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Development of a draft British Standard: the assessment of heat strain for workers wearing protective equipment

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***Development of a draft British Standard:
The assessment of heat strain for workers
wearing personal protective equipment***

MA Hanson and RA Graveling

**September 1999
IOM Research Report TM/99/03**

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Wearing personal protective equipment (PPE) should protect wearers from hazards; however, wearing some forms of PPE may increase the risk of the wearer experiencing heat strain. This is mainly because, by providing a barrier between the worker's body and the hazard, the PPE will usually increase the insulation of the body and/or reduce the opportunity for evaporation of sweat.

Two methods of assessing heat strain are enshrined in British and International Standards (BS EN 27243 and BS EN 12515). These assume that the worker is wearing light, vapour permeable clothing. As most forms of PPE either have a higher insulative value than that assumed or are water vapour impermeable, these 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. The BSI Standards subcommittee PH/9/1 (Ergonomics - Thermal Environments) commissioned and oversaw a research programme which was conducted by the IOM to develop a draft Standard ('The assessment of heat strain for workers wearing personal protective equipment').

The research comprised a literature review and discussions with experts, a questionnaire survey to potential users of the Standards, and consideration of reported physiological data. The information collected was used to develop the draft British Standard which provides information and data on:

- The general effect of PPE on heat balance of the body
- 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
- The proportion of the body covered by different types of PPE
- The effect of an air supply (BA) to the wearer.

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SUMMARY

In many industrial situations workers are required to wear personal protective equipment (PPE) in order to protect them from hazards. Although offering protection, it is known that the wearing of some forms of PPE in some conditions may increase the risk of an individual experiencing heat strain. This is because whilst PPE provides a barrier between the worker's body and the hazard, it will also usually increase the insulation of the body and/or reduce the opportunity for evaporation of sweat from the body. In situations of heat stress, evaporation of sweat is usually the main route of heat loss from the body.

Under the Management of Health and Safety at Work Regulations 1992 it is the employer's responsibility to assess the risk to their workers' health and safety of the work activities. This will include assessing the risk of heat strain for workers wearing PPE. Heat strain can be measured directly (physiological measurements) but in many situations this is not practical, and therefore different methods for estimating potential heat stress to which the workers may be exposed have been developed. Two such methods are enshrined in British/International Standards concerning ergonomics of the thermal environment. These are:

BS EN 27243: 1994, *Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*.

BS EN 12515:1997, *Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate*.

Both these Standards allow an estimation of acceptable thermal environments or exposure times based on the dry bulb temperature, the wet bulb temperature, air velocity and metabolic heat production rate.

BS EN 12515: 1997 is more sophisticated (computing likely heat strain using a BASIC program) and, as well as these factors, also takes account of the thermal insulation of any clothing and the proportion of the body uncovered. However, one assumption made by both these Standards is that the clothing worn by the individual is water vapour permeable and BS EN 27243: 1994 also assumes that the clothing is relatively light. Because most forms of 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 seen to be a need to develop a British Standard which would allow interpretation of these existing Standards for workers wearing PPE.

In 1996 the BSI Standards subcommittee PH/9/1 (Ergonomics - Thermal Environments) commissioned a research programme concerning heat strain for workers wearing PPE. The main purpose of the research was to provide a draft British Standard on heat strain of workers, taking account of PPE worn. The research programme was conducted in close collaboration with a steering group appointed by the BSI Standards subcommittee PH/9/1.

This report outlines the research which was undertaken in the development of the draft British Standard entitled 'The assessment of heat strain for workers wearing personal protective equipment'. It was issued as a draft for public comment on 15th May 1998.

The research which was conducted to develop the Standard comprised of a literature review and discussions with experts, a questionnaire survey to potential users of the Standards, and consideration of physiological data collected experimentally and in work situations. The literature review concentrated particularly on filling the gaps in the existing thermal Standards for workers wearing PPE.

The use of correction factors for the WBGT index were considered and, based on scientific evidence, included in the draft Standard. Alterations to the Required Sweat Rate calculations (BS EN 12515) were also supported from the findings of the literature review. Additional supporting information was also identified in the literature, such as metabolic heat production rates and thermal insulation values for different forms of PPE, the proportion of the body covered by PPE, the impact of the fit of clothing on heat stress, and the effect of an air supply (e.g. Breathing Apparatus).

Two questionnaire surveys were undertaken to determine the needs of potential users of the draft Standard; the two groups of potential users of the draft Standard were identified as manufacturers and health and safety specialists. Questionnaires were sent to 22 manufacturers and 48 health and safety specialists and follow up telephone discussions were undertaken where appropriate. Response rates for each questionnaire were approximately 50%. The results showed that most manufacturers of PPE which could increase the risk of heat stress were aware of this and some provided information concerning heat stress with the items they manufactured, although this was in general limited to a warning. Health and safety specialists reported the conditions in which the risk of heat stress could arise in their organisation, and described what methods they had used to reduce the risk of heat stress. This was primarily introducing work: rest schedules and allowing the workers to take regular breaks, although a small number had attempted to reduce the ambient temperature by shielding radiant heat sources or introducing air conditioning. Respondents were asked which (if any) heat stress Standards they used. The results indicated that BS EN 27243 (WBGT index) and the ACGIH guidance were widely used, although BS EN 12515 and physiological monitoring were not used. However, more recent reported discussions with users indicates that BS EN 12515 may be more widely used than this survey indicated.

Limited physiological data obtained mainly from field work was examined to determine the validity of the recommendations made in the draft Standard. Although little data was available, it did support the recommendations made in the draft Standard. However, examination of data in this way also highlighted the difficulties experienced in collecting substantial, good quality physiological data in the field.

The information collected by these methods was used to develop the draft British Standard. The draft Standard provides information and data on:

- The general effect of PPE on heat balance of the body (the ability of the body to maintain the 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
- The effect of the PPE on the proportion of the body covered
- The effect of an air supply (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 Annex B of the draft Standard.

The ways in which the equations in BS EN 12515:1997 (which are the basis of the BASIC program used in the calculation) should be changed to take account of the PPE are also given (Annex D).

The draft Standard was circulated and discussed at a UK Clothing Science Meeting held on 1st June 1998. Public comments concerning the draft Standard were invited, and will be received by BSI by 31st July 1998.

1. INTRODUCTION

In many industrial situations workers are required to wear some form of personal protective equipment (PPE) in order to protect them from hazards. These hazards may include impact and collision, noise, dusts, chemicals and other toxic substances. It is a requirement under current legislation (e.g. The Personal Protective Equipment at Work Regulations 1992) that employers reduce the need for wearing PPE as far as possible and, where a risk to workers still exists, that they then select and maintain suitable PPE for protection against the hazards. Although protecting workers from hazards, it is known that the wearing of some forms of PPE in some conditions may increase the risk of an individual experiencing heat strain. Because PPE provides a barrier between the worker's body and the hazard, it will usually increase the insulation of the body and reduce the opportunity for evaporation of sweat from the body. In situations of heat stress, evaporation of sweat is usually the main route of heat loss from the body. Heat strain is thought particularly to be a problem with chemical protective clothing where the potential for evaporation of sweat is often severely limited. Heat strain may be manifest in heat related health problems, such as heat cramps, prickly heat, headaches, nausea, vertigo, weakness, thirst, giddiness and fainting. More severe heat stress may cause unconsciousness, convulsions or mental confusion (heat stroke), and may result in death. Alternatively, thermal discomfort may prompt a wearer not to wear PPE correctly, resulting in a reduction in protection against the original hazard.

Under the Management of Health and Safety at Work Regulations 1992 it is the responsibility of the employer to assess the risk to their workers' health and safety from their work activities. One hazard which workers wearing PPE may be exposed to is heat stress. There is therefore the need for guidance for employers in terms of assessing the likely heat stress in a given working environment. One way such guidance can be given is in the form of British Standards. There are currently several British and International Standards concerning ergonomics of the thermal environment. These include:

BS EN 27243: 1994, *Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature).*

BS EN 27726:1994, *Thermal environments - Instruments and methods for measuring physical quantities.*

BS EN 12515:1997, *Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate.*

BS EN 28996:1994, *Ergonomics - Determination of metabolic heat production.*

ISO 9886:1992, *Evaluation of thermal strain by physiological measurements.*

BS ISO 9920:1995, *Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble.*

BS ISO 10551:1995, *Ergonomics of the thermal environments - Assessment of the influence of the thermal environment using subjective judgement scales.*

BS ISO 11399:1995, *Ergonomics of the thermal environment - Principles and application of relevant International Standards.*

ISO/DIS 12894:1998, *Ergonomics of the thermal environment - Medical supervision of individuals exposed to extreme hot or cold environments.*

Of these Standards, there are three which allow assessment or estimation of the effect of the thermal environment on heat stress (BS EN 27243, BS EN 12515 and ISO 9886). The most comprehensive of these is the evaluation of thermal strain by physiological measures (ISO 9886), which allows a direct physiological measure of the effect of the environment, work rate and clothing on the individuals, and takes account of the differences between individuals. As measurements are made of individuals, no assumptions are made of the differences between individuals. (It is widely recognised that there are differences in the way individuals respond to the heat, e.g. Leithead and Lind, 1964). Because this method takes account directly of the impact of the clothing on the individual, there was no need for a method of interpreting this Standard for workers wearing PPE to be included in the draft Standard.

Therefore, the two remaining Standards which allow assessment of the environment in terms of its effect on the individual are BS EN 27243 and BS EN 12515. One assumption made by both these Standards is that the clothing worn by the individual 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 to workers wearing PPE. There was therefore seen to be a need to develop a British Standard which would allow these existing Standards to be interpreted for workers wearing PPE.

In 1996 the BSI Standards subcommittee PH/9/1 (Ergonomics - Thermal Environments) commissioned a research programme concerning heat strain for workers wearing PPE. The main purpose of the research was to provide a draft British Standard on heat strain of workers taking account of PPE. Another purpose of the study was to provide information from laboratory and workplace studies and existing knowledge which would give a sound scientific basis for proposed revisions of relevant heat strain Standards.

This report 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.

1.1 Aims

The broad aim of the research was to prepare a draft British Standard which supplements each of the existing Standards relating to hot thermal environments, with specific advice on incorporating the influence of PPE.

In order to achieve this, the specific aims of the project were to:

1. establish the limitations of current knowledge in the area of thermal stress and PPE.
2. identify and prioritise limitation in the scope and application of BS EN 12515, BS EN 27243, ISO 9886 and other related Standards.
3. propose a prioritised research programme to eliminate or reduce these limitations and identify guidance which can be provided concerning the assessment of heat strain for workers wearing PPE.

4. carry out limited laboratory and workplace evaluations to verify the acceptability of the proposed draft.

1.2 Objectives

In order to meet these aims the following objectives were specified:

1. Based on a literature review and consultation with experts, determine the limitations of:
 - a. current Standards on the thermal environment (including their scope and application);
 - b. the existing knowledge of the relationship between thermal strain and PPE.
2. From this, propose a prioritised research programme to eliminate or reduce the limitations of current Standards and existing knowledge, concerning heat strain and PPE.
3. Following the consideration of the limitations of current thermal environment Standards, and using expert knowledge produce a draft Standard.
4. Evaluate this draft Standard as far as possible both in workplaces and the laboratory, and make revisions based on the findings.

1.3 Overview of the research

The research programme was undertaken in three main stages:

1. A literature survey and collation of relevant literature concerning heat stress and wearing PPE was conducted, and discussions were held with recognised experts in the field. From this, guidance was produced for the draft Standard, with amendments or correction factors for existing Standards based on the collated research. In addition, the gaps in current knowledge relating to the assessment of heat strain for workers wearing PPE were identified, and a prioritised research plan was developed for meeting these needs.
2. Limited validation of the draft Standard was undertaken using experimental data. This data was also used to supplement the findings of the literature review.
3. Two postal questionnaire surveys were conducted, firstly of manufacturers of different forms of PPE and secondly, of those responsible for the health and safety of workers wearing PPE where the risk of heat strain for workers wearing PPE could be expected. The purpose of this was to understand more fully their needs and requirements concerning information regarding heat stress problems, and to understand if and how they currently use existing heat stress Standards.

All three elements of the research programme contributed to the outcomes of the project, namely:

1. A draft British Standard for workers wearing PPE
2. A prioritised research plan for filling the gaps in current knowledge concerning workers wearing PPE.

2. LIMITATIONS TO THERMAL STANDARDS IN RELATION TO USE OF PPE

2.1 Introduction

As outlined in the introduction, there are a number of British/International Standards which exist concerning the assessment of the thermal environment and factors which relate to it. This section outlines the main limitations of these thermal Standards in relation to the use of PPE. No reference is made to other problems of interpretation or application of Standards which may exist. In each case, attempts have been made to focus attention at a level of detail appropriate for the Standard concerned. For example, detailed clothing science considerations would not be applicable to BS EN 27243 (WBGT).

The heat stress Standards fall into two main categories; those which can be used to assess the impact of the thermal environment on the individual, notably 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 ISO 9920 and BS EN 28996. The introductory Standard (BS ISO 11399) explains how the Standards relate to one another and how they should be used.

There are three Standards which can be used in assessing heat strain, with varying levels of sophistication. BS EN 27243, the WBGT index, is designed to provide a simple assessment of the working environment, taking account of the wet and dry bulb temperatures, radiant heat, air velocity, and metabolic heat production rate (classified into low, moderate, high and very high). A more complex analysis of the thermal environment can be undertaken using BS EN 12515 which utilises a computer program to predict the degree of heat stress. It takes account of wet and dry bulb temperatures, radiant heat, air velocity, metabolic heat production rate (specific value), external work done, clothing insulation and proportion of the body exposed to the environment. This will give a more accurate estimate of the effect of the thermal environment than BS EN 27243, but will still be an estimate of the effect, based on the predicted response of individuals, offering protection for the individuals with the lowest degree of heat tolerance.

In accordance with occupational health and safety practice, the limits embodied in BS EN 27243 and BS EN 12515 are established at levels which provide protection for the majority of the working population. Beyond the limiting conditions indicated, some individuals may be able to continue to work safely. However, it is not normally possible to identify those individuals in a working population who will be at risk and, therefore, these limits need to be adhered to.

The most direct method of assessing the thermal stress which individuals experience is to directly measure their physiological response to the heat. This is described in ISO 9886, and its use is recommended for extreme conditions, or those where the thermal conditions experienced exceed those covered by other thermal Standards (BS EN 27243 and BS EN 12515). Physiological monitoring allows assessment of heat strain to be undertaken for the individual and may therefore be used to allow work to continue safely where thermal index values are exceeded. It is the physiological response ('core' temperature and heart rate) which limits the exposure to the environment. All other methods of heat stress assessment predict the conditions in which physiological limits will be exceeded, so that action can be taken to maintain them within acceptable limits. As outlined above, the physiological response of the body will be affected by the clothing which is worn. The existing Standards may not be applicable to environments when PPE is worn. The limitations of the existing Standards when PPE is worn are outlined below. This was the starting point for preparing the draft Standard.

2.2 BS EN 28996: Ergonomics - Determination of Metabolic Heat Production

Although not directly quantifying heat stress, this Standard is important as estimates of metabolic heat production/workload are required for the application of other Standards. BS EN 28996 presents a series of approaches for determining metabolic heat production rate, of increasing detail and potential precision. However, it is known that PPE can have a significant effect on the physiological cost of work and no reference is made to this at any point in the Standard.

In practical terms, this is probably only of importance for the intermediate technique presented of estimation of metabolic heat production rate from the components of the work. The simplest classification technique (Annex A) is acknowledged as being a very rough estimate and the errors inherent in this procedure are such that clothing or other forms of PPE are normally unlikely to have a significant influence, although heavy, thick or bulky PPE may have an effect. The second rough procedure, that of classification by occupation, is also relatively coarse. In addition, it could perhaps reasonably be assumed that where PPE is habitually worn by those in the occupations given, this will be reflected in the metabolic heat production rates quoted. To some extent, the same will presumably apply to the typical activities cited in Annex E; at least for specific occupational activities such as building work or forestry, if not for the more generic activities such as walking, or transporting a load. There is, however, a risk that users will seek to apply the activities described to similar actions in other occupations, where the level of PPE worn may differ. At the other extreme of precision, the determination of metabolic heat production rate by direct measurement will include the impact of any PPE being worn at the time of measurement, so again no real problem arises. However, for the intermediate approaches, estimating metabolic heat production rate from activity components (Annex D), or the generic aspects of the typical activities in Annex E, the lack of account of the impact of PPE does present a more significant risk of error because the assumed accuracy may tend to be somewhat higher than it will be in reality (particularly as values are generally given with a resolution of 5 Wm^{-2}). There was therefore a need for the metabolic heat production rate due to wearing different forms of PPE to be included in the draft Standard.

2.3 BS ISO 9920: Ergonomics of the thermal environment - estimation of the thermal insulation and evaporative resistance of a clothing ensemble

In BS ISO 9920, values for intrinsic (i.e. basic) clothing insulation are presented. As with BS EN 28996, this Standard does not provide a direct estimation of heat stress but provides information which can subsequently be used in other Standards (notably BS EN 12515). It is important therefore that any deficiencies in this Standard in relation to PPE are acknowledged. One deficiency is specifically acknowledged in the scope of the Standard, namely that of not dealing with different levels of insulation on different parts of the body. A further, related issue is that, in summing the insulation or body coverage of different clothing items, no indication or guidance is given as to the likely effect of overlapping items or of the significance of the air trapped between different layers of clothing.

Furthermore, the information provided regarding the insulative characteristics of items of PPE is sporadic. Some items of PPE are included, such as flame retardant arm protectors, but commonly encountered items such as safety boots or industrial safety helmets are omitted.

The Standard makes reference to various relevant clothing parameters, but does not always provide suitable information to address these. The relevant parameters include the thermal insulation (given for some items of clothing, particularly more conventional workwear such as coveralls); clothing area (again given for clothing, gloves and some footwear but not for items covering the face or head); the estimation of the evaporative resistance; and the influence of body movements

Reference is made to the potential scale of effect of body movements (pumping effect) on insulation with a quoted range of a 5-50% reduction in effective insulation with movement. Interim correction factors based on metabolic rate (presumably as an index of gross level of activity) are recommended in this Standard. Related to the pumping effect is the influence of external air velocity. This can clearly have a direct effect on thermal insulation of the fabric, with the effective insulation being reduced according to the air permeability of the fabric. In turn, permeability of the fabric will also bear some relationship to vapour permeability or evaporative resistance. In the Standard, methods for estimation of evaporative resistance can be applied using thermal insulation, but only for one or two layer permeable clothing. A method for estimating evaporative resistance, when other forms of clothing are worn, requires information about the moisture permeability index of the garment. Limited information is presented in the Standard, with the only forms of PPE being included (as part of ensembles) being arm protectors, aprons and aluminised coats. Despite the inclusion of some ensembles in the Standard (including heat protective clothing) the range of impermeability indices covered is very narrow (0.3-0.4). Although these issues are raised within the Standard, their effect and application is only discussed in relation to the thermal insulation characteristics of clothing and clothing ensembles. There was therefore a need to present further information on thermal insulation and evaporative resistance of items of PPE in the draft Standard.

2.4 BS EN 27243: Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)

This Standard provides guidance on the calculation of the WBGT thermal index and also interpretative reference values. These are specifically limited to normal workwear ($I_{cl} = 0.6$ clo and permeable to air and steam). A sub-note specifies that, if normal workwear is not being worn, the reference values shall be modified. Apart from indicating that impermeable clothing would necessitate a decrease in the reference values and that reflective clothing may result in an increase, no further guidance is given, the Standard user being recommended to consult a specialist. No reference is made to any possible role of other forms of PPE, for example the impact on metabolic heat production rate and the effect on heat loss from the body. There was therefore a need to address this in the draft Standard. It was recognised that because this Standard is a relatively simple method of assessing the environment, any corrections should be simple and appropriate to its level of sophistication.

One other limitation of BS EN 27243 is that the assessment of risk is based on a time weighted average exposure. Although workplace conditions may be above a threshold for heat stress, there may not be undue risk for workers for a limited time period (Bernard, 1998). Conversely, time weighted average exposure may mask peaks in metabolic heat production rate which can be associated with heat stress (Morris and Graveling, 1986). This issue may need to be clearly explained in the draft Standard.

2.5 BS EN 12515: Hot environments - analytical determination and interpretation of thermal stress using calculation of required sweat rate

This Standard is based upon the calculation of the contribution of the various elements in the heat balance equation to overall heat load. This is interpreted in terms of the amount of heat which the body needs to lose to maintain thermal equilibrium and the amount of heat which the surrounding environment is capable of accepting. Although provision is made for some modification of heat exchange by clothing this is clearly limited. The computer program requests an input value for the clothing thermal insulation, and for the proportion of the body covered by the clothing. Clearly therefore, factors such as the evaporative resistance/vapour permeability of the clothing are not accommodated. Nor, it would appear,

are other factors such as the pumping effect or the extent to which the air permeability of clothing and ambient air velocity interact to influence heat exchange via air or vapour transfer. With impermeable protective clothing and other forms of PPE which are largely vapour impermeable (helmets, respirators, hearing defenders etc.), these omissions are potentially quite significant. As a special case, with the use of self contained BA or air-fed respirators, respiratory evaporation would be changed (air would be dry and cool), and when closed circuit BA is worn, the inspired air will be warm. Again this is not accounted for in the equation.

The deficiencies of the Standard were demonstrated by a recent study involving workers wearing various styles of vapour impermeable clothing (with significant differences in detailing such as cuffs and ankles open or elasticated); full face respirators; helmets; rubber boots; and rubber gauntlets. With these items of work clothing it was not possible to derive an assessment of the risk of heat strain from the Standard program.

In addition to these deficiencies, other assumptions and limitations can be identified from the text of the Standard. Firstly, the mean skin temperature is estimated from a regression equation and then utilised extensively within the further calculations. However, an accompanying table of the variables included in the regression show that only clothing insulation in the range 0.1-0.6 clo had been utilised in developing the regression. This may be a significant limitation. Similarly, calculation of the reduction factor for sensible heat exchanges, subsequently used in determining both convective and radiative heat flow, is based upon an equation described as being for cotton clothing.

The ranges of individual parameters for which the equation is applicable are given as:

air temperature	22.9-50.6	(°C)
radiant temperature	24.1-49.5	(°C)
vapour pressure	0.8 - 4.8	(kPa)
air velocity	0.2 - 0.9	(ms ⁻¹)
metabolic heat production rate	46.4 - 272	(Wm ⁻²)
clothing insulation value	0.1-0.6	(Clo)
mean skin temperature	32.7 - 38.4	(°C)

Beyond these limits, the Standard may be in error, and other forms of assessing heat strain should be considered.

The BASIC program which is appended to the Standard requires the input of the following parameters:

- duration of exposure [minutes]
- dry bulb air temperature [°C]
- globe temperature (indicating radiant heat load) [°C]
- wet bulb temperature (psychrometric) [°C]
- air velocity [ms⁻¹]
- metabolic heat production rate [Wm⁻²]
- proportion of the body exposed to the environmental conditions [non dimensional]
- thermal insulation of clothing [clo]

It is clearly important that these factors are considered for the effect of PPE on them. The three which are most obviously effected by PPE are the metabolic heat production rate (wearing PPE may increase the rate beyond 272Wm⁻²); the proportion of the body exposed to the environmental conditions; and the clothing insulation value which wearing PPE may increase. These input values can be altered directly

to take account of the PPE worn. However, the underlying assumptions made in the program limits its applicability when PPE is worn. In particular, the limitations are that the evaporative resistance of the garment is not taken into account, and the inspired air temperature is always assumed to be the ambient air temperature.

A BIOMED project being led by Professor Malchaire is looking at revisions to this Standard. This work involves several research centres throughout Europe. As a result of this work, modifications to BS EN 12515 are likely. The three major modifications are likely to concern firstly, exponential averaging for the calculation of predicted sweat rate and core temperature at specific times, taking into account the exposure history. Secondly, new ways of calculating the influence of clothing in convection and evaporation. Thirdly, predicting the DLE for the 'average' worker (50% of the population) reaching a core temperature of 38°C, rather than the 'Danger' and 'Alarm' levels used at present. A number of minor modifications are also anticipated. These concern new prediction formula for skin temperature, respiratory evaporation, respiratory convection and evaporative efficiency. The proposed modifications to this work are expected in 1998, and these will be validated in the remainder of the BIOMED project. BS EN 12515 will be revised in 2002 under the 5 yearly review, although recommendations for changes arising from the BIOMED research programme may mean earlier revision.

The equations which are used in the calculation of required sweat rate and the ways in which they should be modified to take account of any PPE were considered. Following discussion, it was decided that the equations and the alterations to them should be included in the draft Standard. BS EN 12515 includes the listings of a computer program, and it would be possible to suggest changes to the program to take account of the PPE worn. However, it would also be possible for someone to write a computer program based on the equations which are included in BS EN 12515. The equations in that Standard are included as normative, while the program is included as informative. Therefore it was important to include the alterations to the equations rather than simply alterations to the program. In fact, many of the alterations to the program recommended could not be included without a considerable re-write of the program. Some re-writing may arise as a result of the BIOMED project, and in the interest of writing a Standard which would be useable, recommendations on altering the program were not made in the draft Standard. However, the alterations which would be required (some extra information/data would be required to what is currently collected) are presented in the draft Standard in Annex D.

BS EN 12515 includes allowance for movement of the body in relation to air velocity, so that a resultant air velocity is obtained. However, it is apparent from the equations that the air velocity due to movement is added to any movement of the air (i.e. body movement is into the direction of air velocity). No further indication is given as the assumed relationship between metabolic heat production rate and movement. One other factor to consider in relation to air movement is the pumping effect, which does not appear to be taken account of in the Standard. Allowance for this can be made by reducing the clothing insulation, but the effect of movement of air on evaporation of sweat within the clothing is not considered.

Kampmann (1993) also refers to the limitations of BS EN 12515. Although most of the limitations listed are not related specifically to clothing/PPE, he does identify the need for further research into the insulation properties of clothing which is saturated in sweat.

2.6 Conclusions

There are limitations to several of the existing thermal environments Standards when they are considered for workers wearing PPE. While some of these limitations are a lack of suitable data (as in ISO 9920),

others concern assumptions which limit the applicability of the Standards for workers wearing PPE (as in BS EN 12515).

The limitations of these Standards were to be addressed in the draft Standard, so that the draft Standard could put forward methods of applying these existing Standards to workers wearing PPE. Information based on the literature review and discussions with experts was considered for ways in which it could be used in the draft Standard.

3. LITERATURE REVIEW

3.1 Aims

A literature review was undertaken with particular reference to available objective information on which to base assessments of heat stress, and 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. Correspondence (letter or e-mail) or discussions (usually telephone) were held with them in order to glean extra information which could be relevant of the draft Standard. The general aim of the literature review and discussion with experts was to propose guidance on the assessment of heat strain for workers wearing PPE to be incorporated into the draft Standard. More specifically, the aims were to:

1. Consider the application of correction factor to the WBGT index (eg the American Conference of Governmental Industrial Hygienists - ACGIH).
2. Collate documented data on the metabolic cost of wearing different forms of PPE.
3. Supplement BS ISO 9920: 1995 with additional data from the literature and discussions with experts concerning the coverage, clo value and evaporative resistance of items of PPE which are not covered in the Standard.
4. Further consider the literature on ventilation of garments (the pumping effect) and how this affects heat strain.
5. Seek further information on the fit of clothing and its effect on heat strain.
6. Consider information which relates to specific forms of PPE, such as respiratory protective devices and heat reflective clothing.
7. Examine literature which discusses the validity of the existing thermal Standards.

The literature search was conducted using the databases HSEline, NIOSHtic and CISDOC, and relevant literature was obtained. The literature was considered for its ability to meet the aims described above.

3.2 WBGT index and correction factors

Morris (1984) gives a summary of the development of the WBGT index. It was developed by Yaglou and Minard (1957), originally for military use in conditions where there was a high radiant heat load. The index was subsequently revised to give greater weighting to the effects of air velocity (Minard and O'Brien, 1964). Two equations were put forward for the determination of index values:

$$\text{WBGT} = 0.7 t_n + 0.2 t_g + 0.1 t_a \text{ (outdoor environments with solar radiant heat)}$$

$$\text{WBGT} = 0.7 t_n + 0.3 t_g \text{ (indoor environments)}$$

Although it is a simple index to use and interpret, and was successful in its original application (Minard *et al*, 1957), WBGT has been criticised for underestimating the climatic heat load in conditions where air temperature exceeds skin temperature and air speed is high (MacPherson, 1962). Ramanathan and Belding (1973) also found that physiological responses were not independent of the combination of climatic factors at a given level of WBGT, and therefore concluded that two WBGT scales were required; one for hot-dry conditions and one for hot-humid conditions. Although this practice has never been adopted, it is an important point to note, particularly when considering forms of PPE which impede evaporation of sweat.

Despite its poor predictive ability, WBGT has been used as the basis for several heat stress Standards (Henschel, 1980). It is also an international and European Standard BS EN 27243 and forms the basis of American guidance (ACGIH).

Threshold limit values to take account of different work conditions have been put forward by several authors to take account of various factors which may increase heat stress, for example metabolic heat production rate, acclimatisation, air velocity and clothing. The reference values in BS EN 27243 are for individuals who are normally clothed (thermal insulation index $I_{cl} = 0.6 \text{ Clo}$), physically fit for the activity being considered, and in good health.

Ramsey (1975) put forward some threshold limit values for workers in hot environments (Table 1). These were developed by OSHA's Standard Advisory Committee on heat stress.

Table 1. Threshold WBGT levels (Two hour time weighted average values)*
(from Ramsey, 1978)

Metabolic cost	Threshold WBGT °C
Light work (less than 200 kcalhr ⁻¹)	30
Moderate work (201-300 kcalhr ⁻¹)	28
Heavy work (301-400 kcalhr ⁻¹)	26
Very heavy work (over 401 kcalhr ⁻¹)	25

* assumes: adult male, normally clothed, acclimatised, physically fit, good health and nutrition

Ramsey (1978) later suggested refinements to these limit values, to take account of clothing, acclimatisation and physical fitness of the worker. The author also subdivided the metabolic categories to include a resting value. These limit values were based on observations rather than experimental data.

Ramsey emphasised that the guidelines are not upper limits or tolerance levels, but rather are levels that indicate the need for instigation of work practices to reduce adverse thermal effects. They represent an aggregation of information and rules concerning work in the heat, and cover situations where the clothing and the condition of the individual varies. The limits assume that the person exposed is male, normally clothed, acclimatised, physically fit for the job and in a good state of nutrition and health. In order to account for variations from this, further guidance is given for adjustment to these threshold limits, as shown in Table 2.

Ramsey (1978) argues that by adjusting the WBGT values indicated in Table 1 by those factors indicated in Table 2, a new estimated threshold WBGT level can be obtained. This value then represents the WBGT level for initiation of measures to reduce the heat stress. If the resulting temperature is below

the thermal comfort level (20°C WBGT) then the stress is primarily a 'work stress' from internally generated heat, rather than an environmental heat stress. In this case, corrective actions and work practices should be directed towards reducing the work load or increasing the evaporative capability of the worker. The extent of internally generated heat becomes particularly of concern when PPE which prevents evaporation of sweat is worn as little heat will be able to be lost to the environment.

Table 2. Modification of threshold WBGT (Ramsey, 1978)

Factors	WBGT°C modification
1. Unacclimatised, not physically fit	-2
2. Air velocity above 1.5ms ⁻¹ and air temperature below 35°C	+2
3. Clothing: shorts, semi-nude	+2
impermeable jacket or body armour*	-2
raincoat, fireman's coat*	-4
completely enclosed suits*	-5
4. Obese, elderly	-1 to -2
5. Female	-1

* Modification for increased air velocity not appropriate with impervious clothing.

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, considering 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 are discussed below.

Reneau and Bishop (1996) reviewed the literature, looking at the effect of water vapour impermeable clothing on the WBGT index. They considered the findings of six studies which had investigated the use of WBGT for workers wearing some form of encapsulating protective clothing. They compared the data from four studies: Bishop *et al* (1991), Wilson *et al* (1975), Kamon *et al* (1979) and Tanaka *et al* (1978), where there were similar work loads, but different WBGTs. They also considered the findings of Paull and Rosenthal (1987) and Kenney (1987). These studies are outlined below.

The study by Paull and Rosenthal (1987) evaluated the effects of wearing full body protective suits. The clothing worn in the trials were a laminated PVC-Tyvek chemical resistant hooded suit, rubber boots, elbow length gloves, full facepiece dual cartridge respirator and hard hat. Full-length cotton underwear was worn beneath the suit.

Adjustments to the WBGT index when workers wear protective clothing were calculated using two methods. Firstly, data were collected for work undertaken without the protective suits, to allow a comparison between the clothing. Based on the resting and working heart rates with the chemical protective clothing, and the heart rates when working without the chemical protective clothing, it was estimated that the WBGT differential caused by wearing the protective clothing was between 6° and 11°C. In other words, the chemical protective clothing caused a physiological heat strain comparable

to adding approximately between 6° and 11°C to the WBGT index. They checked this using a second technique which considered the microclimate of the protective suit by measuring temperatures inside the suit. Based on 100% saturation inside the suit, this WBGT value was then compared to the ambient WBGT level. The difference between the calculated inside- suit WBGT and the measured ambient WBGT was 9.5°C, which was close to that estimated based on heart rates. It was concluded that the wearing of protective clothing produced an increased level of experimental heat stress comparable to adding approximately 6°C to 11°C to the WBGT index. However, the environmental conditions in which this was conducted were not reported; although the WBGT index value was, there was no indication of whether this was a warm and humid or hot and dry environment.

Paull and Rosenthal (1987) report that this modification to the index is comparable to the findings of Toner *et al* (1981) who compared the data of Goldman *et al* (1965) on resting unclothed individuals exposed to hot-humid environments to data obtained from marine tank crewmen wearing fully enclosed protective suits. They concluded that, based on sweat production rates, the chemical protective clothing (in addition to light work loads) produced an effect comparable to adding approximately 6°C to 10°C to the WBGT index. The authors do point out that the WBGT differentials found in this study only apply to one work rate, one type of protective suit and one set of environmental conditions and therefore caution against the wider application of the findings.

Based on the (at the time) most recent NIOSH criteria for empirical adjustments to WBGT, 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 300W (258 kcalhr⁻¹). The experiment was undertaken with 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. These are shown in Table 3 below.

Table 3. WBGT adjustments for work^a in protective clothing ensembles (Kenney, 1987)

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

^aMetabolic heat of approximately 300W (258 kcalhr⁻¹); heat acclimatised workers

The recommendation that no adjustment is required for cotton coveralls is based on the NIOSH 60 minhr⁻¹ Recommended Exposure Limit for work at 300W.

In considering these data Bernard (1998) suggests that 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, these values may overstate the effects of the clothing. When looking at mean values, the results are closer to those of Bernard (see below).

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°C 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. At this metabolic heat production rate, the difference in reference value for acclimatised and unacclimatised workers is 2°C (BS EN 27243), indicating that this reasoning is relatively justified.

Reneau and Bishop (1996) conclude from their review of this literature that the 5°C adjustment for encapsulating protective clothing as suggested by Ramsey (1978) is not sufficient, while an adjustment of 14°C appears too great. From this, they argue that the 10°C adjustment which was present in the ACGIH 1990 guidance would seem to be reasonable. Kenney (1987) showed that a WBGT difference of 10.6°C elicited similar responses when an enclosed suit was compared to normal summer work clothing (cotton shirt and trousers). Furthermore, Paull and Rosenthal (1987) showed that a WBGT difference of 11°C elicited a similar response between an enclosed suit and summer work clothing. It would therefore seem that the suggested adjustment of 10°C is appropriate when workers are wearing encapsulating protective clothing.

A study by Mihal (1981) looked at the physiological impact of wearing vapour-barrier clothing. It was found that the physical work effort required was greater for workers wearing vapour-barrier clothing than for those not wearing this clothing. Also, the workers' extrapolated oral temperature reached a limiting value (37.6°C) at a temperature 2.8°C WBGT lower than the workers not wearing the vapour-barrier clothing. Mihal reasons that this finding is consistent with the guidelines suggested by Ramsey (1978), although other authors (e.g. Reneau and Bishop, 1996) have suggested that Ramsey's (1978) correction factors for completely encapsulating clothing may be too low. During the trial, Mihal found that none of the workers wearing vapour-barrier clothing, exposed to conditions of up to WBGT index of 27.2°C for up to 45 minutes, experienced oral temperatures exceeding 37.6°C (the value taken to correspond to a deep body temperature of 38.0°C, Dukes-Dobos and Henschel, 1973). These data are consistent with the findings of Reischl and Reischl (1978) where it was concluded that a 35 minute exposure to a subject wearing a firefighter proximity suit appeared to be short enough not to generate excessive metabolic heat buildup.

A study by Nigg *et al* (1992) compared different coverall fabrics for use in pesticide spraying. These fabrics had variable degrees of permeability. They were worn by workers outside, in ambient conditions with the mean WBGT value of 29.9°C. The equipment used (the Metrosonics Portable Heat Stress Monitor) computes a 'stay time' based on the environmental conditions (assuming no protective clothing and light work wear), and a work level (presumably based on metabolic heat production rate) of 1-6. The authors conclude that the work level (determined as 4, partly to take account of the protective clothing worn) could not be maintained over an 8 hour shift, which should therefore be reduced to 5 hours. This clothing is described by the authors as being water barrier, permeable protective clothing, with a WBGT correction factor of -6°C, yielding a WBGT limit of 24°C for light, continuous work (ACGIH 1991-92). In these conditions (WBGT 29.9°C) and with suggested WBGT limit of 24°C, heat strain was experienced. The physiological responses of the workers indicate that by midday (the time that they started is not clear) they were approaching physiological stress situations, with heart rates, core temperatures and skin temperatures approaching the limiting values. This suggests that (if they had been applied) the WBGT limit values would have protected the workforce.

Reneau and Bishop (1996) summarise the different corrections to WBGT suggested by authors. These are shown in Table 4.

**Table 4. Suggested WBGT adjustment guidelines and sources
(Reneau and Bishop, 1996)**

Author	Clothing	WBGT adjustment (°C)
Ramsey 1978	shorts, seminude	+2.0
	impermeable jacket/body armour	-2.0
	raincoat, fireman's coat	-4.0
	completely enclosed suit	-5.0
Kenney 1987	cotton T-shirt and trousers	+3.6
	cotton coveralls	0.0
	cotton coveralls x 2	-2.6
	vapour-barrier suit (hood, gloves, boots)	-7.0
ACGIH 1980	established by an expert	
ACGIH 1990	summer work uniform	0.0
	cotton coveralls	-2.0
	winter work uniform	-4.0
	Goretex (water barrier)	-6.0
	Tyvek (vapour-barrier)	-10.0
	(fully encapsulating suit, gloves, boots, hood)	
ACGIH 1991	summer work uniform	0.0
	cotton coveralls	-2.0
	winter work uniform	-4.0
	Goretex (water barrier)	-6.0

Following their work on vapour impermeable clothing, Kenney *et al* (1993) reported studies on vapour-permeable clothing. The results 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 level of strain resulting from the use of vapour permeable clothing reduces the heat load by the equivalent of some 4-5°C over equivalent 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). The findings are shown in Table 5, along with some other reported data (Paull and Rosenthal, 1987; Kenney *et al*, 1993). The closest equivalent correction factor from the ACGIH (1990) guidance is also included for comparison. However, because of differences in materials and clothing styles, it is difficult to make a direct comparison.

Table 5. Clothing ensembles and CAF (after Bernard, 1998)

Ensemble description	CAF (°C)	Source	ACGIH guidance, 1990 (°C)
Work clothes	0.0	O'Connor & Bernard, 1998	0.0
Cloth coveralls	3.5	O'Connor & Bernard, 1998	2.0
Cloth coveralls over scrub suit	4.5	O'Connor & Bernard, 1998	4.0
Limited use coveralls (polypropylene)	-1.0	O'Connor & Bernard, 1998	-
Limited use coveralls (polyethylene)	2.0	O'Connor & Bernard, 1998	-
Polyester coveralls	0.0	O'Connor & Bernard, 1998	-
Polyester coveralls with scrubs	3.0	O'Connor & Bernard, 1998	-
Water-barrier, vapour-permeable coveralls (limited use)	6.0	Kenney <i>et al</i> , 1993	6.0
Water-barrier, vapour-permeable coveralls	2.5	O'Connor & Bernard, 1998	6.0
Vapour-barrier coveralls	8.5	Kenney <i>et al</i> , 1993	10.0
Totally encapsulating suit or turn-out gear	11.0	Paull and Rosenthal, 1987	10.0
Flame-retardant shirt & trousers	0.5	O'Connor & Bernard, 1998	-
Flame-retardant shirt & trousers	1.0	O'Connor & Bernard, 1998	-
Flame-retardant shirt & trousers with single-layer jacket	2.0	O'Connor & Bernard, 1998	-
Flame-retardant shirt & trousers with double-layer jacket	3.0	O'Connor & Bernard, 1998	-

The data shown in Table 5 demonstrate the variability in effect on heat stress between different ensembles. They show that the material used in apparently similar ensembles can have a clear effect on heat stress (see for example the limited use coveralls). There is some variation between the ACGIH guidance and the values presented by O'Connor & Bernard (1998). It is thought this may be because of differences in materials, fit, and other garments worn with the ensemble (for example, it is not clear what footwear is worn with the ensembles which were tested). Further work may be required to clarify these descriptions of clothing ensembles and develop more generic classifications, and also to validate the correction factors if they are to be incorporated into the draft Standard. At present, it is recommended that the ACGIH (1990) correction factors are incorporated into the draft Standard, although with sufficient scientific evidence additional values based on Bernard's work could be incorporated in the future.

The ACGIH correction factors for clothing are widely used, both in the US and in the UK, in order to assess work in situations of heat stress. The findings of the questionnaire surveys (Section 4) show that, where respondents were using the WBGT index to assess the work situation, three quarters were also using the ACGIH correction factors. Although it does not have any standing as guidance in the UK, it

is widely used, and this acceptance gives it some credibility. Due to its widespread acceptance and supporting scientific evidence, it is recommended that these correction factors are 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°C correction factor for the Tyvek (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 other correction factors. Furthermore, there was concern about the use of this correction factor with environments in which cooling by evaporation of sweat would usually play a significant part, as sweat cannot be evaporated through the water vapour impermeable garment. It was therefore decided by the committee as better to provide no guidance on this issue (Bernard, personal communication).

The ACGIH correction factors have been in place for approximately 8 years to date. The ACGIH review and revise the guidance they produce on a regular basis. The threshold limit values (TLV's) will be revised in September 1998 and changes will be made to the analysis of heat stress to take account of the clothing (Bernard, personal communication). The correction factors will no longer be taken away from the limit value to reduce it, but will be *added* to the measured WBGT index value so that the effect of the clothing is reflected in the value obtained for the environment. It is thought that this may be simpler for people to understand.

It could be argued that in the UK adopting these guidelines, the correction factor should also be added to the measured WBGT index value and follow US practice. However, the reference value (limit) against which the WBGT index value (measured) is compared, takes account of the metabolic heat production rate of the individual and whether there is any air movement, so some factors of the environment are already taken account of in the reference value. Taking account of the clothing in this reference value should not be difficult conceptually. In the authors' opinion, the only benefit of adding the correction factor to the index value rather than taking it from the reference value is that it may be less confusing (adding a positive value may be an easier concept than adding a negative value). Bernard (1998) recognises that as far as the clothing effect is concerned, there is no real difference in the approaches other than opposite signs.

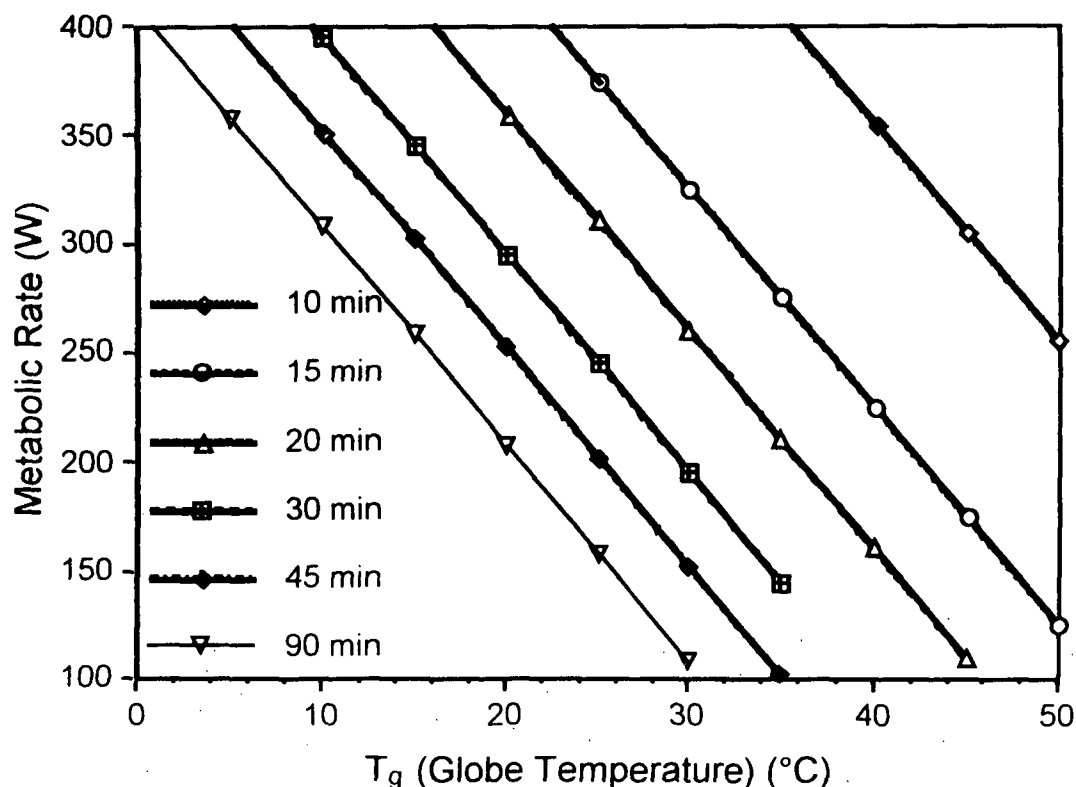
In considering clothing correction factors, compatibility with correction factors introduced to take account of other significant heat stress influences must also be considered (eg the correction factors introduced because of air velocity). EN 27243, ACGIH and Ramsey (1978) all state that an adjustment to these maximal TLV WBGT levels must be made for unacclimatised individuals (and values for this adjustment are given in EN 27243 and ACGIH), and EN 27243 and Ramsey further suggests an adjustment for increased ambient air velocity, although natural wet bulb theoretically allows for air velocity. While these adjustments are understandable, Reneau and Bishop (1997) argue that they are not necessarily applicable to encapsulating protective clothing. In particular, an adjustment for air velocity would not seem appropriate for those wearing totally encapsulating clothing as there is no possibility of the evaporation of sweat.

Reneau and Bishop (1996) point out that combinations of environmental conditions with different humidities can produce the same WBGT, although they acknowledge that this is of limited importance where there is little opportunity for the evaporation of sweat, i.e. when the skin is totally encapsulated in vapour-barrier clothing. They therefore question whether TLV's should be based simply on the dry bulb and radiant heat temperatures for workers wearing encapsulating clothing rather than the WBGT value.

Bernard (1998) reports that ACGIH are considering the use of suggested stay times for different metabolic heat production rates, based on the ambient globe temperature. These are shown in Figure 1. This recognises that the wet bulb temperature is not relevant when this type of clothing is worn. Although this assessment is a different approach to that used in WBGT, it may provide a more accurate prediction of heat stress when wearing this clothing. Further information on this should be considered for the draft Standard.

Discussions with experts suggests that there is some concern about the inclusion of correction factors for water vapour impermeable clothing. 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 they should be applied to the WBGT index. 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). Based on these decisions to include a correction for water vapour impermeable clothing to the WBGT index, the -10°C correction factor was recommended as appropriate, based on the scientific literature reported here.

Figure 1. Chart recommending stay times while wearing vapour-barrier, total encapsulating clothing as a function of globe temperature and metabolic heat production rate, from Bernard (1998).



There is limited research published in this area, and there is a clear need for 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 can be applied in a linear manner to all thermal environments (hot/dry; warm/humid etc) or to all metabolic heat production rates.

3.3 Effect of PPE on Metabolic Heat Production Rate

Nunneley (1989) drew attention to the propensity for clothing to increase the metabolic cost of work, both by adding weight and by restricting movement. As an example of the latter, the author cites a study demonstrating a 10% increase in oxygen consumption resulting from wearing multi layered arctic clothing, beyond any increase attributable to the extra weight of the clothing. Love *et al* (1996) reported an increase in oxygen uptake of approximately 15-20% when wearing full fire-kit (including boots and helmet but excluding BA) although no attempt was made to differentiate between the effect of the weight of the PPE ensemble and any restriction of movement.

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. In many instances it is difficult (if not impossible) to differentiate between heart rate increases attributable to increased metabolic heat production due to clothing and those increases resulting from thermal stress. This is particularly the case with heavy or complex clothing ensembles. For example, White *et al* (1989) reported an increase in heart rate of approximately 25% associated with wearing a totally occlusive ensemble consisting of a polyurethane on nylon three-piece suit, including a hood and with taped cuffs and ankles, together with nitrile gloves and neoprene boots. As only a final value is presented, it is not possible to estimate the relative contribution of heat and work load. However, the fact that this value is substantially higher than those cited above for much heavier ensembles (eg firefighters' turnout gear) supports the suggestion of a significant thermal component.

Even where oxygen consumption data are obtained, any increase in metabolic cost may only be partly associated with the energy cost of thermoregulation. Teitlebaum and Goldman (1972) briefly discuss this possibility in a report on multi-layer arctic clothing. The authors report an average increase in metabolic heat production rate of 16% when wearing the arctic clothing ensemble compared to working in normal clothing but wearing a weight belt equivalent to the increased clothing weight. They discount a significant thermal component because of the short duration of the test and the stability of the metabolic data over time, concluding that this increase is due partly to 'friction drag' between layers of clothing, and partly attributable to the bulk of the clothing and its impact on movement. This value is similar to that reported for firefighter's turnout gear of a 15-20% increase in oxygen consumption (Love *et al* 1996), although it is accepted this increase may be due to weight as well as restrictions to movement. However, both are higher than the value of 10% reported by McClellan *et al* (1993) for forces using NBC clothing, as well as the value cited earlier from Nunneley (1989).

Holmer *et al* (1992) compared the physiological effects of coveralls made from different fabrics (light chemical coveralls). The heart rate data show an increase for different garments of approximately 1-6%. As there were only modest changes in core temperature this could be interpreted as indicating that the increased heart rate is due primarily to metabolic heat production rate rather than thermal loading. However, metabolic heat production data, derived from oxygen consumption, do not reveal any systematic increase for different garments. Skin temperature readings showed a substantial increase for each form of coverall. The most likely explanation is that the increased thermal load imposed by the coveralls results in an increase in skin vasodilation (which accounts for the increase in skin temperature. This, in turn, causes blood pressure to fall, resulting in a compensatory increase in heart rate. The

complex inter-relations between different physiological components illustrated here demonstrates the difficulties which can occur in interpreting physiological data.

The equivocal data from Holmer *et al* (1992) appears to be mirrored in work reported by Rissanen *et al* (1991). The authors report oxygen consumption data for a variety of asbestos-stripping tasks. However, these values are actually estimated from heart rate data and therefore subjected to the limitation referred to above. The authors conclude that there seemed to be no clear difference in physiological strain between permeable and impermeable suits and that the effect of the respirator seemed to be minor. As there appeared to be little or no overlap between clothing worn and tasks performed and no indication of instances where a respirator was not worn, it is not immediately apparent on which physiological data these assertion are based.

The effect of weight of PPE on oxygen (metabolic) cost has been demonstrated for self-contained breathing apparatus (BA) by Love *et al* (1996) who reported a 15-20% increase for firefighters wearing BA (but not under air), in addition to the effect of clothing. However, the study also indicated that weight was not the sole parameter, suggesting that weight distribution and its effect on the second moment of inertia was also an influential factor. Other forms of respiratory protection were studied by Hodous *et al* (1989), who appeared to show an increase in cardiorespiratory load with the use of a variety of forms of respirator. However, as the authors concede, variations in respirator wear were almost completely confounded by variations in the type of work being performed in this workplace study. It is not possible therefore to interpret the findings or ascertain loading factors with any degree of reliability.

Recent research into a new design air cylinder which is smaller and lighter than traditional cylinders (tested by DERA, and featured on BBC's Tomorrow's World on 21.1.98) has shown that it reduces the oxygen consumption by 10% compared with the traditional cylinder. This is comparable to the findings of Love *et al* (1996) who reported a reduction on oxygen consumption of 5-10% (depending on workload) through the use of a conventional design but light weight (fibre-wrapped) BA air cylinder. This supports the suggestion that weight and position of the load influences metabolic heat production rate.

Sharratt *et al* (1987) also reported an assessment of the physiological impact of wearing respirators in the heat. Two studies were conducted, both utilising a full-face respirator. In the first, the impact of increased breathing resistance was studied by utilising the respirator with or without a filter. The effects were small, typically averaging some 2-4% increase in heart rate (higher values at higher workloads). In a second study, the effects of work with or without a respirator were studied. At normal ambient temperatures, the increase in heart rate over resting values for work wearing a respirator compared to the same work without a respirator varied considerably, being 10% less for older males; 22% more for younger males; and 78% more for younger females. However, care should be taken in interpreting or applying these figures as each represents the mean for just two subjects.

In a recent study, Hettinger *et al* (1997) reported the results of an extensive study of the physiological effects of using RPE. The authors showed that the increase in heart rate concomitant with wearing respiratory protection was positively related to respiratory resistance and work load. From field-based studies they also showed that the demands imposed by certain types of respirator (notably the P3 high performance particulate filters) could be increased during wear as the respiratory strain was increased by the increasing dust load on the filters. Most RPE designs resulted in an increase in heart rate of approximately 5%. However, at heavy work loads, a heavily loaded high performance filter could result in a 10% increase in heart rate. As with the work of Sharratt *et al* (1987) there was considerable variability in the results produced but these percentages appear to offer a reasonable approximation.

Several papers have reported variations in energy cost of activities (principally walking) attributable to the weight of footwear. Legg and Mahanty (1986) summarised previous studies which appeared to show an increase in energy cost of approximately 1% for each 100g increase in footwear weight, a finding which was confirmed by their own studies. However, Smolander *et al* (1988) did not identify such a large effect. For treadmill walking, changing from winter jogging shoes to rubber boots (increasing the weight by 1kg) produced a 2.5% increase in mean oxygen consumption, with a further 2.5% increase in changing from rubber boots to rubber safety boots (0.6kg weight increase). Walking in snow removed any difference between the two forms of boot although the increase over jogging shoes was greater (4.5%). The authors suggest that the smaller increases in energy cost, recorded during their studies, might be attributable to the generally slower walking speed, particularly in the snow. Nevertheless, the study did confirm that wearing heavier footwear could increase the energy cost of movement.

No specific references have been found to describe any physiological impact of other forms of PPE. Adverse comments have been documented regarding the weight of industrial helmets (Abeysekera and Shahnavaz, 1988) and firefighters' helmets (Graveling, unpublished report) and of powered helmet respirators (Howie *et al*, 1987) although no data are given which could be regarded as indicative of any resultant increase in energy cost.

Similarly, Rushworth *et al* (1986) reported on the interference with movement imposed by fall-arrest harnesses but did not perform any tests which could indicate any impact on physiological cost. Clearly however, any form of PPE which imposes an additional weight penalty or in some other way creates a burden to the body can be expected to have an impact on the physiological cost (and consequent metabolic heat load) of performing work.

It is clear that the effect of PPE on metabolic heat production rate will vary with the activity. As the metabolic heat production rate due to the activity increases, the effect of the PPE will also increase. Ideally, a series of percentage-based corrections would be utilised to relate the metabolic cost of PPE to the metabolic heat production rate of the activity. However, the available data was not considered sufficient to allow these to be compiled. In addition, such a method was considered to be out of keeping with the 'simple' approach encapsulated by BS EN 27243. The data presented therefore represent approximations utilising generally accepted conversions between physiological parameters such as heart rate and metabolic heat production rate (assuming the conventional low level of muscle activity).

Based on the available literature, the affect of various forms of PPE on metabolic heat production rate are summarised in Table 6 in terms of Wm^{-2} , so that they are in the same unit of measurement as the existing heat stress Standards. The values presented below are for the individual items of PPE. Where more than one of these items is worn, the relevant values should be added together.

Table 6. Additional metabolic heat production rate due to PPE

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

Note: Respirator classifications P1, P2 and P3 are defined in BS EN 143.

It will be noted from Table 6 that the body surface area on which the metabolic heat production rate is based is usually assumed to be 1.8m^2 . There was some concern as to whether this assumption introduced errors of accuracy if body surface area varied from this. Data presented by Flugel *et al* (1986) for the body surface area of males and females of different ages in Germany are reproduced below.

Table 7. Body surface area of males

Mean age (and range) in years	Body surface area (m^2)
21.8 (17 - 28)	1.78
34.2 (30 - 39)	1.83
44.1 (40 - 49)	1.79
55.1 (50 - 59)	1.82
65.8 (60 - 72)	1.79

Table 8. Body surface area of females

Mean age (and range) in years	Body surface area (m^2)
21.0 (18 - 27)	1.63
40.3 (30 - 40)	1.63
54.7 (45 - 60)	1.59
67.6 (61 - 77)	1.60

This suggests that a body surface area for males of 1.8m^2 is relatively accurate, and that there is limited variation around this value. For females a body surface area of 1.6m^2 appears to be reasonable. Quoting these values to 1 decimal place indicates the degree of accuracy which can be attributed to them. Within the accuracy of the metabolic heat production rate estimates, assuming that all males will have a body surface area of 1.8m^2 and females of 1.6m^2 , is unlikely to introduce significant errors.

3.4 Thermal insulation of PPE

Other than the tables of clothing insulation values included in BS ISO 9920, few values for the insulative characteristics of PPE have been found in the literature. As stated previously, BS ISO 9920 mainly includes clothing and most of this is normal everyday clothing or workwear, rather than the specialised protective clothing which might give rise to a risk of heat strain. Of those in the published literature, few have actually been experimentally derived using the manikin method described in BS ISO 9920. Most have estimated the insulation, normally deriving values from those published in BS ISO 9920. However, not all papers detail the manner in which the thermal insulation has been estimated or calculated. Movements of the wearer and the fit of the garment to the body may alter the thermal insulation of the PPE, which may result in different values from those which are derived from testing on a manikin. The importance of this is illustrated by the report published by Holmer *et al* (1992) on asbestos-protective clothing. The thermal insulation for the three garment ensembles, measured on a thermal manikin, was 1.3 clo. However, when detailed analyses of heat balance were conducted using human subjects, the effective thermal insulation was calculated to be 0.9-1.0 clo.

Another source of variation in thermal insulation values arises from the failure of many authors to specify garment details sufficiently precisely. For example, an examination of BS ISO 9920 shows how even a simple item such as long socks can vary in thermal insulation from 0.03 to 1.0 clo, or trousers ranging from 0.16 to 0.28 clo. Adding these variations across a complete ensemble can therefore potentially lead to considerable differences in the value derived for effective insulation. For garments included in BS ISO 9920, the fabric used is often detailed. Therefore, if coveralls are made from 100% cotton or a cotton/polyester mixture, a (hopefully) more accurate estimate of thermal insulation can be derived. However, where these materials are not used there is little guidance on how to estimate thermal insulation. Furthermore, fabric details are not provided for all garments unfortunately including 'chemical protective coveralls'.

In addition to those values published in BS ISO 9920, a selection from which are also published in BS EN 12515, McCullough and Honel (1993) report values for probably the largest selection of ensembles. However, these are primarily conventional indoor combinations and only three, incorporating a lab coat, bib overalls and coveralls can be regarded as workwear.

Although some estimates of thermal insulation have been published for workwear ensembles, some of which include more specialised protective clothing, ancillary items are largely neglected in these ensembles. For example, in reporting values including a chemical coverall, Kenney (1987) does not refer to the type of footwear worn. Items such as safety footwear, industrial helmets, industrial gloves, respiratory protection (full-face or half-face) are largely ignored. One notable exception is given in the paper by Paull and Rosenthal (1987) who, as well as detailing the outer and under garments worn, also detail the use of gloves, helmet and rubber boots, yielding an estimated insulative value of 2.0 clo. However, such detail is exceptional.

In general, the conclusion is that, although the thermal insulative characteristics of general workwear is reasonably documented, little or no data are available from the published literature on more specialised protective clothing, including garments such as those made from leather traditionally worn in potentially

hot occupations such as welding. In addition, virtually no data are available for additional items such as boots, helmets, gloves and RPE which, although individually possibly not significant, collectively could make a considerable difference to the effective thermal insulation of an ensemble.

Based on the findings of the literature review, two summary tables were drawn up which provide details of typical clothing insulation values for items of clothing and PPE. These are included in the draft Standard. Table 8 provides ranges of values for typical items of workwear. It must be remembered that the actual value for any specific item will depend upon the cut and fabric used. More detailed specific values can be obtained from BS ISO 9920. Where available, a 'standard' value from BS EN 12515:1997 is provided for calculation where a more specific value is not known. Apart from various forms of protective coveralls, no insulation values have been identified either for other forms of specialised clothing, such as leather garments worn in welding or other industries involving molten metals, PVC chemical resistant clothing or for any other forms of PPE such as hard hats or respiratory protection. It may be possible to estimate these from values given for other items.

Table 9 presents a selection of ensembles together with their individual and collective thermal insulation values. These ensembles are based upon those observed by or reported to the authors in compiling this Standard. The clothing insulation value (clo) in BS ISO 9920 reflect intrinsic (i.e. basic) insulation. During activity, this insulation is reduced by the movement of air between the clothing and the environment through collars and cuffs (i.e. the pumping effect). The intrinsic insulation, obtained either by adding the individual values or by using one of the Standard ensembles, has to be adjusted to take account of this and to obtain the resultant insulation which is used in calculations of required sweat rate (BS EN 12515). ISO 9920 specifies that the thermal insulation should be reduced by 10% for metabolic heat production rate is less than 100Wm^{-2} and by 20% where it is over 100Wm^{-2} to take account of this pumping effect.

Table 10 provides thermal insulation values for a sample of typical clothing ensembles derived from measurements of the entire ensemble using a heated manikin. As the garments worn in an ensemble were not necessarily the same style, fabric or size as the garments listed in Table 9, there may be some slight inconsistencies from values which would be obtained by adding the values for individual items (as in Table 9). Values for other ensembles can be obtained by adding the insulation value for additional items to a basic ensemble or, where necessary, by compiling an ensemble value from the individual values given.

Table 9. showing clothing insulation values for typical clothing and PPE

Clothing item	range of clo	'standard' clo value
Underwear		
briefs / bra and panties	0.03 - 0.04	0.03
singlet / vest	0.04 - 0.06	0.04
short socks	0.02 - 0.05	0.02
long socks	0.03 - 0.10	0.10
Shirts		
short sleeved T-shirt	0.08 - 0.12	0.09
short sleeved shirt	0.15 - 0.25	0.15
long sleeved shirt	0.15 - 0.34	0.25
sweatshirt (round neck)		0.36
Trousers		
Trousers	0.16 - 0.28	0.25
denim trousers		0.15*
shorts	0.06 - 0.17	0.06
Coveralls		
coveralls	0.49 - 0.55	0.5*
bib and braces	0.24 - 0.30	0.28
chemical protective coverall	0.60 - 1.20	1.0*
lab coat	0.34 - 0.36	0.35*
aluminised coat	0.42 - 0.94	0.63*
aluminised trousers		0.33*
insulating trousers	0.30 - 0.40	0.35
insulating jacket (short)	0.32 - 0.45	0.40
insulating jacket (long)		0.69*
insulating overalls	0.52 - 1.13	0.90
flame retardant apron (cotton)		0.12*
flame retardant leggings (cotton)		0.80
Footwear		
light shoes	0.02 - 0.03	0.02
heavy shoes	0.04 - 0.05	0.04
boots		0.10
Hand / arm protection		
fabric gloves	0.05 - 0.08	0.05
flame retardant arm covers (full length, cotton)		0.05*
aluminised arm protectors		0.11*
Head covering		
cap (woollen)		0.01*

*Not from BS EN 12515

Table 10. Typical clothing insulation value of different ensembles

Examples of clothing ensembles	Insulation value (clo)
Underpants, coverall, socks, shoes	0.70
Underpants, shirt, trousers, socks, shoes	0.75
Underpants, shirt, coverall, socks, shoes	0.80
Underpants, shirt, trousers, coverall, socks, shoes	0.96
Underpants, T-shirt, work jacket and trousers, socks, shoes	0.99
Underpants, T-shirt, shirt, trousers, work jacket and trousers, socks, shoes	1.27
Underpants, shirt, trousers, lab coat, socks, shoes	0.91
Cotton shorts, disposable chemical resistant coverall with hood, taped at wrist and ankles, cotton gloves, socks, shoes	1.30
Full length underwear, coveralls, chemical protective coverall, socks, shoes	1.42
Full length cotton underwear, laminated disposable chemical resistant coverall with hood, full-face respirator, hard hat, elbow length rubber gloves, rubber boots	2.00
Underpants, T-shirt, coveralls, aluminised jacket and trousers, socks, shoes	1.48

3.5 Effect of PPE on evaporation

Any item of equipment or clothing which imposes a barrier between the surface of the body and the surrounding air is likely to have an effect on heat transfer. In some instances, such as the use of aluminised clothing for radiant heat protection, or the highly insulative clothing worn by firefighters, this is deliberate. In many cases however, the effect is coincidental to the primary purpose of the PPE. Where the coverage is considerable then the interference with heat transfer can be substantial and an increased risk of heat strain can arise. This is acknowledged in BS EN 12515 where the insulative characteristics of a clothing ensemble, together with the extent of the body surface covered, are taken into account in calculating heat transfer characteristics. However, it has long been recognised that evaporation of sweat is normally the main avenue for heat transfer from the body to the environment in hot conditions and, as described in Section 2, BS EN 12515 makes no provision for the manipulation of this parameter.

Extensive studies have been performed of the influence, primarily of clothing, on sweat evaporation and an entire industry has developed around the concept of water barrier, vapour-permeable fabrics, allegedly allowing sweat evaporation whilst preventing the ingress of water or other aqueous liquids.

Without exhaustively reviewing all the literature on this topic, 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 (e.g. Goretex) to liquid/vapour-barrier impermeable fabrics such

as PVC or Tyvek F, providing other factors are kept constant. However, most of the beneficial effects of a vapour permeable fabric layer have been demonstrated when this has been incorporated into a relatively thin fabric such as those used in disposable coveralls. Several authors (e.g. White and Hodous, 1988) have reported that the benefits of such fabrics are severely curtailed when incorporated into thicker fabrics such as those used for firefighters. The benefit of water barrier, water vapour permeable clothing is thought to reduce when a high metabolic heat production rate is maintained, and large quantities of sweat are produced (e.g. Frim and Romet, 1988 and Goldman, 1990). Calculations based on typically quoted vapour transfer rates and the latent heat of evaporation of water show that the level of heat loss through this avenue is unlikely to be sufficient where the required rate of sweat evaporation is high.

A study by Smith (1980) compared stay times (limited by deep body temperature of 38.5°C or heart rate of 180 bmin⁻¹ or irregular, or subject withdrawal) for subjects wearing four different ensembles. These were wearing only shorts (control), a cotton boilersuit and ventilated face mask, a wetted cotton boilersuit and ventilated face mask, and a plastic suit and ventilated face mask. Subjects were exposed to four climates; all were extreme, two of which were more humid. The climates were dry bulb 50°C, 50% humidity; 50°C, 25% humidity; 45°C, 50% humidity; and 45°C, 25% humidity.

In the most extreme climate (dry bulb 50°C, 50% humidity) there was little difference between the four ensembles, with the stay times being between 20 and 30 minutes for all these ensembles. Stay times were longer for the other environments, but the stay time was always shortest for the plastic suit. The maximum stay time for this garment was less than 35 minutes (45°C, 25% humidity). This is likely to be because the extreme environments becomes a more significant factor in heat stress than the clothing.

A full discussion of the effect of water vapour permeable clothing and correction factors for the WBGT index are given in Section 3.2.

O'Connor & Bernard (1998) show the relationship between the clothing adjustment factor (see Section 3.2) and estimated total insulation (I_t) and computed total evaporative resistance (R_{et}) of the ensemble. Graphs relating the CAF to these factors are shown in Figure 2 and 3. R^2 is the multiple correlation coefficient, showing the degree of fit of the line to the data points. The total insulation (I_t) of the ensemble was estimated as:

$$I_t = 0.55 (I_{cl} + I_a)$$

where I_{cl} is the intrinsic thermal insulation of the clothing and I_a is the thermal insulation of the boundary air layer. They reason that because large changes in I_t result in small changes in R_{et} the approximation of I_t is not important (Bernard and Matheen, 1998). The graphs show that there is a closer correlation between the CAF and computed total evaporative resistance than between the CAF and estimated total insulation of the ensemble, although this correlation is reasonable.

These values can also be used to estimate F_{cl} and F_{pcl} , the reduction factor for sensible heat exchange due to wearing clothes; and the reduction factor for latent heat exchange due to wearing of clothes respectively. These are calculated as:

$$F_{cl} = 1 / [(h_r + h_c) I_t]$$

$$F_{pcl} = 1 / 16.7 h_c R_{et}$$

where h_r is the radiative heat transfer coefficient and h_c is the convective heat transfer coefficient. Figures 4 and 5 show CAF plotted against F_{cl} and F_{pcl} .

Figure 2. Graph showing the relationship between Clothing Adjustment Factors and estimated total insulation of the ensemble (from Bernard, 1998)

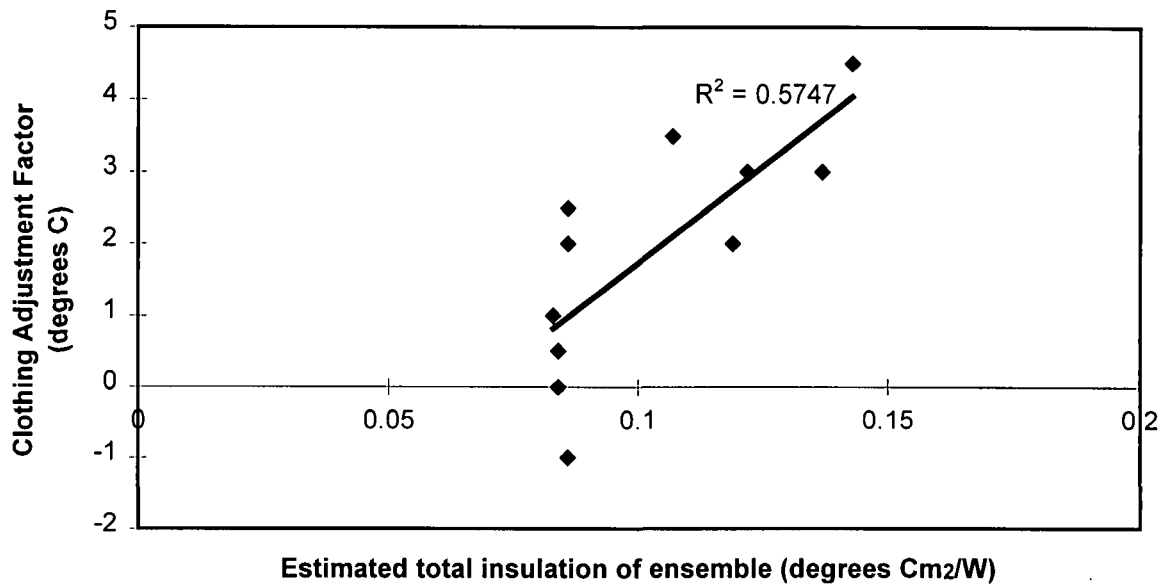


Figure 3. Graph showing the relationship between Clothing Adjustment Factor and computed total evaporative resistance of the ensemble (from Bernard, 1998)

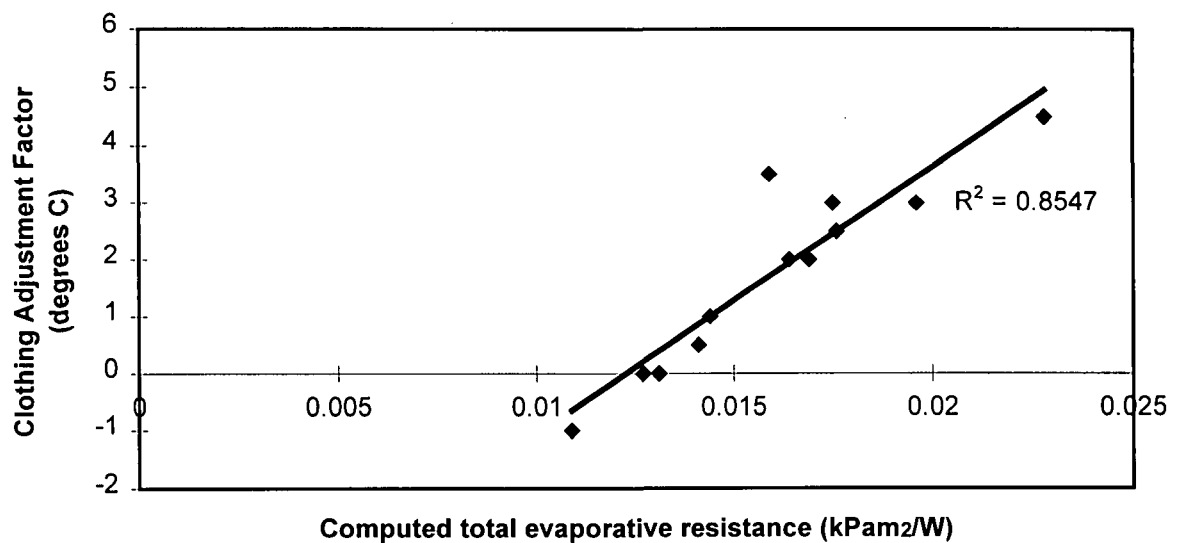


Figure 4. Graph showing the relationship between Clothing Adjustment Factor and F_{cl} (from Bernard, 1998)

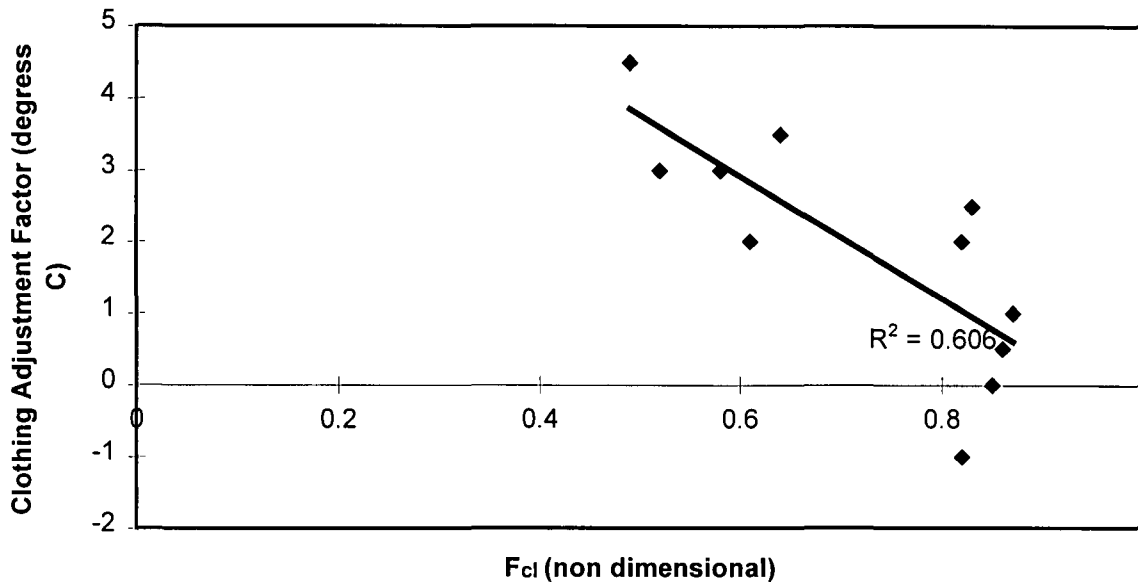
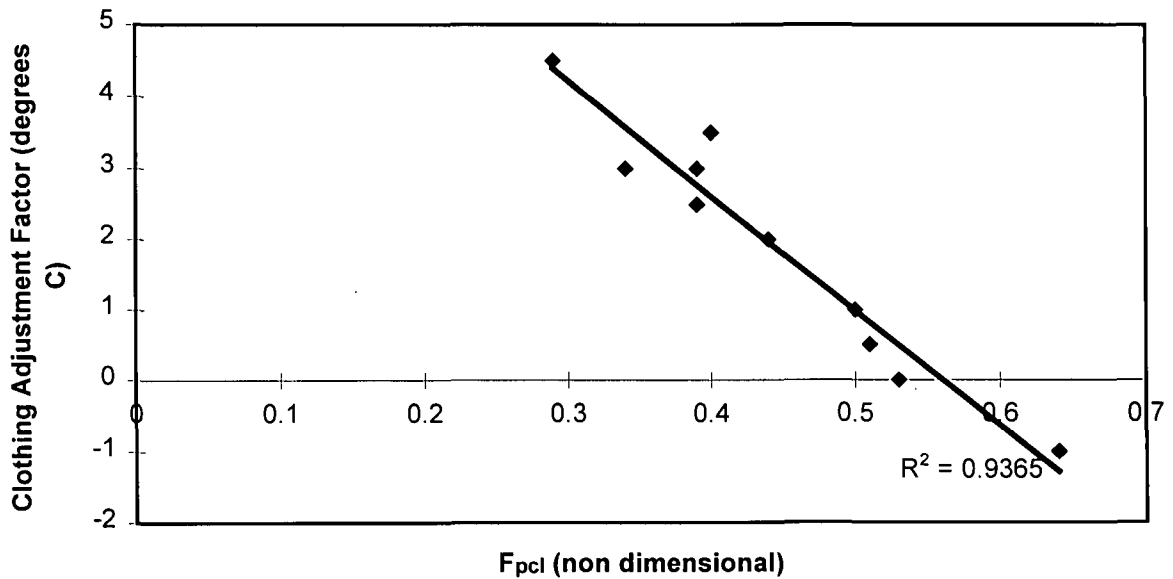


Figure 5. Graph showing the relationship between Clothing Adjustment Factor and F_{pcl} (from Bernard, 1998)



From these graphs it can again be seen that there is a close correlation between the computed F_{pcl} and the CAF. Bernard (1998) suggests that these estimated values of F_{cl} and F_{pcl} for different ensembles could be used in the required sweat rate analysis (BS EN 12515) and that they can be refined as further information becomes available.

These findings suggest that the evaporative resistance of the garment is more significant than the thermal insulation in determining the effect it will have on the heat loss from the body. This is certainly the case in situations of heat stress (i.e. hot environments or where the individual is generating heat in large quantities) where the main route of heat loss from the body is via evaporation of sweat, but may be less so in cooler environments where the main route of heat loss is via convection. Efforts should therefore be concentrated in describing evaporative resistance of garments and in incorporating allowance for this in thermal Standards.

For all clothing ensembles, a micro-climate will exist in the air trapped between the skin and the clothing, and this will directly affect the heat exchange at the skin surface. When garments which have a high evaporative resistance (e.g. water vapour impermeable clothing) are worn, 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, an internal condensation cycle is set up within the clothing with sweat being evaporated from the skin and condensing on the inner surface of the water vapour impermeable garment. The air within the garment will rapidly become 100% saturated with water. The heat produced by the condensation of sweat is conducted to the outer surface of the clothing and then convected away. The higher the external air velocity, the more effective the condensation/evaporation cycle becomes. However, the total heat loss resulting from the condensation of water vapour within the garment will be less than if the same amount of water had evaporated through the garment.

Where sweat cannot be evaporated from the body because water vapour impermeable garments are worn, in effect the wet bulb temperature is equal to the dry bulb temperature. This means that for the particular case of water vapour impermeable garments, the usual principle of the evaporation of sweat being the main route of heat loss of the body does not apply.

In terms of the WBGT index, there is a large weighting given to the wet bulb component of the environment (0.7 of wet bulb temperature plus 0.3 of dry bulb temperature where there is no radiant heat load). Obviously a range of environments can produce the same WBGT value (hot and dry may give the same WBGT as warm and humid). This may lead to errors being made when the WBGT index is applied to situations where clothing is worn which prevents the evaporation of sweat. The correction factor suggested for water vapour impermeable clothing (-10°C) is thought to be derived from moderate environments, but more research is required to further test the validity of this correction factor in a range of humidities. An alternative method of assessing the effect of water vapour impermeable clothing on heat stress in terms of globe temperature was discussed by Bernard (1998) and was outlined in Section 3.2.

With BS EN 12515, no account is taken of potential variation in the water vapour resistance of the material; it is assumed to be low (i.e. have a high water vapour permeability). At present the Standard does not appear to have a way of adjusting the evaporative resistance of the material within the BASIC program. This may be included in the future. However, where evaporative resistance is known to be high (i.e. in the case of a water vapour impermeable garment) it should be assumed that the ambient wet bulb temperature is equal to the dry bulb temperature.

Different fabrics will have different degrees of vapour resistance. At present there is insufficient information available concerning the vapour resistance to say much more than that vapour resistance is

high or low. As more information becomes available, more refined adjustments to the Standards can be made based on the degree of vapour resistance of the material. However, further information is required concerning the vapour resistance of materials, and ways in which this can be accounted for in the existing Standards, particularly BS EN 12515.

A number of papers on clothing have included the incidental use of a variety of other forms of PPE. Few however have systematically studied the influence of this PPE itself on evaporative heat exchange. However, some evidence relating to this can be obtained from studies of airflow in helmets. Reischl (1986) reported on a study of firefighters' helmets which were shown to significantly disrupt heat flux from the head directly under the helmet shell and in the regions affected by the harness. It was recommended that attention should be paid to enhancing the flow of air between the head and shell in order to facilitate heat loss. However, Johnstone *et al* (1996), drew attention to the fact that in severe environments, such as those likely to be encountered by an operational firefighter, this could be counter-productive. Limited evidence was also produced to indicate that certain helmet design features could channel heat into this airspace. Spaul *et al* (1987) reported on the extension of the work reported by Reischl to examine industrial helmets as well as other items of PPE worn on the face (respirator, goggles, faceshield). Airflow over the top of the head was markedly reduced by either the industrial helmet or a baseball cap. Wearing either goggles or a half-face respirator in conjunction with the helmet had only minimal further effect producing an average of -2% (goggles) or +2% (respirator) change in ventilation in relation to the hatless control. (As no variability data are provided and no statistical analyses presented, these variations must be interpreted with caution). Nevertheless, the results do at least provide some quantification of the disruptive effect of a Standard safety helmet on airflow over the scalp and, through this, an indication at least of an expected effect on heat stress.

Attempts to reduce the level of heat stress created by standard safety helmets were reported by Abeysekera and Shahnava (1988). However, helmets modified by cutting holes in the shell were not at all effective and wearing an unmodified helmet or any of the modified versions typically all resulted in an increase in exercise test heart rates by approximately 20% over the helmet-free control. The high increase in heat rate is unlikely to be only (or even significantly) due to the metabolic cost of wearing the helmet, and the disruption to heat loss by covering the head must be the reason for this.

3.6 Proportion of the body covered by clothing

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.

Dr B Olesen and Dr Elizabeth McCullough were contacted as the main researchers who were involved with the development of BS ISO 9920. They were asked whether they had any further information about clo values, proportion of the body covered by forms of PPE, or of evaporative resistances. However, all the information that they had collected was included in the Standard and they had no additional information. Based on the available information and expert opinion Table 11 was constructed. It was felt important to point out where overlap may occur between garments and the impact this may have on the percentage of the body covered. Although this will vary between individuals and will depend on the clothing, some guidance could be given.

Table 11. Summary of relevant body coverage of clothing from BS ISO 9920:1995

Garment	Percentage body covered	Page in BS ISO 9920:1995
Helmet / hat	4%	p 42
Hood / balaclava / cowl	7%	expert opinion
Respirator face piece	3%	expert opinion
Short sleeved top	35%	p 38
Long sleeved top	45%	p 38
Long sleeved top with hood	60%	p 41
Trousers	45%	p 36 *
Vest	30%	p 34 *
Shorts	25%	p 36
Gloves	5%	p 42
Shoes	7%	p 42

* NB where trousers or shorts are worn with a top, it is important to remember that these items will overlap, meaning that the total coverage is not additive. The overlap between the garments is approximately 10%. In other words, the total body coverage of a vest and shorts is likely to be 40% (p 45); and of a long sleeved top and trousers is approximately 80% (p 37). Further information on the amount of the body covered by different clothing ensembles is given in BS ISO 9920.

3.7 Movement ventilates PPE

Movement of clothing relative to the body causes flow of air (and water vapour) through clothing openings in an effective 'bellows' action. This is known as the 'pumping effect' (Nunneley, 1989). It is known that the pumping effect is applicable to clothing, but no papers have been identified regarding the existence of this or similar effects with other forms of PPE. This is hardly surprising as most other items of PPE rely for their function on being relatively firmly held to or around parts of the body. However, where PPE is worn over clothing, it could be expected that this will influence the pumping effect, probably adversely. Where items such as BA harnesses or fall-arrest harnesses are worn therefore, a greater degree of heat stress might be anticipated than would arise from the same clothing ensemble without those items of PPE. Although the expected effect would be less, any PPE worn on a belt, such as the increasingly widely used array of powered helmet respirators, would also restrict clothing movement. Other items of PPE where such an effect might be anticipated (although no documentation to that extent has been identified) include the disruption of air flow down the legs by rubber boots and, similarly, the partial occlusion of cuffs by gauntlet-style gloves. Knee pads could also be expected to have a disruptive effect on air exchange.

ISO 9920 recommends reduction of clothing insulation by 10% when metabolic heat production rate is below 100Wm^{-2} and by 20% when it is above 100Wm^{-2} . It is reasonable to conclude that where a belt or harness is worn, these corrections should not be applied as the potential for the pumping effect to occur is limited.

Bouskill *et al* (1998) demonstrated the effect of the fit of clothing on the pumping effect and consequently on the heat strain experienced by the wearer. The research showed that the better the fit of the garment, the less ventilation there was of the clothing and consequently the less potential for heat loss by evaporation. Therefore the closer the fit of the garment to the wearer, the greater the heat stress

on the wearer.

PPE may also have other modifying effects on the heat transfer properties of clothing. For example, Love *et al* (1996) document reports of burns occurring under firefighters' tunics, apparently relating to the compression of the fabric layers by BA harness straps and the consequent acceleration of inward heat transfer. Although not normally so extreme, the exclusion (or reduction) of air gaps between or within fabric layers will clearly influence the effective thermal conductivity of any garment.

Finally, although not created artificially by the movement of the wearer, the ventilation of powered respirators can have a cooling effect. Setting aside those deliberately designed to provide cooling, the provision of an airflow of approximately 36-40 litres minute⁻¹ to the breathing zone might be expected to have a beneficial effect even where it is drawn from the ambient air. If the source is compressed air (either from a compressor or bottled) then any effect will be enhanced by the low relative humidity of air from such sources. Depending on the length of the supply line such air may also be cooler than ambient air temperature.

3.8 Effect of an air supply

Many workers wearing PPE will also be required to wear some form of respiratory protective equipment. Breathing apparatus is usually in one of two forms, either open circuit, where the wearer inspires air from a compressed air cylinder, or closed circuit where the wearer inspires air which has been through a chemical filter which 'cleans' it. Both of these processes have an effect on the temperature of the air which will be inspired, and because of this, will have an affect on the ability of the body to lose heat through the lungs. With open circuit breathing apparatus, compressed air is fed into the mouthpiece.

Because the air is compressed, it expands and therefore cools as it enters the mouthpiece. The temperature of the air entering the mouthpiece has been measured at less than 12°C. However, this air will mix with the exhaled air (which has been warmed in the lungs) and the actual inspired air temperature has been measured at approximately 25°C (Hanson, unpublished). There is obviously some cooling potential of the face and lungs by this air. With closed circuit breathing apparatus works with the wearer breaths air which has been passed through a chemical filter. This chemical process heats the air, and the inspired air temperature will usually be above body temperature. The Standard prEN 145:1994 for closed circuit breathing apparatus specifies that 'the temperature of the inhaled air independent of humidity shall not exceed 45°C.' It is thought that most closed circuit systems will operate at close to this as discussions with one manufacturer indicated that they had experienced difficulty in reducing the inspired temperature to this level.

Where a simple filter is worn, the inspired air temperature is likely to be slightly higher than ambient air temperature, as some expired air will be trapped within the filter and will warm the inspired air. The inspired air temperature in this case may be close to body temperature.

3.9 Heat reflective clothing

In situations of high radiant heat load, the wearing of heat reflective clothing should, in theory, reduce the amount of heat stress the individual experiences. However, there is a mixed message about the benefit of heat reflective garments. Smith (1980) conducted an experiment looking at different forms of protective clothing. In the trial, subjects wore a plastic suit, gloves, hood and breathing apparatus and the same garment covered with reflective metallised plastic sheeting. The environmental conditions were dry bulb of 45°C, 25% relative humidity and 55°C globe temperature. The stay time (to limiting physiological criteria or subject request) for the plastic suit was an average of 19 minutes, while for the

reflective garment it was an average of 27.25 minutes, an average increase in stay time of 43%. It was noted that the protection afforded by the reflective cover varied with time and that the material became wrinkled by the heat.

In an experiment by Kaufman and Bothe (1986) into the thermal insulation of different materials, rate of heat transfer through fabric samples was measured. They found that reflective material placed between layers of fabric had no significant effect on heat transfer. Highly reflective material was not different from material of low reflectivity. A slight benefit was observed by Kissen and Hall (1963) who compared a reflective garment (aluminised asbestos fibreglass) with non-reflective clothing in extreme temperature conditions (93, 121, 149, 177°C for 15, 12, 9 and 2 minutes respectively). The heat reflective garment showed marginally better protective qualities than the non-reflective assembly.

However, a study by Belding *et al* (1960) found that ordinary work clothing blocked radiant heat by 30-40%, a reflective apron increased protection against radiant heat by 52%, and a reflective coat increased protection to 66%. However, they point out that metallic reflective clothing needed to permit good ventilation to allow for evaporation of sweat, otherwise such clothing gave rise to more strain than would ordinary work clothing. Another study showed that metallising the surface of multiple-layered clothing increases the resistance to radiant heat by 27-32% (Afanaseva and Gorskova, 1973).

One of the difficulties with these data is that there are different forms of heat reflective materials which may have different heat reflective properties. It is therefore difficult to generalise about the affect of heat reflective garments. Furthermore, the reflective ability of the fabric is only one element in the heat stress which the wearer will experience. Other factors to consider include the fit of the garment, whether it is sealed to the body, its thermal insulation and the amount of the body covered.

Most data identified concerning the protection provided by heat reflective garments are relatively old. The developments in fabric technology may allow for improved protection offered by heat reflective clothing. However, at present, it would appear that it is difficult to define the amount of protection afforded by heat reflective clothing. It is recommended that for the purposes of the heat strain Standards it is treated as normal clothing, and its clothing insulation value and evaporative resistance be taken into account in calculating its affect on heat strain. No beneficial affect of the clothing should be incorporated into the draft Standard. Further work is required to evaluate the protection afforded by heat protective materials.

3.10 Wearer alters PPE characteristics

Nunneley (1989) refers in particular to the effect that sweat can have on wetting clothing and therefore significantly altering its thermal properties. The wearer may also modify the clothing to some extent by, for example, not completely fastening closures, possibly in an attempt to reduce thermal discomfort. In some instances, the modification may be to not wear the PPE at all. Thus Abeysekera and Shahnava (1988) refer to the reluctance of employees to wear safety helmets, often citing thermal discomfort as a cause. Similar complaints have been levelled against hearing defenders and some forms of respiratory protection. The conflict between PPE being worn (and worn correctly) resulting in an increase at least in thermal discomfort and the relaxation of its use (with a consequent increase in exposure to other hazards) is peripheral to the present study although clearly an important occupational health and safety issue. For the purposes of the draft Standard it will be assumed that PPE is worn correctly.

3.11 Individual characteristics affect heat strain

Any additional load created by the use of PPE will have a differential effect dependent upon the individual characteristics of the wearer. Heavy clothing or self-contained BA will have a proportionately greater effect on a light person; respiratory protection imposing an increased inspiratory resistance will have a greater impact on those with poor respiratory characteristics (e.g. smokers). Such factors are additional to the individual variation in susceptibility to the heat.

Nunneley (1988) classified some wearer characteristics which will affect heat strain, such as the effect of clothing fit on the potential for heat exchange and the possible influence of anthropometric characteristics on the disposition of clothing apertures and resultant scope for air exchange. Extending this to other forms of PPE, helmet size and head size and shape and hair will clearly have an effect on the resultant air gap between the scalp and the shell, although no papers quantifying such effects have been identified. Given the lack of knowledge of the impact of the air-gap, detailed tuning of this knowledge to the influence of individual variation seems of secondary importance.

One important individual factor concerning heat stress is the degree of acclimatisation of the individual. BS EN 27243 provides WBGT limit values for both acclimatised and unacclimatised workers. The ACGIH guidance limit values are based on acclimatised workers. It has been suggested that acclimatisation offers no advantage when wearing water vapour impermeable clothing, and may even be a disadvantage in these conditions (Lind). This may be because one of the advantages of acclimatisation is to produce greater quantities of sweat, but if this cannot be evaporated the acclimatised individual is more likely to experience dehydration. The -10°C correction factor for WBGT when wearing water vapour impermeable clothing is based on Kenney (1987) which was undertaken with acclimatised workers. Therefore the disadvantage of acclimatisation when wearing this clothing is already taken into account in the correction factor.

Because Standards are designed to protect all the working population who are physically fit for the work they perform, these individual variations will be inherently incorporated into the Standards. The recommendations put forward in the draft Standard should protect all workers who are physically fit for the work they perform. Many workers will be able to safely exceed these limits.

3.12 Applicability of existing heat stress Standards

Ramsey and Chai (1983) discussed the accuracy of heat stress assessment methods. They argued that the degree of estimation of factors (particularly metabolic heat production rate) and the potential for variation in some factors (such as air velocity) meant that there is potential for very inaccurate assessment of the risk of heat strain in an environment. Because the internal generation of heat by the body is one of the significant ways in which the body gains heat, it is important that the amount of heat generated is estimated accurately. This is particularly the case with the WBGT index where metabolic heat production rate is grouped into five categories (resting, low, moderate, high and very high), and the range within one category may be up to 70 Wm^{-2} . Ramsey and Chai demonstrate clearly that this variation and the variation in air velocity can produce a significantly different estimate of the strain imposed by the environment.

It is important to remember this potential inaccuracy when considering thermal Standards. As mentioned, the most accurate method of assessing heat stress is to directly measure an individual's physiological response, but in most industrial situations this is impractical. When an assessment is undertaken using estimates of the value of the factors which are significant in heat stress, errors are likely to be introduced. With BS EN 27243 and BS EN 12515 while some parameters can be measured directly

(wet and dry bulb temperatures, globe temperature, and air velocity), estimates are made of the metabolic heat production rate, the thermal insulation of the clothing and the proportion of the body covered. Assumptions are also made of the evaporative resistance of the clothing. As demonstrated by Ramsey and Chai, it is particularly the variation in estimate of metabolic heat production rate which may reduce the accuracy of the assessment. A more accurate estimate of metabolic heat production rate, may allow a more accurate prediction.

Bernard (1998) outlined the plans for expected changes to the ACGIH guidance in 1998. It is proposed that physiological monitoring will be suggested as an alternative method for protecting the workforce from heat stress. The push for increased use of this method is thought to be because of the difficulty in predicting the impact of protective clothing on heat stress. However, as Bernard points out, physiological monitoring is reactive, and therefore it is difficult to use as a predictive tool. The proposed revisions also include a recommendation that heat stress controls be considered whenever water vapour impermeable clothing is worn, indicating the perceived risk of heat stress associated with wearing this clothing.

There is currently a suggestion that manufacturers of PPE should provide information concerning the environmental conditions in which the PPE can be used, and any restrictions to this. This is being discussed by the committee CEN/TC 122/JWG 9 as they draft European Standards concerning the design of PPE.

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

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

4. SURVEY OF USERS OF STANDARDS

4.1 Introduction

In preparing the draft Standard it was important to understand the needs of those who may ultimately use it. Two main groups of stakeholders were identified. These were manufacturers of PPE, and those people in organisations who are responsible for the health and safety of workers who may be exposed to heat stress through wearing PPE. Little was known about whether heat stress was considered to be an issue by manufacturers of PPE. There was also a lack of knowledge concerning the use of existing British and International heat stress Standards, how organisations were assessing the risk and what heat stress situations workers may be exposed to. In order to answer these questions, two surveys were undertaken; one of manufacturers and one of those responsible for the health and safety of their employees who wear PPE. The surveys both took the form of questionnaires with categorical responses (using tick boxes) and space for comments (qualitative information). These were followed up with telephone discussions with those organisations which indicated they were willing to participate.

4.2 Survey of Manufacturers

4.2.1 Aims

The aims of the manufacturers' survey were to:

1. Determine what information is provided by manufacturers concerning heat stress effects of wearing their PPE. The information they currently supply concerning their PPE was to be established, particularly relating to clothing insulation, evaporative resistance, fit etc.
2. Determine what items of PPE are most widely sold, in order to establish the most likely sources of heat stress problems.

4.2.2 Methods

A one page questionnaire (two sided) was developed with the above aims in mind, and with the guidance of the BSI steering committee. It was piloted on three manufacturers, and minor changes made based on the responses. A letter, the questionnaire and a pre-paid envelope were sent to 22 manufacturers of PPE. The questionnaire is shown in Appendix A. These manufacturers were identified through existing IOM contacts, and client lists at two relevant exhibitions. Manufacturers of garments which were thought likely to give rise to heat strain based on the literature review were particularly targeted.

4.2.3 Results

Thirteen completed questionnaires were received (59% response). All of the categories of PPE mentioned on the questionnaire were represented by the range of manufacturers who responded.

Of those which responded, eight organisations manufactured clothing which it was thought may pose a particular risk of heat strain i.e. clothing which protected against chemical / biological agents or asbestos. Of these, six (75%) provided information on heat stress with the garments.

Altogether eight of the manufacturers said that they provided information concerning heat stress with

the garments they manufacture. For seven of these organisations this was in the form of a user manual or instructions, but one organisation (producing firefighters' clothing) had developed a training video.

The clothing for which heat stress information was provided included fire fighter protective clothing, high barrier chemical protective work wear, limited use chemical protective work wear, bomb disposal suits and vessel entry work suits.

The following quotes show the information provided by manufactures with their products and are taken directly from the sales or information literature supplied by the respondents.

- Due to the high barrier properties of the material, wearers may be subjected to heat stress and discomfort during prolonged periods of wear time. This can be reduced by appropriate suit ventilation equipment.
- Due to the high barrier properties of some of these materials, wearers may be subjected to heat stress and discomfort during prolonged periods of wear time. This can be reduced by appropriate suit ventilation equipment and/or moisture absorbing underwear.
- The apparatus [BA] should not be operated outwith the temperature range specified in EN 138 [presumably to maintain technical integrity].
- Beware! Microguard 3000 & 4000 are manufactured from non-breathable fabrics. High work rates in these garments for a period could result in heat exhaustion. The use of Microguard 3000 Vented can reduce this risk.
- If the garment is to be worn for long periods at high temperatures or high work rates then due to the nature of the material the wearer may experience 'heat stress'.
- Vented upper body helps to reduce heat build-up inside garment during wear; will allow air to circulate and heat to escape; promotes wearer comfort over longer periods of time.
- Reduces heat stress.

Where information is provided, only one organisation is providing a very simple warning with no recommendations for how to reduce heat stress. Some organisations are providing more information than a simple warning, and are making recommendations on how to reduce heat stress. Reducing heat stress by venting appears to be the main method suggested by manufacturers of reducing heat stress.

All manufacturers said that they considered heat stress in the design of their clothing. Organisations were then asked whether they had used any Standards in the assessment of heat stress. None used the WBGT index or ACGIH guidance, one reported using physiological measurements, one company said that it used ISO 12515. Various other Standards relating specifically to the design of PPE were mentioned. In discussion with the manufacturers of PPE and clothing it was clear that they considered the heat stress issue from a clothing science stance, looking at increasing the potential for evaporation of sweat through developing vapour permeable fabrics, or improving venting into the garments without compromising the protective qualities of the clothing. One manufacturer is involved with the an international Standards committee looking at developing a predictive computer model of heat stress based on the different fabric layers used, and taking into account movement, ventilation and the thermal environment. Because of the overlap between the work reported here and the work of the other Standards committee, it is hoped that good communications will be developed with this group.

4.2.4 Conclusions

Some manufacturers were considering heat stress in the design of their clothing, and were providing information on the risk of heat stress with the PPE they manufacture. However, this is usually a limited warning. Formal assessment of heat stress when wearing the items of PPE does not appear to take place. It is unlikely that manufacturers will make extensive use of the draft Standard.

4.3 Survey of those responsible for the health and safety of workers wearing PPE

4.3.1 Aims

The aims of the user survey were to determine:

1. Which types of PPE are worn, where, for what duration, in what conditions, and by whom
2. Whether organisations perceive there to be a heat stress problem for workers wearing PPE
3. How they assess the risk of heat stress for their workers
4. What information they would require to assess in more detail the heat stress risks

4.3.2 Methods

A two page, (four-sided) questionnaire was developed based on the above aims and in discussion with the BSI steering group, and the questionnaires were piloted on four organisations with which the IOM had contact. Slight changes were made to the questionnaire based on the findings of the pilot study. The questionnaire used is shown in Appendix B.

The questionnaire, covering letter and a pre-paid envelope were sent to 48 organisations which had been identified from the IOM's client base and known listings of professional occupational hygienists as having workers who may be exposed to heat stress through their clothing. Both large and small organisations were contacted, and those organisations which it was thought would have workers wearing PPE were particularly targeted. As far as possible, organisations where there may be a heat stress issue without an additional radiant thermal load were targeted. Organisations which were contacted represented the following industries: chemicals, manufacturing, power generation, heavy engineering, the fire brigade, off-shore workers and mines.

A reminder letter, second copy of the questionnaire and a pre-paid envelope was sent five weeks after the initial mail-out to those organisations which had not responded.

4.3.3 Results

Completed questionnaires were received from 23 organisations (48%), and one questionnaire was returned undelivered.

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. The conditions reported where workers may be exposed to heat stress are described below as reported by respondents.

Table 12. Work situations where employees are exposed to hot conditions when wearing PPE

Co.	Type of work	Temp/ humidity	Typical work duration	PPE worn
1	Chemical plant operation	ambient	short repeated periods (10-15 mins)	Full acid protective clothing i.e. impermeable 'PVC'
2	Work inside vessels - welding and general fabrication - cleaning activity, mechanical work	30°C <100%	<2-4 hours	Can be impervious suits dictated by the need to provide chemical protection
	Heavy manual work	30°C <100%	2 hours	Impervious suits to protect from hot water splashing
3	Tank cleaning	37.7-43.3°C 100%	Regime defined by WBGT	Full face mask + air line, full coverall + gloves, hard hat in some cases
	Maintenance activities in process areas			
	Gulf coast USA plants are most at risk			
4	Most likely in planned maintenance and non-routine situations in summer	Hot summer days	Variable	Negative pressure respirators
	Glassblowing		Variable - 2 hours	Goggles, lab coats, RPE not necessary routinely
5	Operation of batch reactors during chemical processes	20-28°C 30-60%	<60 mins	Full air suit or chemical protective coverall
6	Onboard boats, welding after metal is preheated. Can be in confined spaces	In 1989-90 ranged from 15.5-33.6°C & <10% humidity	8 hours a day	Proban overalls + either proban jacket or leather jacket. Leather gloves + proban hood. Most welders also wear shirt + trousers underneath their overalls.
7	Special machinery trials in reactor compartment / measurements, light work	55°C 30-40% humidity	15 mins+	Full cotton overall, nylon cap, rubber gloves, cotton shoes covers
8	Welding / burning in confined spaces	WBGT 32-41°C	From 1 hour to 4 hours	Welding clothing, e.g. Proban overalls, leather skull caps, leather apron, leather sleeves, leather leggings, gauntlets, helmets, respirators, visors
	Opening valves, taking readings	WBGT 41°C	Varies. 30 min work + 30 m rest Or 15 m work + 45 m rest	Cotton/nylon one piece overall with nylon gloves, hair covering and overshoes

Co.	Type of work	Temp/ Humidity	Typical work duration	PPE worn
9	Melting of metal, platinum group metal (PGM), gold, silver, and forging of PGM	metal temp 1200°C	1 hour at a time. 3-4 times per shift	Visor, apron, gloves (all heat resistant), flame resistant trousers, foundry boots
	Loading and unloading of muffle furnaces	Furnace temp 800°C	1 hour twice per shift	Safety specs, hard hat, heat resistant apron and gloves, cotton clothing, safety shoes
10	Maintenance preparation	10-25°C	10-20 mins	Full suits, BA sets
	Confined spaces	10-35°C	up to 4 hours with breaks	Full suits, masks, BA sets, air fed masks, suits
11	Light duties, short duration lifting of containers	controlled	varies	Positive pressure half suits or BA with air temperature control
12	Dig out sulphur pits	WBGT approx 30°C	Several days work, take spells	PVC suits, wellies, impervious gloves, BA
	Clearing out petroleum storage tanks in summer	Dependent on weather	Several days, take spells	PVC suits, wellies, impervious gloves, BA
	Constructing scaffold or working on high scaffolds in hot weather	Dependent on weather	Several days work, take spells	PVC suits, wellies, impervious gloves, BA
	Emergency fire-fighting and casualty rescue	Variable, dependent on situation	10-60 mins	Self Contained Breathing Apparatus + turnout gear
13	On top of sodium downs cell operating at 600°C - molten metal and chlorine	35-40°C 20-35%		Wool/nylon shirt, proban treated cotton bib and brace, works boots, helmet, face visor moleskin mitts - respirator carried
	Work in sludge pits	?		Full suit and airline BA
14	Manual handling of corrosive materials in containers etc.	Various, but greatest in summer	approx 30 mins	Full impervious (PVC) suit. Not air fed. Plus visor + hard hat or airfed hood depending on materials handled.
	On standby during tanker unloading (outside)	All weather conditions - outside	up to 60 mins	Full impervious chemical suit plus goggles during work near tanker
	Emergency response	Various	limited to 20-30 mins depending on situation	Special full suit for use with CABA
	Emergency response	Various, but greatest in summer	Could be 1 hr +. Breaks should be provided	Full chemical suit

Co.	Type of work	Temp/ humidity	Typical work duration	PPE worn
15	Packing / milling	Unknown	1-2 hours max	airsuit or air hood / disposables
	Unloading container lorries	Varies depending on the weather	1-2 hours	respirator or dust mask and disposable overalls
	Engineering work	Varies depending on the weather	Variable	disposable overalls and dust masks

It can be seen that the problem of heat stress when wearing PPE may develop in many industries and with a wide range of activities.

Most respondents appeared to be aware of the risks of heat stress as short durations of work were often cited. While most also knew the environmental temperature ranges that their workers were exposed to, fewer knew the humidity levels. The WBGT temperature was quoted quite frequently, indicating that the index was used by some organisations. 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 hours wearing impervious suits; welding in confined spaces at 32-41°C for 1-4 hours wearing heat protective clothing; digging pits at WBGT of 30°C taking spells at the work but wearing PVC suits and BA.

A number of organisations had workers wearing forms of PPE outside, where the degree of heat stress would depend on the weather conditions. This is particularly a cause for concern as there will be no control over the weather, and it may therefore be difficult to predict in advance the extent of heat stress. In addition, the influence of a solar load may be difficult to predict because it varies over time. Particular care should be taken by workers in these conditions, and they should be free to take breaks from the work.

Most organisations indicated that workers were only exposed for short durations when extreme conditions were experienced, or that regular breaks could be taken, indicating that heat strain may be reduced in this way.

In general, respondents were able to give information about the PPE which was worn by workers, although this was sketchy in some cases. The level of information given indicates that the descriptions of PPE put forward in the draft Standard appear to be to an appropriate level of detail.

Assessment of heat stress

Twelve of the organisations which responded said that they undertake assessment of heat stress, although not all these organisations reported having workers in situations where they may be exposed to heat stress. Of the 15 organisations which said there may be heat stress, 9 said they had assessed the risks of heat strain.

Respondents who said they had done some assessment of heat stress were asked how they had done this. Nine organisations said they had used the WBGT index, and 6 of these also used the ACGIH guidance. One organisation only used the ACGIH guidance. One organisation reported undertaking qualitative assessments and another reported undertaking heat stress monitoring. Another reported using guidance

and assessments from the following sources: Bell and Watts 1971 - BMJ 28, 259-264; AIHA (1975) Heating and cooling for men in industry, 2nd edition; McIntyre (1980) Indoor climate, Ch 10; Brief and Confer (1971). None of the organisations had undertaken physiological measurements, and none had used the Required Sweat Rate equation. This suggests that the WBGT index is the most widely used and that guidance in the draft Standard should be written with this in mind. However, informal discussions at a (more recent) conference suggest that BS EN 12515 is being more widely used than would be indicated from this survey (Bethea, personal communication), and clear guidance is also needed for this Standard.

Respondents were asked what factors they took into account in the assessment of the environment. Of the 11 organisations which reported which factors they considered when assessing the risk, all considered the dry bulb temperature, the duration of exposure, the clothing worn and the metabolic heat production rate of the individual. Ten also considered the wet bulb temperature and the radiant heat load. Fewer considered the percentage of the body covered (9 respondents), the air velocity (8), the age of the worker (7), their degree of acclimatisation (6) and their experience (4). This indicates which factors respondents consider as key in undertaking an assessment; it is encouraging to see that those factors which are most significant for heat stress are considered by all or almost all of the respondents.

Difficulties with Standards

Respondents were asked if they had experienced any problems in using these documents. Comments included:

- Illness can still arise.
- Some of the heat stress indices e.g. WBGT (ACGIH) are very conservative i.e. there is a high safety margin which sometimes leads to practical difficulties.
- ACGIH is very useful. We do need supplementary UK / European guidance for hot industries e.g. foundries.
- WBGT difficult to work with at the sorts of temperatures we are experiencing (55°C). Work/rest regimes difficult to interpret.
- The Standards don't cater for high radiative heat situations
- The Standards don't take into account individual differences
- Evaluation of metabolic rates are exceedingly complex
- Clearer guidance is required on how to interpret factors and determine the overall risk of heat strain resulting from short periods of intense physical activity while wearing impervious clothing.
- Guidance would be useful on how much to reduce the WBGT reference values by when insulation factors are greater than 0.6 clo.

It is clear from this that the area where users are particularly experiencing problems with the Standards is in the more extreme conditions where there are high radiant temperatures and high metabolic rates. Both BS EN 27243 and BS EN 12515 have limits to their scope of applicability (e.g. not 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 the draft Standard is clear in its scope. It is also important that it is easy to use.

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, and the methods they had used are shown below.

- Organisation of work - exposed periods interspersed with work in control room and other duties not requiring PPE.
- Currently by restricting the period of exposure and allowing liberal breaks.
- Most frequent control is to limit the time exposed to the high temperatures, i.e. 30 mins work + 30 mins rest. During the rest period plenty of fluids are provided.
- Workers are able to alternate with their colleagues to adjust durations of their work/exposure. No cases suggestive of heat strain have presented in the last six years
- 20 mins max use of BA sets, and 2 hours before return if wearing PVC suits of any quality
- Minimise duration of PPE use.
- By time limitation.
- Use 15:45 mins work:rest schedules as recommended by WBGT. Other methods not possible for this type of work.
- Cyclical process operations generally limit periods of PPE usage. There is significant operator control over work rates. This may change as business pressures increase and we routinely review our hygiene programmes to determine whether we need to give greater priority to thermal stress.
- While this is not a current problem we have had to control working hours and have employees take breaks in cooler locations and provide drinks.
- We control the heat via blankets which block off radiant heat. If this isn't sufficient we limit the time spent in the area and allow the welder to go to a cool place. Reducing the PPE is not practical when welding.
- We have operated a high containment building since 1985. The temperature and humidity of breathing air is controlled - air dehumidified and rehumidified with steam. The work environment is temperature controlled. The nature of the work means that heat strain will not be a factor. There have been no concerns or complaints or problems since 1985.
- Recovery in controlled air-conditioned environment. At least 20 mins per hour rest. Drinks regularly (isotonic occasionally)
- We always try to minimise. But the reason for the heat strain is often that we cannot avoid the PPE.
- Use air-fed suits if possible (Respirex or Plysu)
- PPE is worn in air conditioned environments
- Depends on risk assessments - determines what action to be taken.
- If the risk assessment conclusions indicated need.

It can be seen that various methods were used to reduce the risk of heat stress. These were particularly by re-organising the work and introducing rest breaks. Some efforts were reported of reducing the heat stress at source through screening off the source of heat or providing air conditioning. Rests in cooler

areas and provision of drinks were also mentioned. These methods are likely to be the simplest and most effective to implement. However, it is interesting to note that none of the organisations had introduced different forms of clothing to reduce the risk of heat stress, possibly because there is limited scope for cooling in this way.

Follow up telephone interviews were held with 9 of the organisations which responded. Further information was obtained from them concerning the problem of assessing and preventing heat stress in their industry. During the interviews, the work situations which may lead to heat stress were clarified, together with information as to whether any of their workers had experienced symptoms of heat stress. The individual was asked if they conducted risk assessments and whether they used any of the heat stress Standards. If they did, the discussion covered which Standard they had used, and whether they had used any correction values for protective clothing. Any problems experienced with this were also discussed. If they did not do any heat stress risk assessments, the reason for this was determined. Individuals were asked whether they had heard of the Standards. They were also asked whether they had done or planned to do any physiological monitoring. Methods of reducing the risk of heat stress were also discussed.

Discussions were also held with some individuals who did not complete a questionnaire; these people were usually either suggested by one of the other interviewees, or were professionals not working in industry. The organisations they represented included HSE Inspectorate, Protective Clothing Research Physiology Laboratory (Cambridge University), Institute of Naval Medicine, and University of Aberdeen, Department of Occupational and Environmental Health Department.

These interviews proved very useful in providing additional information concerning how organisations are considering and tackling heat stress. The discussions can be distilled to the following main points.

- Several of the organisations which had admitted having conditions which could result in heat stress were not aware of the existing Standards. They also said that receipt of the questionnaire had prompted their thinking concerning the issue. One individual felt she did not have enough knowledge of heat stress issues currently.
- In the majority of organisations no formal assessment of heat stress is conducted. One reported that the assessments were superficially done.
- Any draft Standard should be clear as to which situations it applies to, i.e. making it clear whether it applies to the assessment of heat stress at high temperatures.
- Heat discomfort is particularly an issue for workers wearing eye protection (removing it when it is steamed up), although this is not really heat stress.
- The Confined Space Regulations have driven a lot of the assessment of heat stress, as they require assessment of the risks of working in confined spaces.
- A few organisations train their workers who are exposed to heat stress, in ways to cope with the conditions, eg regular intake of fluid, identifying symptoms of heat strain, operating a buddy system.
- One organisation was considering the use of personal cooling.
- Two organisations reported that it was difficult to measure WBGT temperature in some conditions as the equipment required was bulky and the heat stress situation was in a confined space. 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. Dry bulb temperature was also seen as giving a more direct (immediate) measure as an indication of heat stress.

- One organisation used the WBGT index to determine work-rest schedules; however, instead of making direct adjustments for clothing (as in ACGIH), they increased the metabolic rate to take account of the clothing (as done by Nigg *et al*, 1992, on the recommendation of Dukes-Dobos).
- ACGIH guidance is thought to be inappropriate for hot conditions.
- The WBGT guidance is conservative.
- One respondent found the BS EN 27243 Standard unclear on evaluation of heat stress, and so now uses the ACGIH guidance.
- One organisation was using the Croner's guidance which is based on WBGT.
- The HSE guidance on working with asbestos was used by one organisation.
- In another organisation workers were wearing BA (sometimes with chemical protective clothing) and were limited to 20 minutes exposure (the length of the cylinder). They would then rest in a cooled area, and would only re-enter the enclosure after 2 hours. 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 with assessing 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.

4.3.4 Conclusion

It appears that there are a number of workers in situations where they may experience heat stress. The most severe conditions are those which involve working in confined spaces, sometimes in environments hotter than ambient conditions, and where full chemical protective clothing is worn. The guidance in the draft Standard should address these work situations.

Just over half of the organisations which reported heat stress conditions had undertaken an assessment of these conditions. The WBGT index was the most commonly used, with the ACGIH guidance. None of the organisations had undertaken physiological monitoring, and none had used BS EN 12515 to assess heat stress.

Problems experienced with the Standards were that they were conservative, and that they did not cover the working environments which some industries experience.

Most of the control measures taken by organisations to reduce heat stress involved limiting the working time, and developing work-rest regimes. These should therefore be clear in the draft Standard.

The draft Standard must be clear which work situations (and environments) it can be applied to, and what situations are outside its scope. Those who use the draft Standard are likely to have some understanding of the issues of heat stress, and be familiar with measures required. It appears that the Required Sweat Rate equation (BS EN 12515) is not widely used, but the WBGT index (BS EN 27243) is. The draft Standard was written with this knowledge base in mind.

5. PHYSIOLOGICAL DATA

5.1 Introduction

The literature review identified areas where there was no available data concerning workers wearing PPE. It was hoped that this data could be provided, in a limited way, from data which could be collected or analysed easily within the scope of the project. It was not intended to collect new data as part of this work. However, where possible, it was proposed to use existing experimental data to supplement the literature review, and to validate the recommendations made for the draft Standard.

The aims of this phase of the research were to:

1. Use existing data to compare values obtained using the thermal Standards (BS EN 27243 and BS EN 12515) with those obtained experimentally for workers wearing PPE.
2. Compare this with findings of the literature review.
3. Determine if the guidance suggested by the literature is appropriate and is supported by the findings of experimental work (i.e. validation of the draft Standard).

5.2 Methods

Physiological data collected both in the lab and in industrial heat stress situations was sought. Different sources were pursued, although with limited success. One difficulty in trying to collect data is that some industrial activities which involve heat stress only occur irregularly (e.g. tank cleaning only takes place approximately every year). The sources pursued were:

1. IOM data from recent work at a chemical clean-up operation
2. Data collected by Loughborough University as part of an HSE funded project
3. Case studies in a large company
4. Case study of a heavy manufacturing company
5. IOM routine testing of PPE

5.3 Results

The results of these efforts are described below.

5.3.1 IOM data from recent work at a chemical clean-up operation

This case study illustrates IOM's experience with using the BS EN 27243 and BS EN 12515 Standards in assessing heat stress for workers wearing PPE.

Data were collected during some IOM field work at a chemically contaminated site where workers were undertaking the clean-up operation. Full chemical protective clothing and respirators were worn. IOM was asked to advise on the risk of heat stress and to determine suitable methods of reducing this (work-rest regime was thought to be the only feasible solution). During the work, physiological monitoring of individuals was undertaken (aural temperature), although there were some difficulties with obtaining

many accurate readings in the field.

Data were collected over a 3 week period. Environmental conditions were varied depending on the location (outside or inside contaminated area). During the first two weeks of data collection the temperature and work rates were lower than had been predicted as this time was mainly spent setting up the work (dry bulb temperatures approximately 11°C. During the third week environmental temperatures were higher; at the start of the third week, inside the contaminated area dry bulb psychrometric temperatures were 17.5°C (18.5°C natural), and psychrometric wet bulb temperatures were 14°C (16°C natural). Outside the contaminated chamber the temperatures were dry bulb 14.5°C (14.5°C natural) and 10.5°C (11.0°C natural). Air velocity was negligible. Although it was difficult to predict how the temperature would change during the work, it was assumed that the air temperature would rise to 22°C once work commenced. Based on the activities observed, two different metabolic rates were assumed of 220 and 260Wm⁻².

The advice given by IOM was initially based on BS EN 27243 (WBGT index). For continuous heavy work and unacclimatised personnel, the reference value for WBGT is 18°C. Assuming a correction factor of -10°C (based on ACGIH guidance for water vapour impermeable clothing), the WBGT reference value was reduced to 8°C for this activity. The measured WBGT values were 18°C. It was therefore necessary to recommend a work-rest schedule. Workers were also resting in the water vapour impermeable clothing in the same climate. For unacclimatised workers resting wearing water vapour impermeable clothing the WBGT reference value is 22°C (32°C-10°C). A 1:3 work:rest schedule would give a time weighted average of 18.5°C WBGT. With acclimatisation this would increase by 2°C (WBGT reference for acclimatised personnel working with water vapour impermeable clothing is 13°C and for resting is 23°C).

Discussions with the works manager about the possibility of a 1:3 work:rest schedule identified that any work:rest schedule other than a 1:1 would not be cost effective from an administrative point of view. They therefore were keen to use this 1:1 schedule. Further evaluation of the work situation was therefore undertaken using BS EN 12515. The values for environmental temperatures, work rates, and clothing were put into the BS EN 12515 BASIC program, with the assumption that because the workers were wearing non-vapour permeable clothing, no sweat could be evaporated and therefore it was equivalent to working in an environment with 100% humidity (i.e. dry bulb temperature = wet bulb temperature). Based on this assumption, the equation indicated that a 40 minute work period was suitable for the type of work in those conditions. Because of the pressure of using a 1:1 work:rest schedule, a reduced exposure time of 30 mins work and 30 mins rest was put into the SW_{req} equation (again assuming 100% humidity). This indicated that such a work regime should be sustainable in these conditions. Therefore a 30 mins work:30 mins rest schedule was recommended. However, it was also recommended that physiological monitoring of workers be undertaken to determine that such a regime was acceptable.

Under these conditions, the physiological response of the workers was monitored. In these conditions, no aural temperatures above 37°C were recorded; in general core temperatures rose by approximately 0.5°C over the duration of work (approximately 1 hour) although isolated increases of up to 1°C were recorded. Heart rate recordings shows that heart rates increased by between 20-40bmin⁻¹ for the shift conditions, from between 80-100 bmin⁻¹ to between 110-140 bmin⁻¹. During the first two weeks of working most working heart rates were around 120 bmin⁻¹. Later on in the work process, as the work load increased, heart rates recorded were between 150-160 bmin⁻¹. However, still no aural temperatures exceeded 37°C.

It therefore appears that the recommended work-rest schedule developed based on the WBGT / ACGIH and BS EN 12515 was suitable for these working conditions.

The general level of physiological heat strain recorded was not as high as anticipated although, as stated above, some increases 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 of individuals so that the estimated metabolic heat production rate was not sustained during the work period. Finally, the environmental conditions were such that an internal condensation cycle as referred to in Section 3, 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 and causing more cooling than would otherwise have been the case.

This study also demonstrated the difficulty in some work situations of conducting physiological monitoring. There was some reluctance on the part of the workers 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 contaminated environment, and for these reasons fewer readings than ideally required were obtained.

5.3.2 Data collected as part of HSE research

Experimental data collected by Loughborough University concerning physiological response to working conditions (when wearing PPE) was approved by HSE to be made available for the project. However, due to experimental delays and technical difficulties it was not possible to obtain this data.

5.3.3 Case studies in a large company

One of the companies contacted as part of the survey had undertaken some investigations of heat stress among its workers. They provided details of two case studies investigating this problem.

In the first case study workers were removing the catalyst from two chemical reactor towers. Workers (wearing chemical protective clothing and BA) were observed to suffer from heat stress and could not work in the conditions for more than 30 minutes. The cleaning activity was repeated almost two years later, using some of the same workers who were involved in the earlier work. During this activity, the temperatures in the towers were 33 and 34 °C with humidity at approximately 30%. Workers were supplied with water cooled waistcoats and workers reported much improved thermal comfort as a result of the waistcoats. Persons were able to work for periods in excess of 2 hours without experiencing heat strain. The company expressed satisfaction with the use of the water cooled waistcoats, although they experienced some problems with the supply of water to them.

In another work situation limited physiological monitoring was undertaken of worker on exit from the hot working area (exact temperature not known). Radial pulse and oral temperature measurements were taken, and based on these a work:rest regime of 1:3 was developed. The physiological measurements were also used to validate that the work:rest regime was suitable.

HSE guidance on the work:rest regimes for asbestos stripping work were followed within the company. Medical surveillance of workers was available and used where conditions were extreme.

5.3.4 Case study of a heavy manufacturing company

One other organisation which took part in the survey indicated that they would be undertaking physiological measurements of workers in a heat stress situation in spring 1998. Unfortunately, due to security reasons, access to the area where heat stress may arise is not possible for personnel from outside the company. They are willing to provide us with these data, but it will not be available until summer 1998, outside the timescales of this project.

5.3.5 IOM testing of PPE

It was planned that physiological data would be collected as part of the IOM's ongoing testing of respirators and protective clothing. These are conducted at ambient temperatures, with the subject walking on a treadmill, and performing squats and standing where chemical protective equipment is tested for inward leakage. Over the past 3 months, the PPE tested has all been respirators, which the subjects wear with their own clothing. The tests conducted involve the leakage into the respirator. Because the only item of PPE being worn was the respirator it was decided that it was not appropriate to undertake physiological measures, as the physiological impact of wearing the respirator was likely to be difficult to detect.

A limited amount of data were however collected during protective clothing trials. Physiological responses were collected for four exposures of wearing a lightweight disposable suit with hood (water vapour permeable) and wearing cotton T-shirt and shorts underneath, on two subjects (two trials per subject). The wearer was monitored for approximately 30 minutes as they stood (3 mins), walked at 6kmhr^{-1} (3 mins), and squatted (approx 25 times per minute for 3 minutes). This sequence was repeated 3 times. Ambient dry bulb temperatures during the trials were 17-19°C with humidities of approximately 40-60%. Neither subject was acclimatised. Aural temperatures were recorded before, during and after the trials. Core temperature increased by between 0.1°C and 0.5°C (mean 0.3°C) over the 30 minute trials, with the maximum aural temperature being 36.4°C. Subjects were asked to rate how they felt at the end of the trial on a scale of 1 to 9 (very cold to hot). For all trials this was rated at 6 (slightly warm). They were also asked to rate whether the environment and clothing was bearable (1) to unbearable (5). For all trials this was rated as 1 (perfectly bearable). It can be concluded that the wearers did not suffer heat stress in the trials.

In order to try to validate the corrections put forward in the draft Standard, the methods were applied using these data. The highest WBGT index value (measured) was 15.0°C. The metabolic heat production rate was estimated to be class 2 (moderate), and for unacclimatised workers this gives a WBGT reference value of 26°C. A correction for the lightweight chemical protective suit of -6°C was applicable, giving a corrected reference value of 20°C. The measured WBGT index value is well below that at 15°C, and heat stress would not be expected to occur in this situation.

The method described for BS EN 12515 was also tested, with the relevant values being input into the BASIC program. This predicted no limit for work duration for unacclimatised workers in these conditions.

Although the conditions are not extreme, and the methods put forward in the Standard are not being fully tested in conditions where heat stress may arise, they do appear to be relevant where the risk of heat stress is low. Obviously further work is required to test the draft Standard in situations of greater heat stress.

5.4 Conclusions

Although considerable efforts were made to obtain data in order to validate the draft Standard, limited data were available. It is 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 the willingness of workers to take part. Furthermore, it was difficult to identify obtain access to suitable sites for conducting measures. Where it was possible to obtain data however, these show that the guidance contained in the draft Standard concerning WBGT is suitable as initial guidance and for devising work:rest schedules, and that BS EN 12515 may provide more accurate estimates of heat stress. Good quality physiological data are hard to obtain, although they may be the preferred method of assessing heat stress (as demonstrated by proposed changes to US guidance, Bernard 1998). This difficulty in collecting good physiological data must be borne in mind when recommending its use as a method of protecting the workforce.

6. DEVELOPMENT OF THE DRAFT BRITISH STANDARD

The draft British Standard was developed in close collaboration with a steering committee appointed by the British Standard technical committee PH 9/1. Regular meetings were held with the committee and drafts of the draft Standard were discussed.

It was recognised that the Standard had to follow the convention of existing Standard layout, and had to use the same definitions and normative references as those already used in existing Standards. It was decided that the Standard should be specifically for 'workers' wearing PPE. It was to exclude the leisure use of PPE, although it was recognised that some forms of PPE worn at work may also be worn in leisure pursuits e.g. protective helmets, dust masks. The Standard was written specifically for those who have a responsibility for the health and safety of workers wearing PPE in situations which may lead to heat strain, and for those who advise them. It was not written for manufacturers of PPE, although they may find it useful if conducting physiological trials of their clothing.

The Standard is written with the usual Standards introductory text including firstly normative references and secondly definitions. These are based as far as possible on existing definitions included in thermal Standards, except where there was no suitable definition or where the existing definition was not adequate. The third part of the Standard discusses the impact of PPE on heat balance in general terms, followed by an explanation, and where possible a quantification of how clothing affects heat stress. Factors about which specific guidance could be included were:

- the alteration to convective and evaporative heat transfer due to the insulative characteristics of PPE
- the alteration to convective and evaporative heat transfer due to the increased proportion of body area covered by PPE
- the increase in metabolic heat load due to weight of PPE
- the increase in metabolic heat load due to restriction on movement due to wearing of PPE

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

- 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 (e.g. chemical respirators: positive load or other means [e.g. cool, dry air from air-fed respirators])
- the pumping of air around a clothing ensemble and the effect of this on heat stress.

Having set out the general principles, these factors were applied to the two existing Standards which provide a method for assessing heat strain (BS EN 27243 and BS EN 12515). Actual detail of conducting 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. These methods were included in an Annex (informative rather than normative and in the main part of the text) because they mention reference to specific versions of the existing thermal Standards (i.e. identified by date). [However, note that these dates were omitted in the draft for public comment. The reason for the inclusion of dates was so that the proposed methods for interpreting Standards when workers wear PPE could be specifically linked to these versions of the Standards. This was felt to be necessary as detailed alterations suggested in the draft for public comment (e.g. making adjustments to specific lines in the BS EN 12515 BASIC

program) had to be tied to specified versions of the Standard; future changes to these existing Standards may alter the corrections which are put forward in this draft Standard].

Three examples of the application of the methods described are included in the draft Standard (Annex B). These were based on scenarios reported by respondents to the questionnaire survey. One of these examples covered the use of BS EN 27243 alone, while the other two covered the use of BS EN 27243 as an initial assessment method, followed by BS EN 12515 used as a more detailed analysis method. The interpretation of the findings of the assessment are also discussed.

Annex C of the draft Standard contains tables of information concerning the clothing insulation values for typical clothing ensembles worn, for reference and application to existing Standards.

Annex D of the Standard will be of most interest to researchers or academics concerned with the science behind heat stress Standards. Taking the equations which form the basis of the BS EN 12515, the Annex outlines the changes to these equations which need to be made to allow it to be applied to workers who wear PPE. These equations are the basis of the BASIC program; the Annex does not put forward detailed suggestions for corrections to the lines of the program. However, it should provide the theory for anyone wishing to alter the program for workers wearing PPE to do this. It should be accepted that it is unlikely that the target reader of the Standard (usually someone with health and safety responsibility for some employees) will use this part of the Standard. However, for the sake of completeness, this Annex was included.

The format and presentation of the draft Standard was influenced by the comments of those who took part in the questionnaire survey. It was important that the draft Standard was easy to use and clear to understand. It was also important that the scope of the Standard was clear, and that it was applicable to their work situation. 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.

During discussions with potential users of the draft Standard in its development, several individuals responsible for the health and safety of their employees were identified as being willing to comment on the draft Standard which was being produced. All those who took part in the questionnaire survey were sent a letter inviting them to come to the UK Clothing Science Group meeting and informing them of how they could obtain a copy of the draft for public comment. They will be able to feed their comments in, via the usual procedures.

During development of the Standard, several problems were identified with the existing Standards, in particular with ISO 12515. Most of these were errors of inconsistency. Details of these are shown in Appendix C of this report.

The draft was circulated for public comment by BSI on 15th May 1998. It was presented at the Clothing Science Group meeting at Loughborough University on 1st June to approximately 100 people, where it was discussed in some detail. All documented comments were invited to be submitted to the British Standard's Institute by 31st July 1998. The draft will then be reviewed and the comments responded to as appropriate. 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.

7. 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 have been identified. In considering their relative importance, three main issues were considered: how significant the factor is in terms of development heat stress; how useful (and usable) this information will be in relation to gaps in the draft Standard and other Standards; and which Standards are most widely used. The following recommendations are in a suggested priority order taking these issues into account.

The recommendations for future research outline areas where further information is required, with the assumption that the effect of these factors will be included in revisions to heat stress Standards.

1. Information is required on the application of correction factors for clothing to WBGT reference values. 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 heat production rates, to answer the question of whether they 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 US, these should be validated fully in the UK.
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. There is a lack of data on the evaporative resistance of different clothing ensembles and PPE. Research is needed to develop such a database.
5. 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.
6. Little is known concerning the amount of protection offered by heat reflective fabrics. At present it is not possible to say by how much they extend safe exposure times in extreme thermal environments, or environments with a high radiative heat load. Research is required to investigate the amount of protection offered by these garments.
7. 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.
8. 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).
9. Research into 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.

10. 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.

8. CONCLUSIONS

The research programme has shown that there are a number of issues to consider concerning heat stress for workers wearing PPE. These have been identified in the literature review and discussion with experts. Where data are available in the literature, these have been used in the draft Standard as the basis for assessing the risk of heat stress for workers wearing PPE. Where data were not available, these have been identified, and research needs outlined.

The survey of users of Standards (both manufactures and those who are responsible for the health and safety of their workers) identified their main needs. It was important that the Standard was easy to use and that its scope was clear.

Manufacturers appear to recognise that heat stress is an issue, but few are assessing the risk of heat stress through the use of thermal Standard. Their primary focus is the clothing science and developing the textiles and design of the garments to reduce heat stress.

Those responsible for the health and safety of their workers recognise that heat stress is an issue and are, in general, taking some measures to reduce the risk. However, comments showed that guidance was needed in some areas, particularly where there was a high radiant load, and where forms of PPE which were outside the scope of the existing Standards were worn. Some comments indicated a lack of understanding about the scope of the existing Standards, where users had tried to apply them to situations to which they were not applicable.

The comments of those responsible for the health and safety of their worker also indicated that of the British and International Standard available, the WBGT index and ACGIH correction factors were the most widely used, possibly because they are the most straightforward and require the least amount of equipment. None of the respondents were undertaking physiological monitoring according to ISO 9886, although one organisations which provided details for a case study was undertaking simple physiological measures. None of the respondents were using ISO 125215, the required sweat rate calculation. The examination of physiological data available from field work identified that obtaining good quality physiological data was difficult in many field situations.

Based on the literature, expert knowledge and 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. However, of necessity, the use of this Standard requires a working knowledge of the use of the Standards which it supports, in particular BS EN 27243 and BS EN 12515. Some of the factors which were considered were its structure, which parts should be normative and which should be informative, and the use of examples to illustrate the techniques being described.

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Appendix A

Questionnaire to manufacturers

Heat strain in workers wearing PPE

Workers who wear Personal Protective Equipment (PPE) may suffer heat strain in some working conditions. The British Standards Institution (BSI) is managing a project, funded by the Department of Trade and Industry, to prepare a draft British Standard which gives ways of assessing the likelihood of heat strain for workers wearing PPE and ways of managing this risk. The Institute of Occupational Medicine has been contracted by the BSI to prepare the draft standard.

We are asking you to support this work by completing this short questionnaire. The information you give will be treated in strictest confidence and will be used only for the purpose of this research.

1. Please indicate which hazards the PPE you manufacture protects against:

- | | |
|-------------------------------|--------------------------|
| General workplace hazards | ☐ |
| Specific hazards: Noise | ☐ |
| Heat | ☐ |
| Chemicals / Biological agents | ☐ |
| Asbestos | ☐ |
| Dust | ☐ |
| Fumes | ☐ |
| Contact / abrasion / impact | ☐ |
| Other, please specify _____ | |
| _____ | |

2. Do you provide health and safety information with any of the protective clothing or PPE you manufacture?

Yes ☐
No ☐

If yes, how is this information supplied?

With **each item** for the following PPE _____

With **each package of items** for the following PPE _____

Please enclose the data sheets or information you provide with the PPE.

3. Do you inform your customers that the PPE may cause heat-related health problems? Yes ☐
No ☐

If yes, which items of PPE do you provide this for?

4. Do you consider the likelihood of heat strain in the design of your PPE? Yes ☐
No ☐

5. Do you use any of the following standards when designing or producing PPE?

Wet Bulb Globe Temperature Index (BS EN 27243:1994 / ISO 7243:1989) ☐

Evaluation of thermal strain by physiological measurement (ISO 9886: 1992) ☐

Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate (ISO 7933:1989) ☐

American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values ☐

Other, please specify: ☐

None of these ☐

6. We may wish to follow up some of your answers with a brief telephone discussion. If you would be willing for us to do this please fill in the details below:

Name: _____

Company name: _____

Tel: _____

***Thank you for completing the questionnaire.
Please return it as soon as possible in the reply paid envelope provided to:***

***Margaret Hanson
Institute of Occupational Medicine
8 Roxburgh Place, Edinburgh, EH8 9SU
Tel: 0131 667 5131***

Appendix B

Questionnaire to health and safety specialists



Heat strain in workers wearing PPE

For the attention of the person in your organisation responsible for health and safety policy.

Workers who wear Personal Protective Equipment (PPE) may suffer heat strain in some working conditions. The British Standards Institution (BSI) is managing a project, funded by the Department of Trade and Industry, to prepare a draft British Standard which gives ways of assessing the likelihood of heat strain for workers wearing PPE and ways of managing this risk. The Institute of Occupational Medicine has been contracted by the BSI to prepare the draft standard.

We are asking you to support this work by completing this short questionnaire. The information you give will be treated in strictest confidence and will be used only for the purpose of this research.

In order to minimise the effort you need to complete the form, we would like you to concentrate on those items of PPE that could significantly affect heat strain; for example, those that cover a significant proportion of the body, prevent evaporation of sweat, are heavy or restrict movement.

Heat strain may occur when wearing these clothing, even at relatively low environmental conditions. Heat strain could result not only in workers feeling hot, but also nauseous, 'tingly', irritable and weak.

1. Do your workers work in conditions where there may be risk of heat strain due to the PPE?

Yes ☐  go to Q 2

No ☐  go to Q 3

2. Specify the situations in your organisation where workers wear PPE, and where there may be a risk of heat strain. If possible, indicate the range of environmental conditions to which they may be exposed, and the forms of PPE which they wear.

Work situation/type of work	Temperature / humidity	Typical duration of exposure	PPE worn

Continue on a separate sheet if necessary

3. **Do you undertake any risk assessments of the likelihood of heat strain occurring for workers wearing PPE?**
- Yes ☐  go to Q 4
- No ☐  go to Q 7

4. **Do you use any of the following documents in this risk assessment?**

Wet Bulb Globe Temperature Index (BS EN 27243:1994 / ISO 7243:1989) ☐

Evaluation of thermal strain by physiological measurement (ISO 9886: 1992) ☐

Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate (ISO 7933:1989) ☐

American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values ☐

Others, please specify: _____ ☐

None of these ☐

If you do not use any of these documents, please explain how you undertake a risk assessment of heat strain

5. **If you have experienced any difficulties in using these documents for risk assessment of workers wearing PPE, we would like to hear about it. Please comment below.**

Continue on a separate sheet if necessary

6. Which factors do you consider when undertaking a risk assessment of heat strain?
We would like to find out the level of detail that you go into when conducting an assessment, so that we can ensure the draft British Standard is appropriate.

Environmental temperature (dry-bulb)	☐
Wet-bulb temperature	☐
Air speed	☐
Radiant heat load	☐
Duration of exposure	☐
Material of clothing / PPE	☐
Amount of the body covered by clothing / PPE	☐
Type of work being undertaken (metabolic rate)	☐
Experience of the worker	☐
Age of the worker	☐
Acclimatisation of the worker	☐

7. To reduce the risk of heat strain, do you control or restrict the work of workers wearing PPE in any way? Yes ☐

No ☐

If yes, please explain how

8. We may wish to follow up some of your answers with a brief telephone discussion. If you would be willing for us to do this please fill in the details below:

Name: _____

Company name: _____

Tel: _____

***Thank you for completing the questionnaire.
Please return it as soon as possible in the reply paid envelope provided to:***

***Margaret Hanson
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8 Roxburgh Place, Edinburgh, EH8 9SU
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Appendix C

Detailed comments on existing Standards

CORRECTIONS TO BS EN 12515

During the development of the standard, some anomalies or inaccuracies became apparent in the existing Standard BS EN 12515. These are documented below.

The scope (page 4)

The second paragraph of the scope states that 'the various terms used in the determination of the required sweat rate show the influence of the different physical parameters of the environment on the thermal stress experienced by the subject.' No mention is made of the metabolic heat production rate or the clothing insulation. The next sentence refers to modifications to parameters to reduce the risk of physiological strain, and since the parameters of metabolic heat production rate and clothing can be modified to reduce physiological strain, these should be mentioned in the previous sentence.

Section 4.1.3 page 6

Reads: 'The heat flow by respiratory evaporation may be expressed, in principle...'
Should read 'The heat flow by respiratory *convection* may be expressed, in principle...'

In determining respiratory heat loss in the lungs, the equation for convective and evaporative heat loss both include a component for body surface area rather than lung surface area. It is accepted that lung surface area involved with gas exchange will vary with metabolic heat production rate, and may therefore be difficult to determine. However it must be questioned whether body surface area is an appropriate indication of lung surface area. Two questions arise: is there scope for refining this element and is it a significant factor in heat exchange? Except in extreme circumstances where cool air is supplied to the lungs (closed circuit BA), it is thought that this may not be a significant route of heat loss, and that the approximation may be sufficiently accurate.

The definition of specific heat of dry air should read:

'C_p is the specific heat of dry air at constant pressure, in joules per kilogram of dry air *per degree kelvin*'

Section 4.2 (page 8)

Below equation 11, the statement: 'r_{req} is the evaporative efficiency of sweating (dimensionless) which corresponds to the required skin wettedness'.

The term 'corresponds' in this context actually means 'is related to'. The term 'corresponds' can imply that it is the same as.

Basic Program

Line 790 definition of P(12) the calculation of mean skin temperature as mean skin temperature is derived from several parameters added or subtracted together. Most of these are contained in line 780. The final parameter is that for clothing insulation - P(10). This should be multiplied by a constant, which in the equation presented on page 19 is 3.57. The value used in the program is 0.533:

$$P(12) = P(12) - .553 * P(10)$$

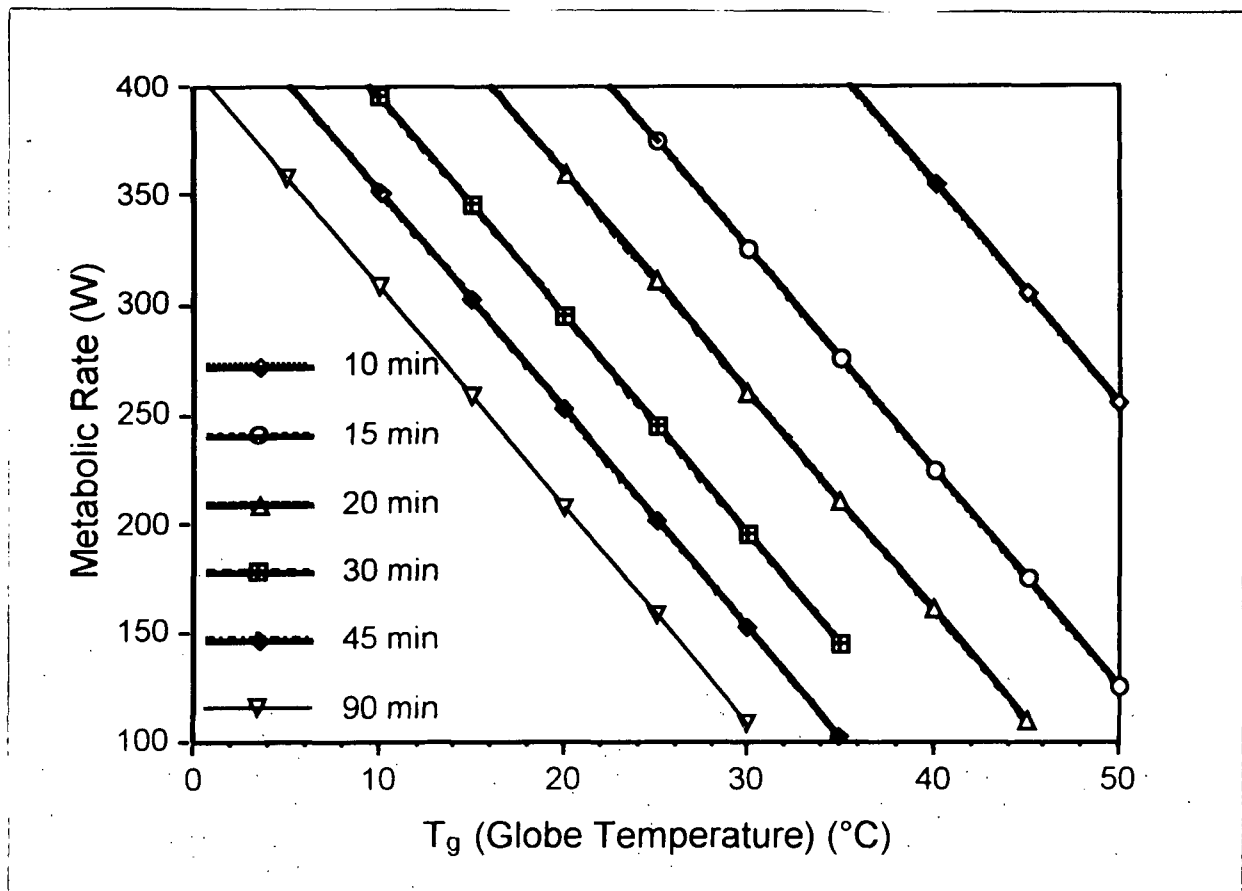
where P(10) is the clothing insulation value.

Line 850 definition of P(16) the constant used is 5.619 in the text (page 11) it is given as 5.624. Although the difference is not large, it is important that the same constant is used in the equation and the Standard.

Bernard (1998) reports that ACGIH are considering the use of suggested stay times for different metabolic heat production rates, based on the ambient globe temperature. These are shown in Figure 1. This recognises that the wet bulb temperature is not relevant when this type of clothing is worn. Although this assessment is a different approach to that used in WBGT, it may provide a more accurate prediction of heat stress when wearing this clothing. Further information on this should be considered for the draft Standard.

Discussions with experts suggests that there is some concern about the inclusion of correction factors for water vapour impermeable clothing. 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 they should be applied to the WBGT index. 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). Based on these decisions to include a correction for water vapour impermeable clothing to the WBGT index, the -10°C correction factor was recommended as appropriate, based on the scientific literature reported here.

Figure 1. Chart recommending stay times while wearing vapour-barrier, total encapsulating clothing as a function of globe temperature and metabolic heat production rate, from Bernard (1998).



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