data collected both experimentally and in work situations were considered. The information collected was used to develop the draft British Standard. It provides information and data on:

- The general effect of PPE on heat balance of the body (the ability of the body to maintain its 'core' temperature within an acceptable range)
- The effect of specific forms of PPE on metabolic heat production rate
- The thermal insulation and evaporative resistance of types of PPE
- The effect of the closure of the garments to the body on heat transfer
- The effect of the PPE on the proportion of the body covered
- The effect of an air supply (for example, Breathing Apparatus [BA]) to the wearer

Guidance is given on conducting an analysis of the work situation, taking account of the impact of PPE. Detailed methods of interpreting both BS EN 27243 and BS EN 12515 for workers wearing PPE are given, taking account of the factors listed above. Three worked examples using BS EN 27243 and BS EN 12515 are given in the Annex of the draft Standard. © 1999 British Occupational Hygiene Society. Published by Elsevier Science Ltd. All rights reserved.

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## INTRODUCTION

In many industrial situations workers are required to wear personal protective equipment (PPE) to protect them from hazards. Although offering protection, wearing some forms of PPE in some conditions may increase the risk of heat strain. To comply with health and safety legislation, employers have a duty to assess the risk of injury due to the work activities. Where heat stress may pose a risk, this can be assessed directly (by physiological measurements) but in many situations this is not practical. Different

methods for estimating potential heat stress have therefore been developed, including the Wet Bulb Globe Temperature (WBGT) index and the Required Sweat Rate index enshrined in British/International Standards BS EN 27243 and BS EN 12515 respectively (Parsons, 1999).

One assumption made by both these Standards is that the clothing worn is vapour permeable; BS EN 27243 also assumes that the clothing is relatively light. Because most forms of PPE either have a higher insulative value than that assumed or are not vapour permeable, the Standards cannot be applied directly to workers wearing PPE. There was, therefore, a need to develop a British Standard which

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would allow the existing Standards to be interpreted for workers wearing PPE.

The existing heat stress Standards fall into two main categories; those which can be used to assess the impact of the thermal environment on the individual (BS EN 27243, BS EN 12515 and ISO 9886); and those which provide methods of obtaining supporting information which can be used in these assessments, for example BS ISO 9920 and BS EN 28996. These supporting Standards take little account of PPE. For example, it is known that PPE can have a significant effect on the physiological cost of work and no reference is made to this in BS EN 28996 (Ergonomics—Determination of Metabolic Heat Production). Furthermore, little information is provided concerning the insulative characteristics or moisture permeability of items of PPE in BS ISO 9920 (Ergonomics of the thermal environment—estimation of the thermal insulation and evaporative resistance of a clothing ensemble).

In 1996 the BSI Standards subcommittee PH/9/1 (Ergonomics—Thermal Environments) commissioned a research programme with the aim of producing a draft British Standard on heat strain of workers. This Standard was to supplement each of the existing Standards relating to hot thermal environments, with specific advice on incorporating the influence of PPE.

This paper outlines the development of that draft British Standard. In the research programme, the term 'PPE' was taken to include all forms of protective clothing and equipment which is worn to protect the health and safety of the worker in some way. The research programme was conducted in close collaboration with a steering group appointed by the BSI Standards subcommittee PH/9/1.

The research was undertaken in three main stages: a literature review and discussion with experts to provide material for the draft Standard; limited validation of the draft Standard using experimental data; surveys of PPE manufacturers and health and safety experts to determine how heat stress is currently viewed and assessed.

This paper assumes a working knowledge of the Standards BS EN 27243 (ISO 7243) and BS EN 12515 (ISO 7933). A detailed description of these Standards is presented by Parsons (1999) in this special issue.

## LITERATURE REVIEW

### *Aims*

A literature review was undertaken to fill the apparent gaps in the existing thermal environment Standards in relation to wearing PPE. Discussions were also held with relevant national and international experts to further supplement the literature. The general aim of this was to propose guidance on

the assessment of heat strain for workers wearing PPE to be incorporated into the draft Standard.

### *WBGT index and correction factors*

Ramsey (1975) first put forward threshold limit values for the WBGT index for workers in hot environments based on variations in metabolic heat production rate. These assumed that the worker was adult male, normally clothed, acclimatised, physically fit, in good health and nutrition. Later refinements to these limit values, to take account of clothing, acclimatisation and physical fitness were based on observations rather than experimental data (Ramsey, 1978).

BS EN 27243 specifies limit values for work, taking account of the metabolic heat production rate, state of acclimatisation (acclimatised or non-acclimatised) and air velocity. As already mentioned, the Standard assumes that light clothing is worn. It has been recognised by many researchers that clothing plays an important part in heat stress, and that adjustments to these limit values are needed when different types of clothing are worn. Considerable research has been done in this area, concerning adjustment for different forms of clothing. Due to variations in the clothing worn in these studies it can be difficult to make direct comparisons between them. However, the relevant literature is discussed below. While there is general consensus on the effect of water vapour permeable clothing, more debate has centred around clothing correction factors for water vapour impermeable garments.

Kenney (1987) undertook a controlled laboratory experiment which could be used to provide WBGT adjustments to the recommended exposure limits for a work intensity of  $165\text{Wm}^{-2}$  using four different clothing ensembles: normal cotton work clothing (shirt, trousers); cotton coveralls worn over shorts; two sets of cotton coveralls worn over shorts; and coveralls plus a one-piece vapour-barrier suit of laminated Tyvek. The respective insulative values were estimated as 0.7, 1.0, 1.5 and 1.2 clo. The experimentally observed limiting WBGT value for the cotton coveralls was exactly the same as that predicted for the work rate (300W and continuous work), showing that no adjustment was necessary. For other clothing, WBGT adjustments based on the observed rise in core temperature were calculated (see Table 1).

In considering these data Bernard (1998) suggests that these values may overstate the effects of the clothing, firstly because critical WBGT values were set as two standard deviations below the mean for all subjects for each ensemble and each test protocol (with the suggestion that these limits were aggressively set), and secondly because there was somewhat more variability in the data as the clothing became more restrictive of evaporative cooling.

Table 1. WBGT adjustments for work<sup>a</sup> in protective clothing ensembles (Kenney, 1987)

Clothing ensemble	WBGT adjustment (°C)
Cotton shirt and trousers	+3.6
Cotton coveralls	0.0
Cotton coveralls ×2	-2.6
Vapour-barrier suit, hood, gloves, boots	-7.0

<sup>a</sup> Metabolic heat of approximately 300W (258 kcalhr<sup>-1</sup>); heat acclimatised workers.

Paull and Rosenthal (1987) evaluated the effects of wearing full body protective suits. They found that the chemical protective clothing caused physiological heat strain comparable to adding approximately between 6 and 11°C to the WBGT index. This is comparable to the work of other authors (for example Toner *et al.*, 1981; Goldman *et al.*, 1965). However, it is recognised that values derived experimentally are often only applicable to one work rate, one type of protective suit and one set of environmental conditions and caution should be exercised in any wider application of the findings.

Kenney (1987) reasons that the main differences between his study and the study of Paull and Rosenthal (1987), which suggested lowering of the WBGT by 6 to 11°C for a similar vapour-barrier suit, were firstly that they used unacclimatised workers and secondly that they added a full-face piece dual cartridge respirator to the ensemble. Thus, an increased adjustment to 11°C could be predicted.

Reneau and Bishop (1996) reviewed this literature concerning water vapour impermeable clothing and the use of the WBGT index. They concluded that the 10°C adjustment which was present in the American Congress of Government Industrial Hygienists (ACGIH) 1996 guidance would seem to be reasonable for water vapour impermeable clothing. They summarise the different corrections to

WBGT suggested by authors. These are shown in Table 2.

Kenney *et al.* (1993) report studies on vapour-permeable clothing. These suggest that such clothing has an effect comparable to wearing two coveralls, with a physiological impact between that of single coveralls and that of a vapour impermeable garment. The authors indicate that the level of strain resulting from the use of vapour permeable clothing reduces the heat load by the equivalent of 4–5°C over comparable vapour impermeable clothing.

Bernard (1998) reports work on the development of clothing adjustment factors (CAF) for use with the WBGT index. The CAF is the equivalent increase in environmental WBGT that the clothing represents (O'Connor and Bernard, 1998). Some of the values reported by these authors support the ACGIH guidance, and the work of other authors, although some ensembles result in different values. Because of differences in materials and clothing styles, it is difficult to make a direct comparisons between ensembles; these data demonstrate the variability in effect on heat stress of different ensembles.

It should be remembered that WBGT is an initial assessment method. Variations in materials, fit and individual wearer variability will mean that only general guidance on adjustments can be given. However, in general, the findings of the literature review supported the ACGIH guidance for correc-

Table 2. Suggested WBGT adjustment guidelines and sources (Reneau and Bishop, 1996)

Author	Clothing	WBGT adjustment (°C)
Ramsey, 1978	shorts, seminude	+2
	impermeable jacket/body armour	-2
	raincoat, fireman's coat	-4
	completely enclosed suit	-5
Kenney, 1987	cotton T-shirt and trousers	+3.6
	cotton coveralls	0.0
	cotton coveralls ×2	-2.6
	vapour-barrier suit (hood, gloves, boots)	-7.0
ACGIH, 1980	established by an expert	
ACGIH, 1990	summer work uniform	0
	cotton coveralls	-2
	winter work uniform	-4
	Goretex (water barrier)	-6
	Tyvek (vapour-barrier)	-10
	(fully encapsulating suit, gloves, boots, hood)	
ACGIH, 1991	summer work uniform	0
	cotton coveralls	-2
	winter work uniform	-4
	Goretex (water barrier)	-6

tion factors provided in 1990 (i.e. with the inclusion of a  $-10^{\circ}\text{C}$  correction factor for water vapour impermeable garments). The widespread use and acceptance of these correction factors both in the U.S.A. and U.K. gives them some credibility. Due to this and the supporting scientific evidence, it was recommended that these correction factors be introduced in the draft Standard. The correction factors for coveralls and heavy work uniform are not widely disputed. As is clear from the above discussion, there is more debate surrounding the correction factors for water vapour impermeable clothing.

The  $-10^{\circ}\text{C}$  correction factor for the vapour-barrier garment was removed in the 1991 ACGIH guidance, although the reason for this is not clear from the guidance itself. However, discussions with a researcher close to the development of these limits indicate that it was due to the fact that weaker evidence supports this correction factor than supports the others. Furthermore, there was concern that the WBGT may not be a good metric for exposures with vapour-barrier clothing due to the heavy weighting the WBGT gives to wet bulb globe temperature. The ACGIH committee therefore chose to provide no guidance on this issue (Bernard, personal communication).

Discussions with experts suggests that there is some concern about the inclusion of correction factors for water vapour impermeable clothing. One alternative proposed was the use of the dry bulb temperature alone. It was decided that changing from a WBGT index to a dry bulb index when water vapour impermeable clothing is worn would cause confusion and, therefore, if limits are to be applied for water vapour impermeable garments, they should be applied to the WBGT index for consistency. It was further decided that it was useful to have a correction for water vapour impermeable clothing in the WBGT index (the alternative being to encourage use of other methods for evaluating heat stress such as BS EN 12515 or physiological measurements). Therefore, inclusion of a correction factor of  $-10^{\circ}\text{C}$  to the WBGT index for water vapour impermeable clothing, was recommended for the draft Standard.

There is limited research published in this area, and there is a clear need for further research to allow accurate judgements concerning the use of the WBGT index in different environments (hot and dry/warm and humid) when water vapour impermeable clothing is worn. It is not currently clear whether the limit values proposed can be applied in a linear manner to all thermal environments (hot/dry; warm/humid etc) or at all metabolic rates.

#### *Effect of PPE on metabolic heat production rate*

Many studies of the metabolic cost of clothing are difficult to interpret because they utilise heart rate as an indirect measure of metabolic heat production

rate. In many instances it is difficult (if not impossible) to differentiate between heart rate increases attributable to increased metabolic heat production rate due to clothing and those increases resulting from thermal stress. Even where oxygen consumption data are obtained, any increase in metabolic cost may only be partly associated with the energy cost of thermoregulation. The complexities of using physiological data to interpret the effects of clothing are demonstrated by Holmér *et al.* (1992) whose study shows that heart rate, oxygen consumption, core temperature and skin temperature are all closely inter-related and considering one of these factors in isolation to determine the thermal impact of clothing can be misleading.

Clothing can increase the metabolic cost of work, both by adding weight and by restricting movement. The effect of weight of PPE on oxygen (metabolic) cost has been demonstrated for self-contained breathing apparatus (BA; Love *et al.*, 1996). The study suggested that weight distribution and its effect on the second moment of inertia were also influential factors on increased metabolic rate. This effect has also been reported for clothing, for example Teitlebaum and Goldman (1972). They reported an average increase in metabolic rate of 16% when wearing an arctic clothing ensemble compared to working in normal clothing but wearing a weight belt equivalent to the weight of the arctic clothing, concluding that this increase is due partly to 'friction drag' between layers of clothing, and partly to the bulk of the clothing and its impact on movement.

A literature search identified data on the metabolic cost of clothing ensembles (e.g. White *et al.*, 1989), footwear (Legg and Mahanty, 1986; Smolander *et al.*, 1988), respiratory protective equipment (RPE) (Hettinger *et al.*, 1997), and air cylinders for use with BA (Love *et al.*, 1996), but little data on the physiological impact of other forms of PPE. The available data on the effect of various forms of PPE on metabolic rate are summarised in Table 3 and are included in the draft Standard. The values presented in Table 3 are for individual items of PPE; where combinations of items are worn, the relevant values should be added together.

The data presented represent approximations utilising generally accepted conversions between physiological parameters such as heart rate and metabolic rate (assuming the conventional low level of muscle activity). Intuitively it would be expected that the additional loading due to PPE would vary with workload and that a percentage increase or graded increase with increasing workload would be more appropriate than a single value. However, the data available in the literature do not tend to support this. Such limited data as are available are based upon graded increases in standard tasks (for example treadmill walking). It would appear likely,

Table 3. Additional metabolic rate due to PPE<sup>a</sup>

PPE item	Resulting increase in metabolic rate (Wm <sup>-2</sup> ) (based on 1.8 m <sup>2</sup> body surface area)
Safety shoes/short boots	10
Safety boots (long)	20
Respirator (low/moderate performance for example P1, P2)	20
Respirator (high performance for example P3)	40
Self-contained breathing apparatus	60
Light chemical coverall (for example disposable)	20
Chemical protective ensemble (for example PVC) with hood, gloves and boots	50
Heavy insulative clothing ensemble (for example firefighters' gear of helmet, tunic, over trousers, gloves and boots)	75

<sup>a</sup> Note: Respirator classifications P1, P2 and P3 are defined in BS EN 143.

therefore, that the loading due to PPE is dependent on activity (movement) rather than workload. Thus the increased load due to safety footwear would not apply to a sedentary or stationary activity. However, no scientific data are available to support this assumption. In the absence of this, graded increases in metabolic rate due to PPE for different activity levels may be useful.

#### *Thermal insulation of PPE*

Tables of clothing insulation values are included in BS ISO 9920, although most of the data cover normal everyday clothing or workwear, rather than PPE. McCullough and Hong (1993) report values for a limited selection of workwear ensembles. Although the thermal insulative characteristics of general workwear are reasonably documented, little or no data are available on more specialised protective clothing. Furthermore, virtually no data are available for ancillary items such as boots, helmets, gloves and RPE.

Based on the findings of the literature review, two summary tables containing details of typical clothing insulation values for individual items of clothing and PPE and of typical clothing ensembles were drawn up and included in the draft Standard. Note that the actual insulative value for any specific item will depend on the cut and fabric used.

#### *Effect of PPE on evaporation*

Any item of PPE which imposes a barrier between the surface of the body and the surrounding air is likely to interrupt evaporation and have an effect on heat transfer. In hot conditions, evaporation of sweat is normally the main avenue for heat transfer from the body to the environment and any barrier, between the body and surrounding air, which prevents sweat evaporation may, therefore, increase heat stress.

Although few authors have systematically studied the influence of PPE on evaporative heat exchange, a number have studied the effect of clothing. Authors have generally demonstrated a continuum of increasing heat stress running from liquid/air/

vapour permeable fabrics such as cotton, through liquid barrier/vapour permeable (for example Goretex) to liquid/vapour impermeable fabrics such as PVC or Tyvek F, providing other factors are kept constant. However, several authors (for example White and Hodous, 1988) have reported that the benefits of water barrier/vapour permeable fabrics are severely curtailed when incorporated into thicker fabrics such as those used for firefighters. Furthermore, the benefit of water barrier, vapour permeable clothing is thought to reduce when a high metabolic rate is maintained, and large quantities of sweat are produced (for example Frim and Romet, 1988; Goldman, 1990).

In all clothing ensembles, a micro-climate will exist between the skin and the clothing, and this will directly affect the heat exchange at the skin surface. For garments that have a high evaporative resistance (for example water vapour impermeable clothing), evaporation of sweat from the body can take place only into the air within the clothing micro-climate. There is some evidence that when such garments are worn and the ambient dry bulb temperature is lower than the dry bulb temperature within the micro-climate, a condensation cycle is set up within the micro-climate with sweat being evaporated from the skin and condensing on the inner surface of the garment. The heat produced by the condensation of sweat is conducted to the outer xsurface of the clothing and then convected away. The higher the external air velocity, the more effective the condensation/evaporation cycle becomes. Therefore, less heat stress is experienced than would be expected. While this effect has been observed, it has not been quantified.

Different fabrics will have different degrees of vapour resistance. At present, there is insufficient information available concerning the vapour resistance of garments to say much more than that vapour resistance is high or low. When vapour resistance is high little sweat can be evaporated and therefore the environmental wet bulb temperature becomes irrelevant to heat loss; in this case the dry bulb temperature then becomes the significant factor for heat loss.

#### *Proportion of the body covered by clothing*

Body coverage is important in considering heat loss from the body. Detail is provided in BS ISO 9920 concerning the proportion of the body covered by different items of clothing. Unfortunately there is only limited information concerning the coverage of items on the head. Based on the available information and expert opinion, data on this were included in the draft Standard.

#### *PPE and the pumping effect*

It is likely that where PPE is worn over clothing, it will adversely effect the pumping effect (see Havanas, 1999). As a result, items such as a BA harness, a fall-arrest harness or an externally worn belt may result in a increased degree of heat stress. ISO 9920 recommends reduction of clothing insulation by 10% when metabolic rate is below  $100\text{Wm}^{-2}$  and by 20% when it is above  $100\text{Wm}^{-2}$  to take account of the pumping effect. It is reasonable to conclude that where a belt or harness is worn over other garments, these corrections should not be applied as the potential for pumping to occur is limited.

#### *Effect of an air supply*

Many workers wearing PPE will also be required to wear some form of BA for respiratory protection. BA is usually in one of two forms, either open circuit, where the wearer inspires air from a compressed air cylinder (inspired air will be cooler and drier than ambient air), or closed circuit where the wearer inspires air which has been through a chemical filter which 'cleans' it (inspired air will be warmer and probably more humid than ambient air). Therefore the type of BA has the potential to cool or warm the lungs and could affect the degree of heat strain. Account was taken of this in assessing heat strain in the draft Standard.

#### *Heat reflective clothing*

In situations of high radiant heat load, heat reflective clothing should, in theory, reduce the amount of heat stress the individual experiences. However, there is conflicting evidence about the benefit of heat reflective garments in reducing thermal stress. Several authors have shown it to be beneficial (e.g. Balding *et al.*, 1960; Afanaseva and Gorskova, 1973; Smith, 1980) while others have shown only a marginal benefit (Kissen and Hall, 1963) or no benefit at all (Kaufman and Bothe, 1986) when tested for its heat transfer qualities. These data consider different heat reflective materials which may have different thermal and reflective properties and it is therefore difficult to generalise about their effect. Based on the limited data currently available it is therefore recommended that for the purposes of the draft Standard heat reflective clothing is regarded as normal clothing, and its clothing insulation value and

evaporative resistance be taken into account in calculating its affect on heat strain.

#### *Conclusions*

The literature concerning PPE and the thermal environment have been reviewed. From this, factors to be included in the draft Standard have been identified. In particular it is recommended that:

- the ACGIH correction factors be applied to the BS EN 27243 in the draft Standard.
- when water vapour impermeable clothing is worn the wet bulb temperature be set to equal the dry bulb temperature as input parameters in the BASIC program in BS EN 12515.
- specific metabolic rates attributable to the PPE be included in the draft Standard and that methods of taking these into account be made clear (relevant to both BS EN 27243 and BS EN 12515).
- details of the proportion of the body covered by PPE be included (for use in BS EN 12515 BASIC program).
- details of the thermal insulation of different forms of PPE be included (for use in BS EN 12515).
- the inspired air temperature be altered in the BS EN 12515 BASIC program when RPE is worn, to  $45^{\circ}\text{C}$  when 'closed-circuit' BA is worn and to  $25^{\circ}\text{C}$  when 'open-circuit' BA is worn.
- the pumping effect be mentioned and its effect on thermal insulation outlined. The effect of PPE on the pumping effect must be made clear.

Some areas where further research is required have also been identified.

### SURVEY OF USERS OF STANDARDS

Questionnaire surveys and telephone discussions were undertaken in order to identify the needs of those who may ultimately use the Standard. These potential users were identified as the manufacturers of PPE, and those people in organisations who are responsible for the health and safety of workers.

#### *Manufacturers*

A short questionnaire was sent to 22 manufacturers of PPE, with manufacturers of garments which were thought likely to give rise to heat strain particularly being targeted. The aims of the survey were to determine what information is provided with PPE concerning heat stress effects, and whether they considered or assessed heat stress in the design of their clothing. Thirteen completed questionnaires were received (59% response), representing a wide range of PPE products. Of those which responded, eight organisations manufactured clothing which it was thought may pose a particular risk of heat strain, that is clothing which protected against chemical/biological agents or asbestos. Of these, six

report that they provide information on heat stress with the garments they manufacture, showing that they recognise heat stress as an issue. The clothing for which heat stress information was provided included fire fighters' protective clothing, high barrier chemical protective work wear, limited use chemical protective work wear, bomb disposal suits and vessel entry work suits.

The information provided was predominantly in the form of a user manual or instructions. It was usually simple, stating that during prolonged wearing or high work rates or high temperatures workers may experience heat stress. Some manufacturers gave information on how to reduce the heat stress (garment ventilation or moisture absorbing underwear).

All manufacturers said that they considered heat stress in the design of their clothing, only two (15%) used the thermal Standards; one of these reported using ISO 7933 while the second reported using physiological monitoring (ISO 9886). From discussions with the manufacturers it was clear that they considered the heat stress issue from a clothing science stance, looking at increasing the potential for evaporation of sweat by developing vapour permeable fabrics, or improving venting into the garments.

#### *Those responsible for the health and safety of workers wearing PPE*

A survey of those responsible for the health and safety of workers wearing PPE was undertaken with the aims of identifying the situations of potential heat stress, determining whether organisations recognise the risk of heat stress and identifying how they currently assess this risk. A short questionnaire was sent to 48 organisations selected from the following industries: chemicals, manufacturing, power generation, heavy engineering, the fire service, offshore and mining. Completed questionnaires were received from 23 organisations (48%). Telephone interviews were conducted with 16 of the organisations which had responded, and with a further five relevant organisations.

*Situations of potential heat stress.* Of those who responded, 15 organisations had workers in situations where they may be exposed to heat stress as a result of wearing PPE. These represented a wide range of industries and activities. Most respondents appeared to be aware of the risks of heat stress as short durations of work were often cited as posing a risk. Some work situations were reported which were particularly likely to give rise to heat stress, such as heavy manual work at 30°C, for 2 h wearing impervious suits; welding in confined spaces at 32–41°C for 1–4 h wearing heat protective clothing; digging pits at WBGT of 30°C taking spells at the work but wearing PVC suits and BA.

In a number of organisations workers wore various types of PPE outdoors, where the degree of heat stress would depend on the weather conditions. This is of particular concern since the extent of heat stress (including the degree of solar load) is difficult to predict in advance.

*Assessment of heat stress.* Twelve of the organisations which responded (52%) said that they undertake assessment of heat stress, although only nine of these had reported having workers in situations where they may be exposed to heat stress.

Respondents were asked how they had undertaken risk assessments. Nine organisations said they had used the WBGT index, and six of these also used the ACGIH guidance. One organisation undertook qualitative assessments and another undertook heat stress monitoring. None had undertaken physiological measurements, or used the Required Sweat Rate equation. Informal discussions at a (more recent) conference suggest that BS EN 12515 is being more widely used than would be indicated from this survey (Betha, personal communication).

Respondents were asked what factors they took into account in the assessment. Of the 11 organisations which answered this question, all considered the dry bulb temperature, the duration of exposure, the clothing worn and the metabolic rate of the individual. Ten also considered the wet bulb temperature and the radiant heat load. Fewer considered the percentage of the body covered (nine respondents), the air velocity (eight), the age of the worker (seven), their degree of acclimatisation (six) and their experience (four). This indicates which factors respondents consider as key in undertaking an assessment; it is encouraging to see that those factors which are most significantly related to heat stress are considered by all or almost all of the respondents.

Five of the people who took part in the telephone interviews (31%) had not heard of the thermal Standards or were only vaguely aware of their existence. There were potential heat stress conditions in each of these organisations. Seven of those who took part in the telephone interviews (44%) reported that they had not undertaken a formal assessment of heat stress. Three companies which have undertaken assessments reported that these were driven by the Confined Spaces Regulations which require assessment of the risks of working in confined spaces. Four of the companies which took part in the telephone interviews said that they wanted to make assessing and managing heat stress a priority in the next 12 months, indicating that awareness of this issue may be increasing.

One large organisation reported undertaking limited physiological monitoring of workers on exit from a hot working area. Radial pulse and oral temperature measurements were taken, and based on these a work:rest regime of 1:3 was developed.

Physiological measurements were also used to validate that the work:rest regime was suitable.

*Difficulties with Standards.* Respondents were asked if they had experienced any problems in using these documents. Comments indicated that there was a clear need for guidance on issues not covered by existing Standards, for example high radiative heat situations, high temperatures (55°C), short periods of intense activity, insulation greater than 0.6 clo, vapour impermeable clothing, individual wearer differences. One commented that the WBGT work/rest regimes are difficult to interpret and evaluation of metabolic rates are exceedingly complex. One thought that some of the heat stress indices, for example WBGT (ACGIH), were very conservative leading to high safety margins and to practical difficulties while, conversely, another commented that illness can still arise when using these guidelines. This illustrates the difficulty in assessing the likelihood of heat strain when considering all potential wearers.

During discussion with respondents, two organisations reported that it was difficult to measure WBGT temperature in confined spaces as the equipment required was bulky. One of these thought that dry bulb temperature was a more appropriate measurement when workers were wearing non-vapour permeable clothing, as in these situations the humidity does not effect how much sweat the person can evaporate (see Section 2.2). Dry bulb temperature was also seen as giving a more direct (immediate) measure as an indication of heat stress. One respondent found the BS EN 27243 Standard unclear on evaluation of heat stress, and so now uses the ACGIH guidance.

It is clear that users of the Standards are experiencing particular problems with thermal Standards in the more extreme conditions, where radiant temperatures and metabolic rates are high. Both BS EN 27243 and BS EN 12515 are limited in their scope of applicability (for example, in high temperatures or situations of high radiative heat load), and it appears that some users may be trying to apply them outside their scope. It is important that users understand the scope of these Standards.

*Reducing the risk of heat stress.* Respondents were asked whether they had reduced the risk of heat stress in any way. Twelve of the respondents said that they had done so; mostly by re-organising the work (that is, restricting wearing/exposure and introducing rest breaks). One organisation had reduced heat stress at source by screening off the radiant heat source, and another provided an air conditioned work environment when wearing PPE. Rests in cooler areas and provision of drinks were also mentioned. None of the organisations had introduced different forms of clothing to reduce the risk of heat stress.

During the telephone interviews three organisations reported training the relevant workers in ways to cope with work in the heat, for example, regular intake of fluid, identifying symptoms of heat strain and operating a buddy system. One organisation was considering the use of personal cooling. In another organisation workers wearing BA (sometimes also with chemical protective clothing) were limited to 20 min exposure (the length of the cylinder). They would then rest in a cooled area, and would only re-enter the enclosure after 2 h. This guidance was based on US firefighters regulations.

It generally appears that altering the work–rest regime is the most common method of reducing heat stress. During the telephone discussions, one organisation mentioned altering the task, so that work in the confined area was not required, but all other organisations looked at alleviating the conditions for the individual. Those involved in the discussions were using a range of documents to help assess the heat stress. These were mainly based on the WBGT guidance (the basis of ACGIH and Croner's guidance). However, some problems with measuring the environment in accordance with WBGT criteria were identified.

#### PHYSIOLOGICAL DATA

Simple validation of the proposed draft Standard was undertaken using physiological data collected both in the lab and in industrial heat stress situations. Unfortunately, limited data were available, partly because some industrial activities which involve heat stress only occur irregularly. One main source of data was considered.

Data for workers wearing chemical protective ensembles were collected during some IOM field work. Full chemical protective clothing and respirators were worn. Physiological monitoring of individuals was undertaken (aural temperature), although there were some difficulties with obtaining accurate readings in the field.

An initial recommendation was made for a work:rest schedule based on BS EN 27243 (WBGT index), assuming a  $-10^{\circ}\text{C}$  correction factor for water vapour impermeable clothing. This indicated that for the particular conditions surveyed, a work:rest schedule of 1:3 was required. Management indicated that a 1:1 work:rest schedule would be easier to manage. Further investigation of the conditions using BS EN 12515 was undertaken. Because water vapour impermeable garments were worn it was assumed that the dry and wet bulb temperature were equal. BS EN 12515 indicated that a 30 min work:30 min rest schedule should be sustainable in these conditions.

This schedule was introduced and the physiological response of workers monitored. No aural temperatures above  $38^{\circ}\text{C}$  were recorded; in general,

core temperatures rose by approximately 0.5°C over the duration of work although isolated increases of up to 1°C were recorded. Heart rates increased by between 20–40 bmin<sup>-1</sup> (beats per min) for the shift conditions, from between 80–100 bmin<sup>-1</sup> to between 110–140 bmin<sup>-1</sup>. During the first two weeks of working, most working heart rates were around 120 bmin<sup>-1</sup>. Later on in the work process, as the work load increased, heart rates recorded were between 150–160 bmin<sup>-1</sup>. However, still no aural temperatures exceeded 38°C. It, therefore, appears that the recommended work–rest schedule arising from the BS EN 27243, BS EN 12515 and the draft Standard was suitable for these working conditions.

The general level of physiological heat strain recorded was not as high as anticipated although some increases in core temperature approaching 1°C were documented. The reasons for this are complex. Firstly, it presumably reflects the extent of inter-individual variability and the consequently conservative nature of the heat stress Standards for many workers. Secondly, there may have been some self-pacing so that the estimated metabolic rate was not sustained during the work period. Finally, the environmental conditions were such that an internal condensation cycle as referred to in Section 2.5 was likely to be established within the protective clothing.

One further difficulty highlighted by this study was that, because the heat load was primarily metabolic rather than environmental, workers experienced chilling whilst resting in the same climate. This was exacerbated by the accumulation of sweat within the clothing ensemble, reducing the effective insulation. This study also demonstrated the difficulty in some work situations of conducting physiological monitoring. Some workers were reluctant to take part in physiological monitoring; they were working in adverse conditions, with extensive PPE and were reluctant to wear anything which may cause more discomfort (aural thermistor). There were also practical difficulties of taking measurements in the environment.

Although considerable efforts were made to obtain data with which to validate the draft Standard, limited data were available. It was difficult to obtain good quality data from the field for several reasons, including the constraints imposed by the activities (work pressures), unexpected variations in work conditions or activities, and unwillingness of workers to take part. However, the data available indicated that the guidance contained in the draft Standard concerning WBGT was suitable as initial guidance and for devising work:rest schedules, and that BS EN 12515 may provide more accurate estimates of heat stress.

#### DEVELOPMENT OF THE DRAFT BRITISH STANDARD

Based on the literature, on expert knowledge and on the identified needs of the respondents, a draft British Standard was prepared. As well as making it scientifically valid, attention was particularly paid to making it readable and easy to use. The Standard discusses the impact of PPE on heat balance in general terms, followed by an explanation, and where possible a quantification, of how PPE affects heat stress. Factors about which specific guidance are included are:

- alteration to convective and evaporative heat transfer due to the insulative characteristics of PPE;
- alteration to convective and evaporative heat transfer due to the increased proportion of body area covered by PPE;
- increase in metabolic rate due to wearing of PPE.

Mention is also made of the following factors, although it has not been possible to fully quantify these due to a lack of available data:

- interference with evaporative heat transfer due to increased proportion of body area covered and vapour permeability characteristics of covering;
- impact on radiative heat transfer of PPE;
- direct contribution of PPE to heat load due to, for example, chemical activity of PPE (for example chemical respirators [that is, cool, dry air from BA sets]);
- the pumping of air around a clothing ensemble and the effect of this on heat stress.

Having set out the general principles, these factors are applied to the two existing Standards which provide a method for assessing heat strain (BS EN 27243 and BS EN 12515). Details of how to conduct an analysis of the work situation is contained in Annex A of the draft Standard with methods being detailed for the BS EN 27243 and BS EN 12515 Standards. Three examples of the application of the methods described are included in the draft Standard, based on scenarios reported by respondents to the questionnaire survey. The interpretation of the findings of the assessment are also discussed.

The format and presentation of the draft Standard was influenced by the comments of those who responded to the surveys. It was important that the draft Standard was easy to understand and use. It was also important that the scope of the Standard and whether it was applicable to their work situation was clear. Although a range of industries and work situations were represented by responders to the survey, there were some common activities which were used as the basis for providing focussed examples of metabolic work rates given in the Standard. The clothing worn was also used as the basis for developing guidance on the proportion of

the body covered by different forms of PPE, and in providing information on the clothing insulation value of different clothing ensembles.

The draft was circulated for public comment by BSI on 15th May 1998. It was presented and discussed at the Clothing Science Group Meeting at Loughborough University on 1st June 1998. Documented comments were invited to be received by 31st July 1998. Once received, the draft was reviewed in the light of these comments. The draft Standard will be the responsibility of the British Standards technical committee PH 9/1 until it is in an appropriate format for becoming a British Standard.

#### RECOMMENDATIONS FOR FURTHER RESEARCH

Based on the findings of the literature review, discussions with experts and the findings of the questionnaire survey, the following research needs were identified.

1. Information is required on the application of correction factors to WBGT reference values for clothing. In particular, firstly, the application of a correction factor for water vapour impermeable garments in different types of environments (warm/humid vs hot/dry); secondly, the application of these correction factors at different metabolic rates, to determine whether WBGT correction factors can be applied linearly.
2. Although the WBGT correction factors suggested in the draft Standard are based on experimental data and have been used extensively in the U.S.A., these should be validated fully in the U.K.
3. There is a lack of data on the clothing insulative values of PPE. There is no data available on most items of PPE. Research is needed to extend the current Standard ISO 9920 to include these items.
4. Information is required on the proportion of the body covered by helmets, face masks, goggles, hearing defenders and other PPE worn on the head and neck.
5. There is a lack of data on the evaporative resistance of different clothing ensembles and PPE. Research is needed to develop such a database.
6. More information is required concerning the metabolic cost of wearing different forms of PPE and whether, and by how much, this alters with different metabolic rates or types of activity.
7. Further research is required into the accuracy of prediction of stay times based on globe temperature when wearing vapour-barrier total encapsulating clothing (Bernard, 1998) for possible inclusion in future revisions of the draft Standard.
8. Research is required to investigate the amount of protection offered by heat reflective fabrics.
9. More research is required on the pumping effect and the extent to which this provides cooling to the body. Quantification of this effect would be useful.
10. More research is required on the fit of clothing to the individual and the extent to which this affects the heat strain experienced. Quantification of this effect would be useful, as well as methods to allow this information to be applied in the workplace (in terms of determining the fit of garments).
11. Research is required into verifying and quantifying the phenomenon of internal evaporation/condensation of sweat resulting in cooling the body of workers wearing water vapour impermeable garments, and the effect this has on heat stress in different environments.
12. The extent of use of the draft Standard and its effectiveness in controlling heat stress should be assessed at a suitable period after its introduction.

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#### REFERENCES

- Afanaseva, R. F. and Gorskova, R. I. (1973) Assessment, from the occupational hygiene viewpoint, of the thermo-insulating characteristics of clothing made of fabrics with high reflective properties. *Gigiena I Sanitarija* **6**, 43–47.
- ACGIH (1996) *1996–1997 Threshold limit values for chemical substances and physical agents and biological exposure indices*. American Conference of Governmental Industrial Hygienists, Cincinnati.
- Balding, H. S., Hertig, B. A. and Riedesel, M. L. (1960) Laboratory simulation of a hot industrial job to find effective heat stress and resulting physiologic strain. *American Industrial Hygiene Association Journal* **25**–31.
- Bernard, T. E. (1998) Heat stress and protective clothing: an emerging approach from the United States. Paper presented at a one day Clothing Science Group meeting at Loughborough University, 1st June 1998.
- BS EN 12515 (1997) *Hot environments—Analytical determination and interpretation of thermal stress using calculation of required sweat rate*. British Standards Institute, London.

- BS EN 143 (1991) *Specification for particle filters used in respiratory protective equipment*. British Standards Institute, London.
- BS EN 27243 (1994) *Hot environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*. British Standards Institute, London.
- BS EN 28996 (1994) *Ergonomics—Determination of metabolic heat production*. British Standards Institute, London.
- BS ISO 9920 (1995) *Ergonomics of the thermal environment—Estimation of the thermal insulation and evaporative resistance of a clothing ensemble*. British Standards Institute, London.
- Frim, J., Romet, T. T. (1988) The role of the moisture vapour barrier in the retention of metabolic heat during firefighting. Ontario: Defence and Civil Institute of Environmental Medicine (DCIEM No. 88-RR-40).
- Goldman, R. F., Green, B. E. and Lampietro, P. F. (1965) Tolerance of hot, wet environments by resting men. *Journal of Applied Physiology* **20**, 271–277.
- Goldman, R. F. (1990) Heat stress in firefighting. The relationship between work, clothing and environment. *Fire Engineering* **May**, 47–52.
- Hanson, M. A. and Graveling, R. A. (1998) *Development of a draft British Standard: The assessment of heat strain for workers wearing personal protective equipment*. Paper prepared for BSI Committee PH/9/1.
- Havanas, G. (1999) *Annals of Occupational Hygiene* (in press).
- Hettinger, Th., Heudorfer, W., Dietmann, U., Berlitz, A., Korzec, T. and Bulheller, S. (1997) *Physiological effects of the use of personal respiratory protection*. ECSC-EEC-ESEC, Brussels, Health and Safety at Work. 5e ECSC medical research programme.
- Holmér, I., Nilsson, H., Rissanen, S., Hirata, K. and Smolander, J. (1992) Quantification of heat balance during work in three types of asbestos-protective clothing. *Int. Arch. Occup. Environ. Health* **64**, 243–249.
- ISO 7243 (1989) *Hot environments—Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*. International Organisation for Standardisation, Geneva.
- ISO 7933 (1989) *Hot environments—Analytical determination and interpretation of thermal stress using calculation of required sweat rate*. International Organisation for Standardisation, Geneva.
- ISO 9886 (1992) *Evaluation of thermal strain by physiological measurements*. International Organisation for Standardisation, Geneva.
- Kaufman, W. C. and Bothe, D. J. (1986) Thermal insulation of materials with possible aerospace application. *Aviation, Space and Environmental Medicine* **57**, 993–996.
- Kenney, W. L. (1987) WBGT adjustments for protective clothing. *American Industrial Hygiene Association Journal* **48**, A576–A577.
- Kenney, W. L., Hyde, D. E. and Bernard, T. E. (1993) Physiological evaluation of liquid-barrier, vapor-permeable protective clothing ensembles for work in hot environments. *American Industrial Hygiene Association Journal* **54**, 397–402.
- Kissen, T. T. and Hall, J. F. (1963) *Physiologic response to transient heat stress in reflective versus non-reflective clothing*. Defence Technical Information Center.
- Legg, S. J. and Mahanty, A. (1986) Energy cost of back-packing in heavy boots. *Ergonomics* **29**, 433–438.
- Love, R. G., Johnstone, J. B. G., Crawford, J., Tesh, K. M., Graveling, R. A., Ritchie, P. J., Hutchison, P. A. and Wetherill, G. Z. (1996) *Study of the physiological effects of wearing breathing apparatus*. Home Office, London, (FRDG Publication No. 13/96).
- McCullough, E. A. and Hong, S. (1993) A database for determining the decrease in clothing insulation due to body motion. *ASHRAE Transactions* **93**(6), 765–775.
- O'Connor, D. J. and Bernard, T. E. (1998) *Continuing the search for WBGT clothing adjustment factors [j]Applied Occupational and Environmental Hygiene*, (in press).
- Parsons, K. C. (1999) *Annals of Occupational Hygiene*.
- Paull, J. M. and Rosenthal, F. S. (1987) Heat strain and heat stress for workers wearing protective suits at a hazardous waste site. *American Industrial Hygiene Association Journal* **48**, 458–462.
- Ramsey, J. D. (1975) Heat stress standard: OSHA's Advisory Committee Recommendations. *National Safety News* **89**.
- Ramsey, J. D. (1978) Abbreviated guidelines for heat stress exposure. *American Industrial Hygiene Association Journal* **39**, 491–495.
- Renau, P. D. and Bishop, P. A. (1996) A review of the suggested wet bulb globe temperature adjustment for encapsulating protective clothing. *American Industrial Hygiene Association Journal* **57**, 58–61.
- Smith, D. J. (1980) Protective clothing and thermal stress. *Annals of Occupational Hygiene* **23**, 217–224.
- Smolander, J., Louhevaara, V., Hakola, T., Ahonen, E. and Klen, T. (1988) Oxygen consumption, heart rate and perceived exertion during walking in snow with boots of differing weights. In *Trends in Ergonomics/Human Factors V*, ed. F. Aghazadeh, pp. 935–940. Elsevier, Amsterdam.
- Teitlebaum, A. and Goldman, R. F. (1972) Increased energy cost with multiple clothing layers. *Journal of Applied Physiology* **32**, 743–744.
- Toner, M. M., White, R. E. and Goldman, R. F. (1981) Thermal stress inside the XM-1 tank during operations in an NBC environment and its potential alleviation by auxiliary cooling. Defence Technical Information Centre, Alexandria, Va, US Army Research Institute of Environmental Medicine, Technical Report T4/81.
- White, M. K. and Hodous, T. K. (1988) Physiological responses to the wearing of firefighters' turnout gear with Neoprene and Goretex barrier liners. *American Industrial Hygiene Association Journal* **49**, 523–530.
- White, M. K., Verduyssen, M. and Hodous, T. K. (1989) Work tolerance and subjective responses to wearing protective clothing and respirators during physical work. *Ergonomics* **32**, 1111–1123.